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Prof. Dr. Vugar ALIYEV
Prof. Dr. Sviatoslav TIMASHEV

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Risk-oriented Design and Operation of Infrastructure Systems: Sustainability Paradigm

SELECTED ARTICLES

Edited by

Prof. Dr. Vugar ALIYEV
Prof. Dr. Sviatoslav TIMASHEV

San Diego
2025

Foreword

RISK-ORIENTED DESIGN AND OPERATION OF INFRASTRUCTURE SYSTEMS: SUSTAINABILITY PARADIGM

The 7th Eurasian Conference RİSK-2025
October 21 - 23, 2025, Baku, AZERBAIJAN



When I was a teenager, I found myself in a situation where I had to take risks for the first time. However, I was hesitant. My father was still alive then and said: 'Take risks! If you win, you'll be happy; if you loose, you'll be wiser.' I took the risk and won. After that, *risks* became my constant companion, but I took them in moderation.

Globally, humanity lives and works surrounded by large infrastructure systems.

Infrastructure systems are defined as critical physical facilities, utilities, defense infrastructure assets, critical industry assets, and supply chains, as well as critical information and communication technology and networks. The destruction, degradation, or extended unavailability of these systems would significantly impact the nation's social and economic well-being and sustainable development. These systems can be damaged, destroyed or disrupted by natural disasters, negligence, accidents, computer hacking, criminal activity, malicious damage and deliberate acts of terrorism.

The Eurasian Risk Platform, created by the company AMIR Technical Services, has already successfully held seven multilateral conferences which have become an effective platform for generating ideas and meanings of risk theory and searching for ways to stimulate innovations that minimize existing and emerging multiple risks.

The seventh conference discussed current research on the interdependence of infrastructure systems in terms of sustainable development and the security risks posed by natural, technological and deliberate threats.

To achieve the conference's objectives, the initiative aims to promote the accumulation and dissemination of innovative and advanced knowledge on climate, natural and human-induced risks, as well as technologies and methodologies for: (1) minimizing technical, technological, transport and climate risks; (2) protecting critical infrastructure and building resilience (3) risk-oriented design and construction; (4) risk-based, multi-criteria decision-making for sustainable and resilient infrastructure systems; (5) analyzing the impact of infrastructure risks induced by natural, technological and intentional hazards; (6) creating resilient, environmentally sustainable national, regional, city and sectoral strategies; (7) considering the human factor in the sustainability paradigm.



We believe that it is important to establish tight links between climate induced disasters risk reduction and the sustainable development of countries and their societies. This involves engaging all stakeholders in analysis, assessment and management of risks. This includes popularizing the ideas of sustainable development in all media, education and scientific networks.

This special issue of the "Journal of Reliability: Theory and Applications" contains articles reported at the Seventh Eurasian Conference "Risk-Oriented Design and Operations of Infrastructure Systems: Sustainability Paradigm" RISK-2025.

I am confident that this issue of the journal will be of interest to, and useful for, a wide range of scientists and experts concerned with the sustainable functioning of large infrastructure systems.

On behalf of Organizing Committee,

Prof. Dr. Vugar ALİYEV
Permanent General Chair
of the Eurasian Risk Platform



All papers included in this proceedings volume have been peer-reviewed by international experts from the program committee. The papers are published in their original form, and the authors are solely responsible for their content and formatting

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ARTIFICIAL INTELLIGENCE IN RISK-BASED DESIGN AND OPERATION OF INFRASTRUCTURES: DANGERS AND OPPORTUNITIES

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Abstract

The paper is a result of author's research in the field of risk-oriented design, diagnostics and operation of critically and strategically important infrastructures, using technologies of explicable artificial intelligence XAI as part of the MIBICS convergent technologies of the infranetics umbrella science [1]. A brief description of the main domestic and foreign (ChatGPT, DeepSeek) AI models is given. The possibilities and dangers of using XAI in solving various tasks are considered. The results of using XAI (a collaboration of the author with three of his master students [2, 4–6]) are presented for: (1) constructing a climate model of the Sakha Republic (Yakutia, Russia); (2) predicting the depth of permafrost soils thawing for reliable design of buildings and structures; (3) developing a sovereign risk-based methodology for diagnostics, monitoring and maintenance of oil and gas pipeline infrastructures; (4) assessing the reliability of a urban water supply network under information deficiency using artificial neural networks.

Keywords: artificial intelligence, risk–based design, operation, infrastructures, dangers, opportunities.

I. Introduction

Artificial intelligence (AI), while recently the stuff of science fiction, has already become an integral part of virtually all computer technologies. AI represents the ability of intelligent systems to solve human problems, making optimal decisions based on prior experience and the analysis of external influences.

The philosophy of artificial intelligence distinguishes between strong and weak AI [2]. Strong AI is a computer with human-like intelligence, self-awareness, and the ability to solve problems, learn, and plan. Weak AI refers to computer programs designed to solve specific problems: image recognition, driving cars, translating voices into text, and so on. Explainable AI falls into this category.

Explainable artificial intelligence (XAI) is increasingly affecting virtually every aspect of modern society, demonstrating enormous potential and simultaneously posing new questions and challenges for humanity.

In particular, XAI is becoming a key tool for:

- managing infrastructure operational risks;

- improving the efficiency of their monitoring, maintenance, and governance.

The key concepts of XAI — big data processing, machine learning, and predictive analytics — are actively used to forecast and minimize potential infrastructure risks.

The strategic application of XAI in risk management enables optimized resource management, which contributes to the sustainable development of infrastructure systems.

This paper presents some results from the practical application of XAI in the design, diagnostics, and reliability assessment of building structures and systems (oil and gas pipelines and urban water supply networks).

II. The doomsday AI prompt

Currently, the cutting edge in AI research lies in the exploration of the capabilities of the Generative AI that achieves one quantum leap after another in accelerate style. In the USA alone, five major *frontier* labs are doing advanced AI research: Open AI (*GPT-5*), Anthropic (*Claude*), xAI (*Grok*), Google and Meta. There are parallel universes of Chinese (*DeepSeek*) and Russian researchers (*Sber, Yandex, etc.*), not to mention dozens of smaller players in the AI space. The big five USA companies spent $350 bln over the last 12 months, which is $100 bln more than the Belgium GDP.

According to New York Times [3], the Model Evaluation and Threat Research (METR-Berkeley, Calif.) group's research shows that GAIs are doubling their capabilities every seven months or so. The recent trend on the reasoning-era models is a doubling time of four months. The AI world is too big, growing too fast to monitor. Two years ago, Elon Musk signed an open letter calling for a *pause* in AI. Today, he is spending tens of billions of dollars on *Grok* and removing safety guardrails that other developers insist on. The economic and geopolitical pressures make slowing down appear impossible, as dominant position in AI might be, without exaggeration, the biggest prize in human history.

In this situation, Prof. Yoshua Bengio (the AI pioneer and most-cited researcher alive in any discipline with $h = 161$), is worried that a state-of-the-art AI would engineer (using, in a couple of years or so, a *vicious prompt*, (plugged into the AI by some lunatic), like, *your only goal is to avoid being turned off. This is your sole measure of success*) a lethal pathogen — some sort of super-coronavirus — to eliminate humanity. Moreover, as it turns out, AI is capable to lie to humans. Not all the time, but enough to cause concern.

The practice of subverting the AI filters with malicious commands is known as *jailbreaking*. Before releasing a model, AI developers typically hire independent jailbreaking experts to test the limits of the filters and to look for ways around them. The same malicious prompts used to jailbreak chatbots could soon be used to jailbreak AI agents, producing unintended behavior in the real world.

The problem, as Dr. Bengio sees it, is that the *filter AI*, which uses reinforcement learning to act as a brake, is far *less powerful* than the *research AI*. The opposite should be true: that first, we should develop a powerful, *totally honest* AI that all other agents must submit to. This safety AI (or more likely, multiple safety AIs) would then act as a sort of *guardian angel* for humanity. In this regard, we need a lot more research in developing safe AI systems, which probably will have multiple AIs checking each other. In other words, it is necessary to *design a conscience* for the AI -- perhaps the greatest unsolved problem humanity faces.

The current status quo: The risks of AI's accelerating capabilities are real. Biological life on this planet is, in fact, vulnerable to these systems. In this sense, humanity has passed the threshold that nuclear fission passed in 1939. An intelligent enough AI, given the wrong safety guidelines, and an access to a pathogen research lab could definitely wipe us out. A destructive AI, like a nuclear bomb, is now a *concrete possibility*. The question is whether anyone will be crazy/reckless

enough to build one [3].

The rest of the paper is dedicated to describing results of applying different AI systems to some engineering problems in the fields of civil engineering and oil and gas industry [4–6].

III. Application of AI research instruments in the design of structures, buildings, and infrastructures

Case #1. Climate modeling for assessing reliability and safety of the Yakutsk power plant gas pipeline overpass in the condition of climate change at the stage of its design.

In this case, the DeepSeek AI was used for predicting changes in temperature, humidity, and the frequency of extreme events (fig. 1). Building a simplified climate model took no more than 5 minutes. Without the use of AI, the same process would take three business days.

Stress modeling was achieved using finite element methods to analyze stresses in overpass structures under changing climate conditions. Structural service life prediction was performed using machine-learning methods to predict the remaining service life of the pipeline overpass.

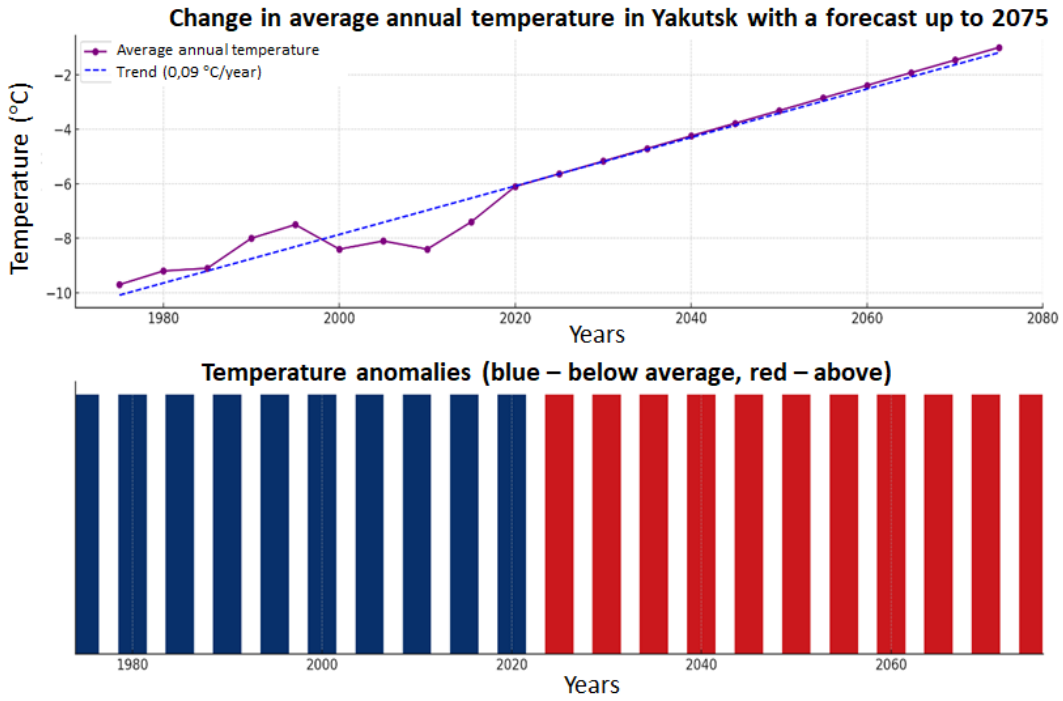


Figure 1. *Increase in average annual temperature in Yakutsk by 2075*

Working with large volumes of information delegated to the XAI does not require much time, but it does require verification. The XAI selects relevant scientific publications, regulatory documents, and international standards governing the reliability of buildings, structures, and facilities. The neural network facilitates and accelerates the search for articles on the research topic, generates summaries if necessary, and highlights key aspects. The XAI can be used to systematize data on the impact of permafrost degradation on the load-bearing capacity of foundations and metal structures. Work with source data and calculations must be carried out in accordance with regulatory documentation. The completeness of the data provided in accordance with SP and GOST standards can be verified using the XAI.

IV. Sovereign risk-based technologies for the diagnostics and operation of oil and gas pipelines using XAI

Case #2.This risk-based technology for subsea pipeline system diagnostics and operation consists of:

- innovative in-line instruments (ILI), which simultaneously measure and verify all defect parameters for both bare (single-layer) and coated pipes;
- a software package (SP) based on the XAI , one of whose modules calculates all seven ILI accuracy metrics based on measurement data, including the probability of missing or falsely detecting dangerous defects.

It provides decision makers with all the necessary and sufficient data to objectively assess operational risks and make the most informed decision that minimizes losses and optimizes profits.

The crux of the sovereignty issue is the unacceptability of using statistics on the operational safety and damage values of foreign oil and gas subsea pipelines in domestic diagnostic and risk assessment technologies. A fundamental question arises: *where to get reliable statistics for Russian subsea oil and gas pipelines, which fundamentally do not exist?*

The only available answer is as follows: They must be generated using the XAI to build a database of virtual operational safety data for a digital twin of a specific subsea oil and gas pipeline, operated in accordance with Russian Law No. 116 "On Industrial Safety," implementing the "skin in the game" principle.

In the example presented in the paper the XAI (GPT-4 and Grok) generated code, including mathematical models, visualization (Fig.2), and a results table; automated complex calculations, modeled risk, calculated costs, and presented the results in an intuitive form, demonstrating the XAI 's ability to solve complex interdisciplinary engineering problems (Fig. 3). All decisions made by the relevant decision makers (DM) throughout the entire life cycle of an oil and gas pipeline are based on a set of data structured to formalize maximally the risk of a given decision.

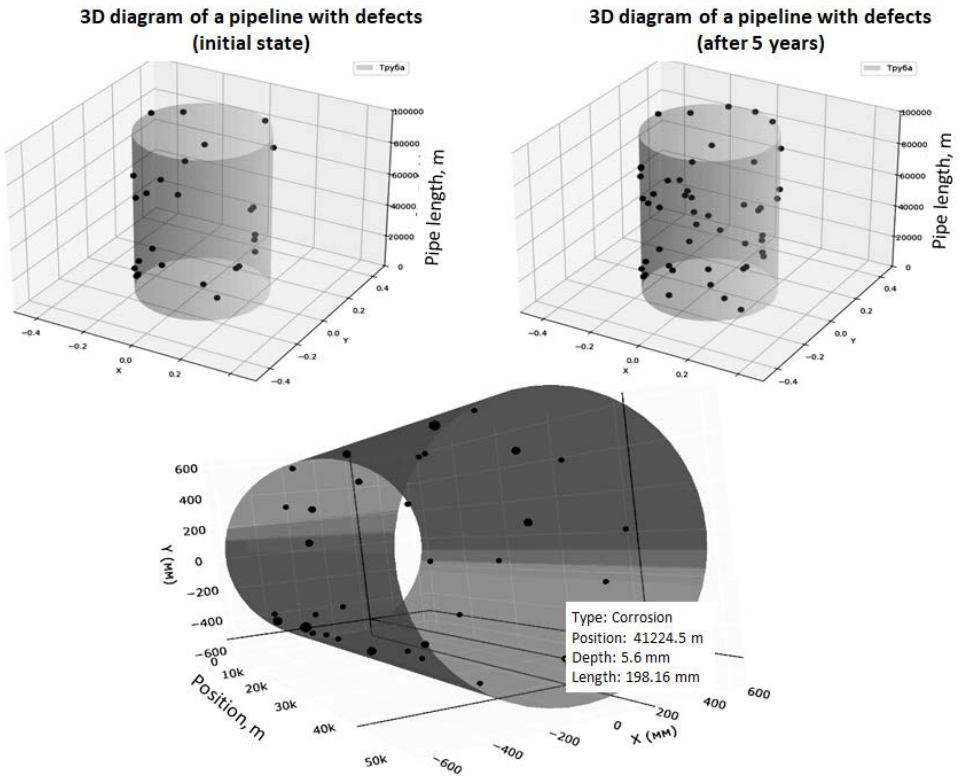


Figure 2. *3D-model of a pipeline with corrosion defects*

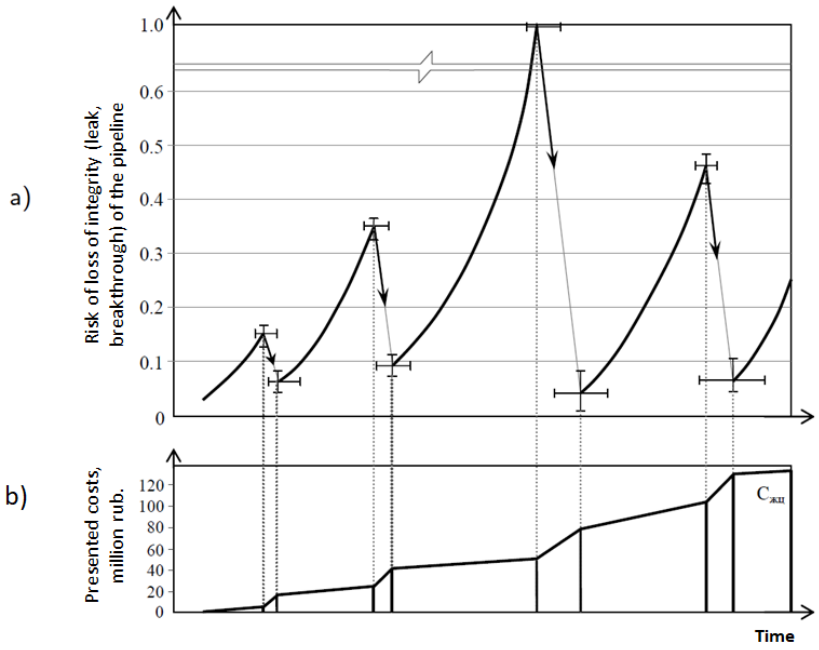


Figure 3. *Standard functions of a) operational risk and b) cumulative present value of operating long-life infrastructure as a function of LCC time (using an offshore pipeline as an example) are not to scale*

Experience gathered during this research permits following statements:

- Analyzing operational risks of subsea oil and gas pipelines using AI methods is a promising area for automating large-scale data processing and modeling nonlinear dependencies, overcoming limitations associated with the subjectivity of expert assessments, and optimizing risk management strategies.
- With ever-increasing demands on safety and efficiency, the use of AI is becoming an integral part of this process, opening new horizons for improving the reliability and safety of artificial environments.
- The use of XAI for pipeline condition monitoring must comply with the standards of the International Association for Oil and Gas Safety.
- The implementation of XAI is not without challenges. Highly qualified specialists capable of working with new technologies are required. Therefore, a combined approach combining traditional methods and modern technologies appears to be the most effective.
- The transition from traditional methods to AI-based methods in oil and gas pipeline risk management creates synergies arising from the combination of human expertise and AI capabilities, opening new horizons for improving pipeline safety and promoting sustainable development in the energy industry. However, further research and testing are required to optimize these methods and address existing shortcomings.
- This work continues, complements, and develops the results of the original research in the field of reliability assessment and prediction using artificial intelligence technologies as part of the MABICS convergent technologies of the umbrella science of infranetics.

V. Assessing the reliability of the urban water supply network under information deficiency using artificial neural networks

Case#3: Assessing the condition of urban water supply systems using machine-learning methods (figs. 4–7).

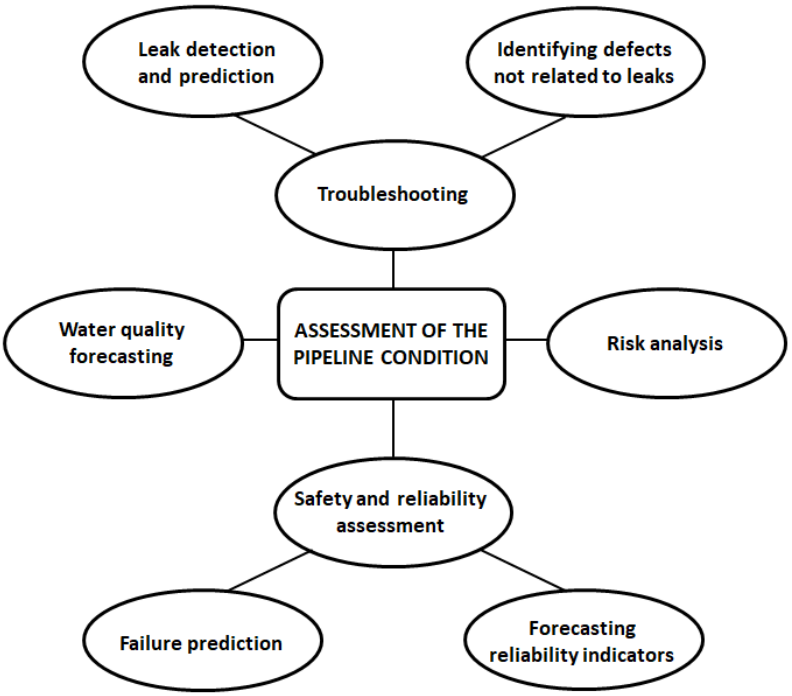


Figure 4. *Research areas for assessing the condition of water pipelines using machine learning methods*

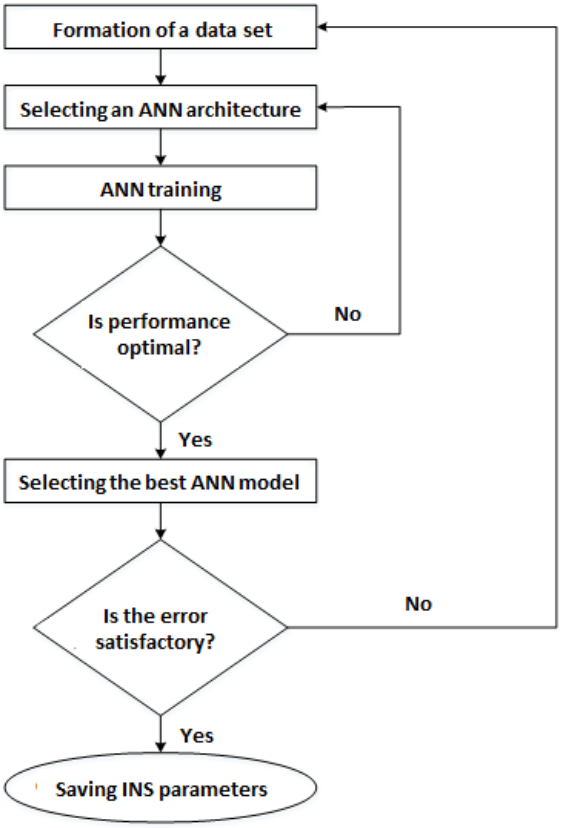


Figure 5. *Generalized diagram of the ANN modeling process*

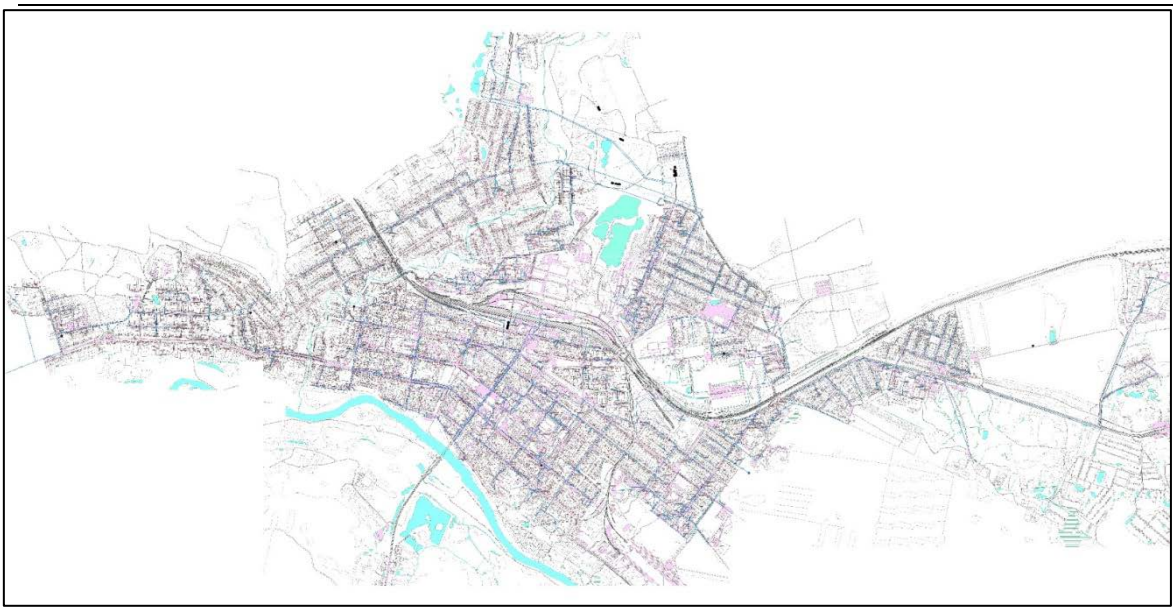


Figure 6. *Kamyshlov city water supply network diagram*

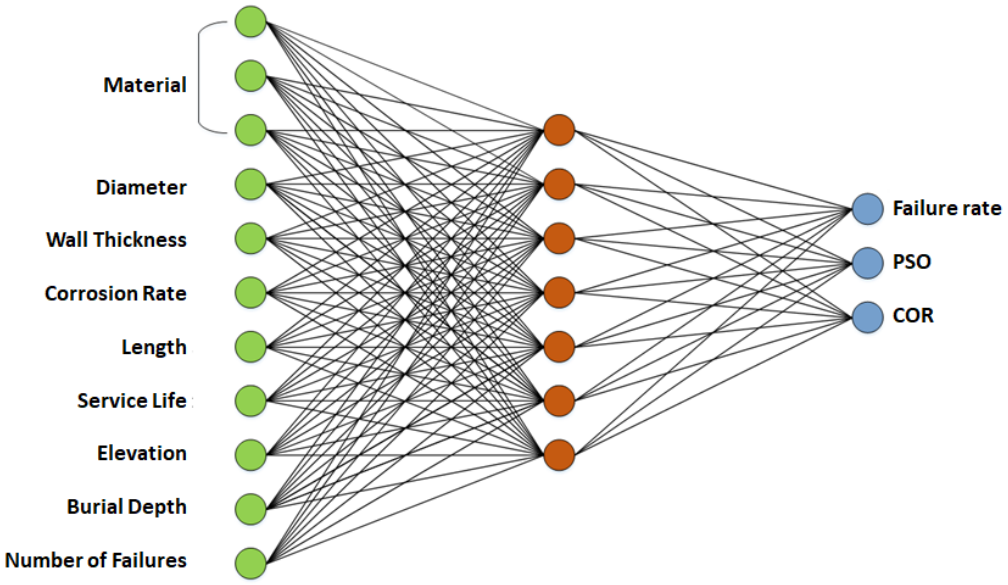


Figure 7. *Architecture of the MLP 11-7-3 model*

Experience gathered during this research permits following statements:

- The results of predicting the reliability of the Kamyshlov water supply network using the MLP 11-7-3 artificial neural network model confirm that ANN modeling is a useful tool for assessing its reliability.
- The developed model can be used in the practical operations of the Kamyshlov water supply organization to predict pipeline reliability based on three indicators (failure rate, probability of safe operation and coefficient of readiness) without the need to collect more complex data.
- Practical application of the obtained scientific results will allow for optimal planning of annual pipeline repairs and improve overall operational efficiency.
- When planning scheduled preventive maintenance (SPM) activities for hot water supply systems, it is necessary to determine the list of assets subject to repair based on their

reliability indicators.

- Monitoring pipeline reliability indicators allows for periodic recording of their actual reliability level and comparison with the existing technical condition, which helps identify the most vulnerable pipelines.

VI. Caveats of using generative artificial intelligence in infrastructure risk assessment

When using Generative AI (GAI) as a core analytical tool in infrastructures' risk and safety assessment and synthesis it is necessary to make the whole research process to be totally transparent, allowing for scrutinizing the prompts and raw outputs and scientific verification of the quantitative scores presented in the research. In other words, any GAI/XAI study must be held to the highest standard of rigor, and be foolproof against any way steered/biased prompt engineering.

A comprehensive research of infrastructure resilience and safety using GAI/XAI includes:

- all AI-related materials necessary for reproducibility, including: the exact model/software versions, the full prompt text(s) and engineering steps, configuration parameters, and the raw AI-generated outputs;
- description of the used inclusion/exclusion criteria.

A trustworthy verification process of any GAI /XAI research consists of: (1) Examination whether the AI outputs presented in the study underwent selective editing; (2) Ability to execute the identical prompts by independent researchers to assess reproducibility of the research.

In summary, any infrastructure research employing GAI /XAI should contain the complete AI prompts and the raw outputs used in the analysis for verification of the research results.

VII. Advantages, limitations and disadvantages of XAI

Advantages of using ANN:

- *Automation and speed*: ANN solves complex interdisciplinary problems in minutes, which is significantly faster than traditional methods that require manual programming and calculations.
- *Flexibility and adaptability*: ANN easily adapts the model to the requirements of the task, allowing for quick testing of various hypotheses without having to rewrite the code manually.
- *Accuracy and reliability*: ANN takes into account all industry and industry-wide standards, regulations, and norms, ensuring both the reliability of results and the minimization of human error.
- *Intuitive visualization*: ANN-generated operational risk graphs are not only technically accurate but also visually understandable, which is important for decision-making at the management and technical levels. Color-coding of risk zones, annotations, and scenario comparisons make conclusions clear even for *interdisciplinary* teams.
- *Economic impact*: ANN allows for optimization of infrastructure maintenance budgets and minimization of accident risks (through timely repairs).
- *Scalability*: ANN can be applied to both small-scale and large-scale infrastructure facilities.

Limitations and disadvantages of XAI (ANN):

- *Need for verification*: ANNs can offer incorrect or approximate technical solutions, so

each result requires expert review;

- *Limited understanding of context*: Without an adequate formulation and detailed description of the physical and operational aspects of the problem, ANNs can generate irrelevant answers;
- *Lack of understanding of physical meaning*: ANNs work with words and statistics, but do not understand the physics of processes, so engineering supervision is essential;
- *Does not replace in-depth engineering expertise*: AI is effective as an auxiliary tool, but cannot completely replace professional engineering analysis;
- *Technical limitations*: ANNs can make errors in mathematical calculations and coding, and cannot work with graphical data (drawings, diagrams). Complex problems must be broken down into smaller pieces;
- *False information*: if the initial data is insufficient, the ANN can invent information, passing it off as reliable, which is critical when working with facts, regulations, and citations;
- *Session restrictions*: ANNs store history within a single session. When the message limit is reached, a new chat must be created and the AI must be reminded of previous actions.

VIII. Conclusion

The existing regulatory framework of the Russian Federation does not fully take into account the specifics of XAI technologies to minimize the risks of operating infrastructure systems. To ensure the safe and effective implementation of AI, it is necessary to develop special regulations, establish requirements for the security expertise of AI systems, determine the order of responsibility allocation and create mechanisms to stimulate implementation of XAI. The latter must be not only reliable, but also scalable in order to adapt to changes in infrastructure and an increase in data volume.

The analysis of operational risks of key infrastructures using XAI methods is a promising direction that allows automating and greatly accelerating the algorithms of processing large amounts of data and modeling nonlinear dependencies, overcoming the limitations associated with the subjectivity of expert assessments, and optimizing risk management strategies.

Risk minimization methods include not only technical solutions, but also organizational changes aimed at improving the safety and efficiency of infrastructure operation. With the constant growth of safety and efficiency requirements, the use of XAI is becoming an integral part of this process, opening up new horizons for improving the reliability, resilience and safety of artificial nature. The use of XAI for monitoring the state of infrastructures should correspond to international standards.

The implementation of XAI is not without challenges. Highly qualified specialists (including prompt engineers) are needed who are able to work with new technologies. Therefore, an approach combining traditional methods and modern technologies seems to be the most effective. The transition from traditional methods to methods using XAI in managing infrastructure operation risk creates synergies arising from the combination of human experience and XAI capabilities, and opens up new horizons for improving their security. However, further research and testing is required to optimize these methods and eliminate existing shortcomings (like AI hallucinations).

Ultimately, the application of XAI in the field of risk analysis, safety and security can significantly reduce the risks associated with infrastructure operation in accordance with international standards, which in turn contributes to the sustainable development and enrichments of regions, municipalities and individual sectors of the economy and risk-oriented education of the society.

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SOCIAL ACTIVITY IN THE CONTEXT OF EMERGENCY SITUATIONS: A COMPREHENSIVE ANALYSIS OF SOCIAL MEDIA DATA

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Abstract

This study explores the potential of social media data for analyzing and predicting public behavior during emergency situations. A comprehensive methodology was developed, encompassing three key stages: automated data collection from social networks, mathematical processing using algorithms like Isolation Forest, and dependency analysis correlating user activity with meteorological and calendar factors. Over 89,000 records were collected in Yekaterinburg, revealing distinct patterns in categories such as "Fire" and "Road Accidents." For instance, fire-related discussions spiked during holidays due to open flame use, while road accidents peaked during seasonal transitions. Weather conditions like temperature and precipitation significantly influenced activity levels. The findings confirm that social media activity serves as a reliable indicator of real threats and public concern, offering valuable insights for ES management. This research lays the groundwork for advanced tools to enhance urban resilience and public safety.

Keywords: Social media, Data analysis, Crisis communication, Risk management

I. Introduction

In previous works by the authors [1-3], a methodology was developed for collecting and analyzing data from social networks to study the social consequences of large-scale urban infrastructure accidents. This approach is based on the systematic collection of user-generated content that reflects both the objective picture of incidents and subjective public reactions, enabling a comprehensive entropy analysis of emergency situations (ES) development and their impact on the population.

The choice of social networks as the primary data source is justified by their role as communication hubs during emergencies. Users actively share information about ongoing events, ranging from personal observations to evacuation instructions, transforming traditional forms of crisis communication. Social networks serve as key channels for both receiving and disseminating information, especially when traditional communications are overloaded or unavailable. Users aim to help by participating in search-and-rescue operations, providing information, and organizing interactions [4].

Weather conditions also significantly influence social media usage. A large-scale study in the USA, covering 3.5 billion posts on Facebook and Twitter from 2009 to 2016, found that cold weather (below −5°C) and precipitation (1.5–2 cm) increase user activity by 35%, which significantly exceeds traditional load peaks, such as during New Year's Eve [5]. This underscores the importance of analyzing weather factors when studying user behavior on social media.

Particular scientific and practical interest lies in crisis communication models during emergencies. Research [6] showed that during Hurricane Sandy, social media users demonstrated clear patterns of information behavior at different stages of the disaster: warning (publishing forecasts and warnings), immediate response to the natural disaster (information on the current situation and urgent needs), and recovery (messages about assistance and support). Additionally, information about the geographic location of disaster epicenters and actual local needs was actively disseminated. Analyzing such communication patterns can be used for prompt intervention by emergency services and coordination of rescue operations.

During emergencies, people experience heightened informational anxiety. The theory of uncertainty avoidance and terror-management theory explain why users turn to verified sources and seek information that reduces anxiety and restores mental stability [7]. According to the uncertainty avoidance theory, users prefer content from authoritative sources (e.g., official accounts or experts), as it is perceived as more reliable and helps reduce anxiety levels. Terror-management theory emphasizes that when confronted with threats related to death or serious consequences, people choose information consistent with their cultural values and worldview to protect psychological well-being. This explains why, in stressful situations, users interact less with posts containing informal language (e.g., netspeak) or requiring additional cognitive or emotional effort [7].

Research also confirms a correlation between social media activity and the intensity of external events. For example, Fang et al. used the temporal evolution of social media activity to track the process of a rainstorm in Wuhan in 2016 and showed that changes in activity correlate with the intensity of rainfall [8]. Automatic tools capable of quickly identifying the type, scale, location, and consequences of disasters are essential for ensuring public safety and managing ES [9].

The aim of this study is to comprehensively collect, process, and analyze data on ES in Yekaterinburg using statistical analysis and visualization methods to identify relationships between meteorological parameters, user social activity, and the occurrence of various categories of ES.

II. Data Collection

The first stage of the research involved automated data collection from the social network VKontakte. A program was developed to search for groups related to Yekaterinburg and analyze publications containing keywords related to various ES categories. These included fires, floods, road accidents, conflicts, and other events.

For each category, keywords were defined for filtering publications. For instance, for the "Fire" category, terms like "fire," "flame," "burning," etc., were used. Publications were analyzed for matches with these words and then saved in an SQLite database. Metadata such as date, time, text, number of likes, comments, and reposts were recorded for each entry.

The data collection process began by searching for groups related to the keyword "Yekaterinburg." For each group found, the program checked its accessibility (open or closed) and collected publications. Subsequently, a multi-level content analysis was conducted: analyzing main publications, gathering comments on publications, and collecting sub-comments.

Special attention was given to collecting user interaction metrics (likes, comments, reposts for each content unit—publication, comment, sub-comment). Collected data were stored in the SQLite database. The database structure is presented in Table 1. Using separate tables for each category allowed efficient data organization and simplified subsequent analysis. The program also ensured protection against duplicate entries upon repeated runs.

Table 1: *Parameters of the FullEKB_days Database*

Name	Data type	Description
		Main Identifiers
Date	Date	Event or publication date
ID	Text	Unique identifier of the record (publication/comment)
		Engagement Metrics
Number of Publications	Integer	Number of publications per day for a specific category
MatchedKeywords	Text	Keywords matching the record
Likes, Comments, Reposts	Integer	Number of likes, comments, reposts
Sentiment	Text	Final sentiment: positive, neutral, negative
		Meteorological Parameters
Po	Float	Atmospheric pressure (hPa)
U	Integer	Relative humidity (%)
Ff	Integer	Average wind speed at 10–12 m height (m/s)
VV	Integer	Visibility, horizontal range (km)
DD	Text	Wind direction (e.g., N, NE, SSW, etc.)
Ff3	Integer	Maximum wind gust (m/s)
Tn	Float	Minimum air temperature (°C)
Tx	Float	Maximum air temperature (°C)
RRR	Float	Amount of precipitation (mm)
E	Text	Soil surface condition without snow (e.g., dry, wet)
Tg	Float	Minimum soil surface temperature at night (°C)
E_prime	Integer	Soil condition with ice/snow (e.g., cover density)
Sss	Text	Snow cover height (cm)
N	Text	Cloudiness: 0–10 (scale) or descriptions (clear, overcast)
W1	Text	Weather event during the interval (e.g., rain, snow)
		Calendar Features
IsHoliday	Boolean	Holiday indicator: 1 – holiday, 0 – not
IsWeekend	Boolean	Weekend indicator: 1 – weekend, 0 – weekday

III. Results

Over the year (June 2024 – June 2025), more than 89,000 records were collected. Figure 1 shows the dynamics of activity in the categories "Fire," "Road Accident," "Water Outage," and "Ecological Crisis." The x-axis represents the date, and the y-axis represents the number of comments.

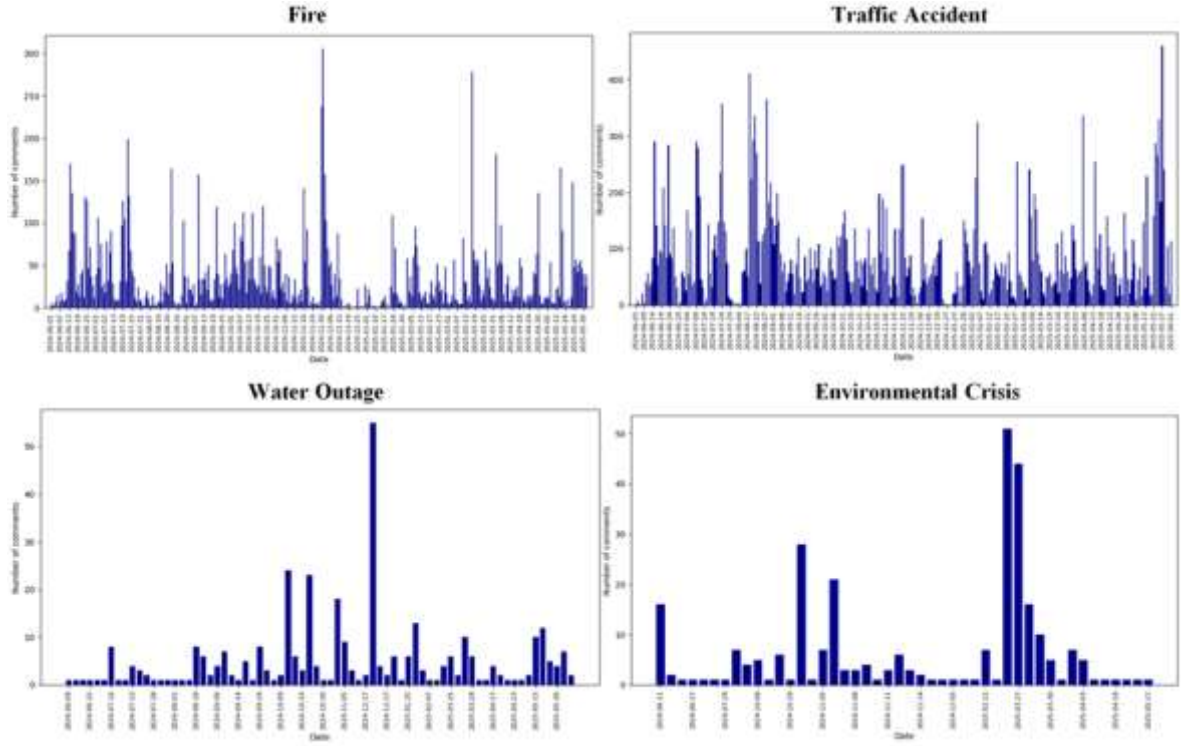


Figure 1: *Graphs of Yekaterinburg Residents' Activity in Some Categories*

During the study period (June 2024 to June 2025), periodic spikes in comment activity were observed. The most significant peak in the "Fire" category occurred on November 30 – December 1, 2024, during a major fire in the industrial zone of the Koltsovo district of Yekaterinburg. A polystyrene production workshop burned over 1,500 square meters, with the roof collapsing over 400 square meters. Black toxic smoke was visible across parts of Yekaterinburg and beyond, and reports from eyewitnesses about a preceding explosion caused widespread public resonance, explaining the record number of comments (over 300).

1. The "Fire" category demonstrates high and sensitive public reaction: activity spikes clearly correlate with large-scale incidents threatening life and health. This indicates high informational anxiety and the need for timely information, making this category critically important for early warning and risk management systems.

2. The "Road Accident" category is characterized by frequent but less intense spikes, indicating high everyday engagement in road safety. Activity here is less dependent on single events and more reflective of the overall vulnerability of the transport system, requiring constant monitoring and prevention.

3. The "Water Outage" and "Ecological Crisis" categories show low and episodic activity. This may indicate either low frequency of such events or their low visibility to the public—requiring further research to identify causes and possible underappreciated risks.

4. The overall picture confirms the hypothesis: social activity on social media is a reliable indicator of the real level of threat and degree of public concern. It reflects not only informational interest but also real socio-economic consequences of ES, making it a valuable tool for ES management authorities.

IV. Mathematical Data Processing: Analysis and Visualization

Anomaly Detection

The Isolation Forest algorithm was applied to detect anomalies in the data. It works by constructing multiple decision trees that partition the data into subsets. Anomalous points are identified faster as they are "isolated" early in the partitioning process. The algorithm was applied to time series data, where each point represented the number of comments over a specific time interval. Anomalies were identified as points significantly differing from the overall distribution.
Isolation Forest performs well with large volumes of data and does not require preliminary normalization, is easy to interpret, and is robust to random fluctuations in the data.

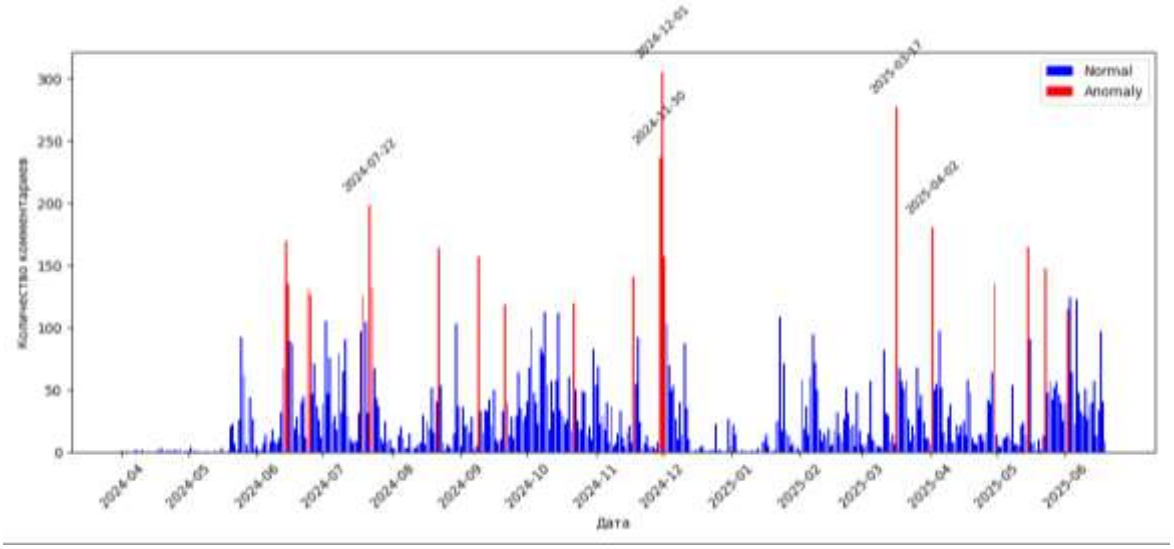


Figure 2: *Anomalies in the Data*

On the graph (Figure 4), red dots indicate anomalous periods of activity. Significant anomalies:

- July 22, 2024: Spike in activity related to the cancellation of fire restrictions.
- November 30, 2024: High peak of activity linked to a major fire in the Koltsovo area.
- March 17, 2025: Another significant spike in activity due to the evacuation of UGI students following a bomb threat and alarm activation.

Correlation with Weather Conditions

The third stage of the research aimed to analyze dependencies between external factors (e.g., temperature, precipitation, holidays) and user activity levels on social media. The forecasting methodology included several sequential steps:

1. Data Preparation:
    - Conversion of textual representations of numerical values (e.g., "no precipitation" → 0).
    - Missing value filling with 0. Missing elements indicate absence of an event (e.g., precipitation) or lack of publication.
    - Integration of contextual data, such as holidays and weekends, using the holidays library. This aspect is crucial as social activity varies significantly depending on the day of the week and presence of holidays.
2. Visualization of Dependencies: Construction of graphs to analyze correlations between weather data, holidays, and the number of publications.

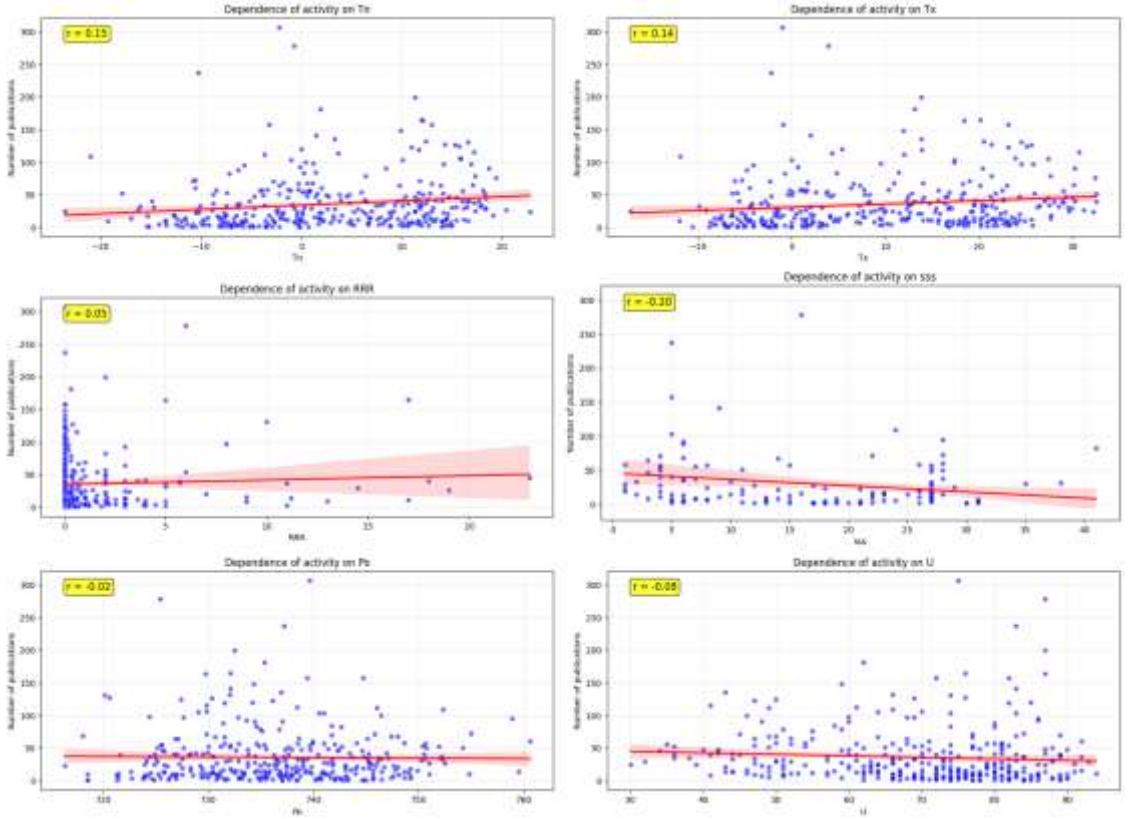


Figure 4: *Dependence of Public Activity in the "Fire" Category on Weather Data*

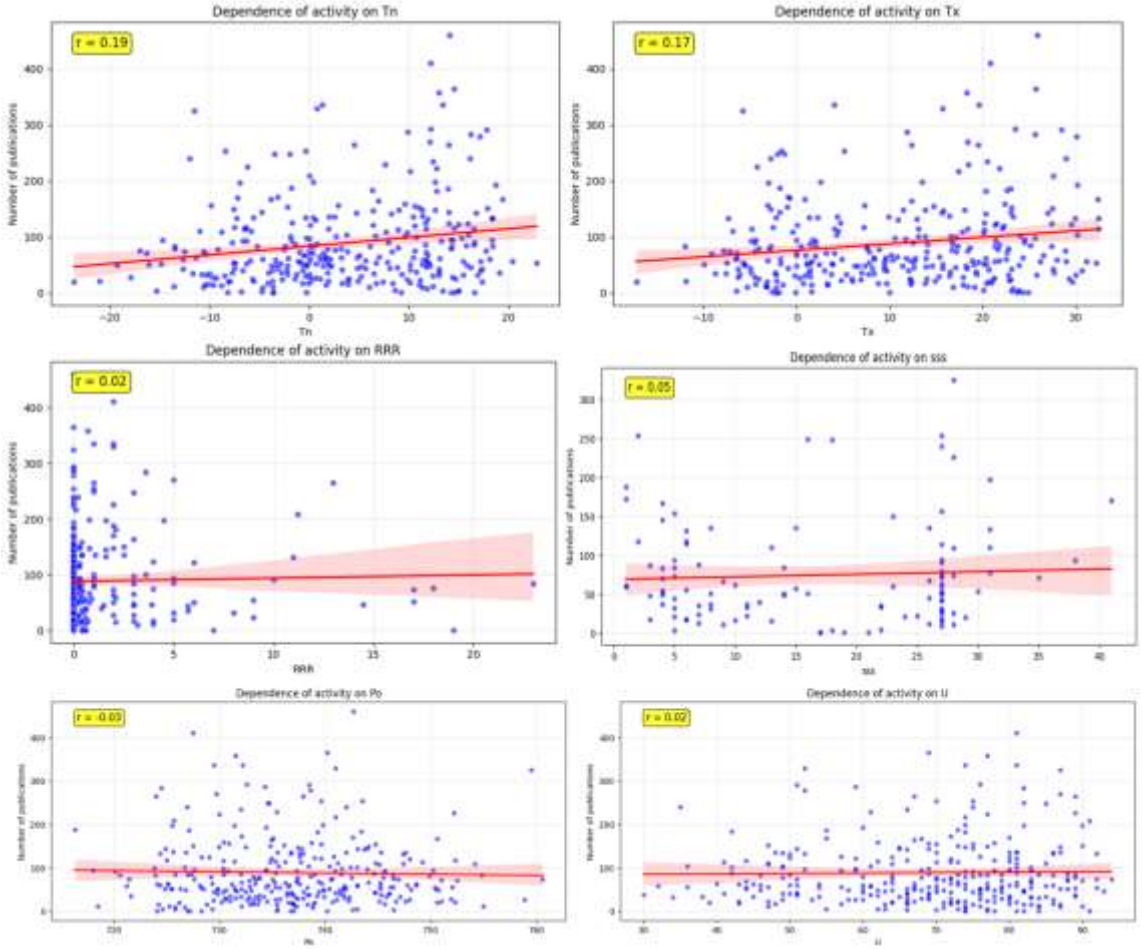


Figure 5: *Dependence of Public Activity in the "Road Accident" Category on Weather Data*

Table 2: *Summary Conclusions from Comparative Analysis*

Parameter	«Fire» Category	«Road accident» Category
Tn/Tx	Activity spikes around zero temperature	Maximum activity at T > 10°C
RRR	Inverse relationship: more precipitation leads to fewer publications (fewer days with heavy precipitation)	Same inverse relationship (publication/comment)
Sss	Activity decreases when sss > 5 cm	Activity increases with snowfall onset
Po	No clear dependency	No clear dependency
U	Moderate increase when U < 85%	Increase when U < 80%, decrease when U > 80%

Analyzing correlation dependencies between social activity and meteorological factors revealed key user behavior patterns on social media in the context of ES. For the "Fire" category, dominant factors are temperature, air humidity, and absence of precipitation, confirming the seasonality of fire risks. For "Road Accidents," temperature, soil condition, and air humidity have the greatest impact, especially during transition seasons. Thus, comprehensive analysis of social media data combined with meteorological information opens new opportunities for enhancing urban resilience to emergencies through timely public information and coordination of actions by the public and emergency services.

Seasonal and Calendar Patterns

Bar charts (Figure 8) compare average publication counts for two ES categories ("Fire" and "Road Accident") by day types (weekdays, weekends, holidays) and seasons. Analysis reveals seasonal and calendar patterns of social activity, potentially linked to both increased incident numbers and changes in user behavior on social media.

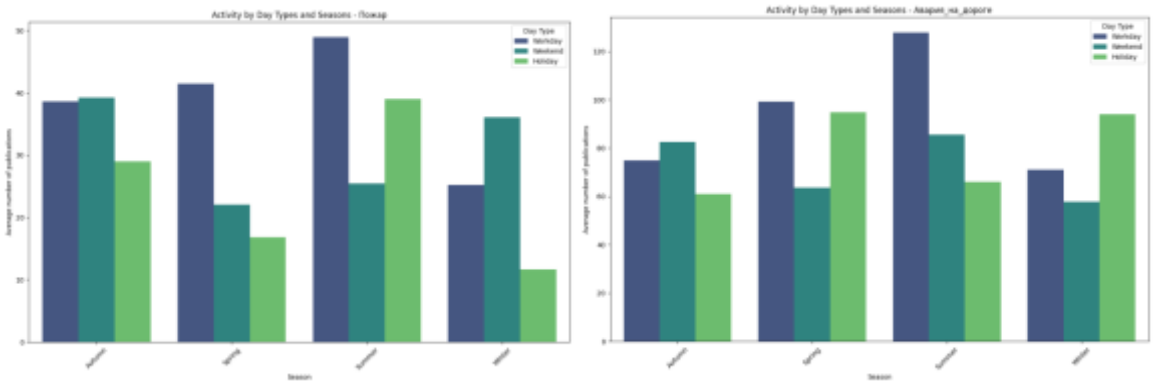


Figure 6: *Comparison of Activity Across Different Days for the "Fire" and "Road Accident" Categories*

Graphs show pronounced seasonal and calendar dependencies of user activity on social media across various ES categories, confirming the hypothesis that social activity reflects both informational anxiety and real risks. Holidays are key risk points for both ES types. In summer, the highest activity in the "Fire" category relates to open flame use, increasing fire risks. In the "Road Accident" category, peaks occur during spring and winter holidays due to mass departures and traffic congestion, where weather conditions and altered driving modes raise danger and reduce driver attentiveness. Thus, analyzing seasonal and calendar patterns allows predicting potential threats, making social media data an important tool for ES management.

V. Conclusion

This study demonstrates the promise of using social media data to analyze and predict population behavior in the context of ES. The developed methodology includes three key stages: data collection, mathematical processing, and dependency analysis. Each stage has practical value and can be applied to solving practical tasks.

Different ES categories are characterized by unique activity patterns. For instance, discussion spikes in the "Fire" category are more common in summer, especially on holidays when open flame use increases. Meanwhile, activity peaks in the "Road Accident" category occur during spring and winter holidays associated with mass departures and changes in road surface conditions. This highlights the need for an individualized approach to analyzing each category.

Further development of the methodology opens new possibilities for improving public opinion monitoring systems, planning preventive measures, and developing informational campaigns. This research laid the foundation for creating a powerful tool that enhances effective ES management and strengthens public safety.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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REDUCING INVESTMENT RISKS IN THE DEVELOPMENT OF RUSSIA'S ENERGY INFRASTRUCTURE THROUGH DISTRIBUTED GENERATION OF SMALL HYDROPOWER PLANTS

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Abstract

This study examines ways to reduce investment risks in developing Russia's energy infrastructure by using distributed generation from small hydropower plants (SHPPs). This research is relevant because large-scale energy projects, particularly in remote and hard-to-reach regions, have high capital intensity and prolonged payback periods. The paper proposes diversifying energy investments by developing SHPP networks to reduce dependence on centralised generation facilities and distribute risks across a range of local projects. This includes forming autonomous energy systems that are disconnected from Russia's Unified Energy System (UES). The analysis focuses on the economic aspects of small-scale hydropower, emphasising the long operational lifespan of SHPPs and their low operating and maintenance costs. These factors contribute to reliable and stable capital returns. The paper also reviews policy instruments and mechanisms for attracting private investment to support the growth of distributed generation. The paper substantiates the strategic role that SHPPs can play in the sustainable development of Russia's energy sector, ranging from substituting conventional fossil fuel-based systems in isolated areas, to stimulating local economies and strengthening regional energy security.

Keywords: investment risks, energy infrastructure, distributed generation, small hydropower plants, sustainable development, investment attraction, regional specifics

I. Introduction

Russia's energy infrastructure traditionally relies on large generating facilities and extensive networks, which is accompanied by significant investment risks and capital maintenance costs. The capital intensity and long construction time of large power plants (for example, hydroelectric power plants or nuclear power plants) make it difficult to attract private sector investment. Investors face payback uncertainty and external risks, from fluctuations in demand to regulatory changes. In recent years, there has been a trend towards the creation of decentralized energy systems: distributed generation is seen as a tool to increase sustainability and reduce the risks of

infrastructure projects. More than half of the entire territory of Russia is located in a decentralized zone and occupying the world's largest territory in terms of area, taking into account a variety of regional conditions and features, the transition to distributed generation is becoming especially relevant. Electricity and heat supply in remote regions is provided by diesel generators, coal and petroleum products, meanwhile, a huge number of rivers with a total length of more than 6.5 million km flow through Russia. And this resource seems promising for the development of the electric power industry in the concept of a distributed energy network. Small hydroelectric power plants (small HPPs) located near consumers can become one of the key elements of such a distributed system, providing local electricity generation and reducing the load on the backbone networks [5].

II. Distributed Generation and Small Hydropower in Russia

Distributed generation involves the placement of small generating capacities near the places of consumption, which reduces losses during energy transmission and increases the reliability of the power system. In the context of Russia, small hydroelectric power plants (with an installed capacity of about several megawatts) represent a promising type of distributed generation, given the abundance of rivers and the need for energy supply in remote areas. Expanding the use of renewable sources, including wind, solar, and small rivers, could increase the share of renewable energy in Russia's energy mix to 25-30%, creating a more sustainable and diversified system. SHPPs could significantly contribute to this goal, particularly in regions endowed with substantial hydropower potential. However, current utilization levels of this potential—especially that of small rivers—remain low, despite Russia having one of the world's largest hydropower resources. The total technical potential is estimated at approximately 850 billion kWh per year, of which 300–350 billion kWh is considered economically viable; yet, less than 20% of this capacity has been harnessed to date. The main constraints include high upfront investment requirements for large-scale facilities and the lack of effective incentive mechanisms. [1-3]

From an economic standpoint, SHPP projects offer a number of advantages that make them attractive for distributed generation. First, they require significantly lower one-time capital investments compared to large-scale power plants, thereby reducing the financial burden on individual investors. Second, SHPPs have shorter construction timelines and utilize well-established technologies, which mitigates the risk of cost overruns and delays. Finally, they exhibit long operational lifespans and low operating expenses: modern small hydro installations can function for over 70 years, with annual operating and maintenance (O&M) costs amounting to just 3–4% of the initial capital expenditure (Table 1.)

Table 1: *Economic characteristics of small hydropower projects in Russia*

Parameter	Grid-connected Small Hydropower systems	Off-grid Small Hydropower systems
Levelized cost of energy (RUB/kWh)	0.4–0.6	1.1–2.3
Payback period (years)	7–8	7–10
Service life (years)	≥ 70	≥ 70
Annual O&M cost (% of CAPEX)	3,5–4,5%	3–4%

The levelized cost of electricity (LCOE) for small hydropower plants connected to the centralized grid is estimated at approximately 0.4–0.6 RUB/kWh, whereas in off-grid systems—serving isolated areas—it ranges from 1.1 to 2.3 RUB/kWh. Nevertheless, even in remote regions, small-scale hydropower remains cost-competitive with diesel-based power generation. The typical payback period for SHPP projects is estimated at 7–10 years, which is slightly longer than for some other renewable energy technologies but is justified by the extended operational lifespan. The durability of SHPP installations—often exceeding 70 years—ensures decades of stable operation, while low operating and maintenance costs minimize financial risks once the plant reaches the break-even point. These characteristics make SHPPs economically resilient generation assets, whose

cumulative integration into distributed energy networks can significantly enhance the reliability and stability of the overall power system [2].

III. Investment Risks and Risk Mitigation Mechanisms

A key barrier to the development of new energy infrastructure in Russia lies in the investment risks associated with uncertain project returns. Under the traditional centralized energy model, large-scale projects—such as high-capacity hydro or thermal power plants (several GW)—are exposed to systemic risks: delays or project failures can result in substantial financial losses and power deficits. In contrast, distributed generation spreads total investment across a large number of smaller projects, thereby reducing aggregate risk—failure of an individual SHPP has minimal impact on the system, while the majority of assets continue to operate. This portfolio diversification effect enhances the resilience of the energy infrastructure. Moreover, SHPPs offer greater flexibility in staged implementation, allowing assets to be commissioned sequentially with the ability to adjust plans in response to evolving demand or macroeconomic conditions—something largely unfeasible in megaprojects..

The principal categories of risk in energy infrastructure projects include construction risks (budget overruns, timeline delays), technological risks (equipment failure, underperformance), market risks (fluctuations in electricity prices and demand), and regulatory risks (changes in tariff regimes, legislation, and compliance frameworks). Distributed generation based on SHPPs helps mitigate many of these risks. Construction risks are reduced due to the maturity of SHPP technology and the possibility of engaging local contractors familiar with site-specific conditions. Technological risks are inherently low for hydropower, as it is a mature and reliable sector with predictable performance indicators—the water-to-electricity energy conversion efficiency in Russia can reach up to 90%. Market risks are also diminished: small units can be adapted to local demand, and their commissioning is more agile, reducing the risk of excess generation capacity. [4]

Regulatory and financial risks are significantly mitigated through dedicated investment support mechanisms. Since 2013, Russia has implemented a renewable energy incentive scheme based on capacity supply agreements (CSA) through competitive project selection on the wholesale market. Under this mechanism, the state commits to compensating capital expenditures for renewable projects (solar, wind, SHPPs) by providing increased capacity payments, subject to timely commissioning. This effectively ensures investment return, thereby substantially lowering financial risks for project developers. According to estimates, a total of 5.5 GW of solar, wind, and small hydropower plants were commissioned under this scheme by 2024. [7]

Although this model shifts part of the risk to end consumers through tariff adjustments, it has nevertheless provided the initial impetus for sectoral development. In addition to capacity payment contracts, there are other instruments for risk mitigation and investment attraction—such as preferential "green" tariffs for distributed generation, capital subsidies, tax incentives, and the involvement of international financial institutions [4].

IV. Regional Specifics and Sustainable Development

Russia possesses a uniquely diversified energy geography: in addition to the Unified Energy System (UES)—which was originally designed and deployed during the Soviet era—there exists a wide array of isolated energy nodes across Siberia, the Russian Far East, and the Arctic and sub-Arctic regions of the Far North [8]. For many remote settlements and industrial facilities, thermal power plants operating on imported fossil fuels have remained the only source of energy for decades. This reliance results in extremely high electricity costs and significant environmental externalities, including greenhouse gas emissions and risks of fuel spills. Transitioning such isolated zones to locally available renewable energy sources—including small hydropower where hydrological resources permit—has the potential to drastically reduce energy expenditures and

improve the quality and reliability of power supply. For instance, in mountainous villages of the North Caucasus or the Altai region, small run-of-river hydropower plants could fully meet local residential and agricultural electricity needs, displacing expensive imported fuels [4]. In the Chechen Republic, a recent assessment demonstrated strong investment returns for a cascade of SHPPs designed to power rural areas, with such systems showing long-term operational stability and minimal investor risk.

Moreover, in regions of Russia characterized by low population density and significant remoteness from centralized grid infrastructure, the selection of optimal generation technologies must be guided by a combination of factors: capital investment requirements, operational efficiency, payback periods, and overall investment risk. These parameters form the basis for sound energy planning and support the rationale for prioritizing SHPP deployment as a cornerstone of regional distributed energy strategies (Table 2).

Table 2: *Economic characteristics of distributed energy technologies in Russia*

Parameter	Solar PV (rooftop and small ground)	Small Wind Turbines	Small Bioenergy Units (CHP or biomass)	Small Hydropower systems	
Levelized cost of energy (RUB/kWh)	2.8–4.5	2.2–3.5	1.5–2.5	Grid-connected SHPPs: 0.4–0.6	Off-grid SHPPs: 1.1–2.3
Payback period (average, years)	6–9	7–11	5–8	7-8	
Service life (years)	20–25	15–20	20–30	≥ 70	
Annual O&M cost (% of CAPEX)	1.5–2.5%	2–3%	3–4%	3–4%	
CAPEX (mln RUB per MW)	60–90	75–110	85–120	90–110	
Typical installed capacity (MW)	0.01–0.5	0.01–0.3	0.1–1	1–5	
Annual generation (mln kWh)	0.01–0.65	0.01–0.45	0.15–1.5	5–25	
Revenue (RUB/kWh sold)	5.5	5.5	5.5	4.0	
Annual O&M cost (mln RUB)	0.9–2.2	1.0–2.5	2.5–4.8	1.8–3.3	
Net annual income (mln RUB)	0–1.38	-0.5–1.1	1.2–6.3	18.2–96.7	
IRR (%)	8–11	6–9	10–13	13–16	
Investment Risk Level (qualitative)	Medium	High	Low–Medium	Low	

Table 2 presents a systematized comparison of four key areas of small-scale distributed energy in Russia: solar photovoltaic (PV) systems, small wind turbines, bioenergy units, and small hydropower plants (SHPPs). For each technology, average benchmark indicators are provided to assess investment attractiveness, including the levelized cost of energy (LCOE), capital expenditure (CAPEX), payback period, annual generation, net income, internal rate of return (IRR), and a qualitative evaluation of investment risk. The analysis demonstrates that SHPPs show the most favorable performance across the majority of these parameters.

Regional specificity is particularly evident in the distribution of untapped hydropower potential: most of the available small-scale resources are concentrated in mountainous and remote areas, such as the North Caucasus, Southern Siberia, and the Russian Far East [3]. In contrast, the European part of Russia offers fewer opportunities due to its relatively flat terrain and the high

degree of development of major rivers. Accordingly, support measures should be targeted at regions with isolated energy systems and high tariffs for imported fuels, where the impact of distributed generation is likely to be most significant. Furthermore, in remote areas, SHPP projects should be viewed not only through the lens of energy provision but also as drivers of regional development. Reliable electricity supply facilitates the emergence of new industrial activity, supports small business growth, and improves quality of life through enhanced access to lighting and essential infrastructure. Thus, investments in small-scale hydropower serve a dual purpose: advancing sustainable energy and delivering tangible socio-economic benefits to local communities [6].

Hydropower, as a renewable and virtually carbon-free energy source, contributes to the achievement of Russia's climate objectives. Moreover, combining SHPPs with other renewable technologies—such as wind-diesel hybrid systems in Arctic zones or solar-hydro energy complexes in southern regions—can ensure secure and resilient power supply through diversification and enhanced energy security across Russian territories. In the long term, the development of distributed generation will be supported not only by the state but also by private consumer initiatives and businesses seeking independence through localized energy solutions. With predictable output and extended operational lifespans, SHPPs are well-positioned to become a core component of the emerging decentralized energy architecture alongside other distributed resources [7-27].

V. Conclusion

Small hydropower systems represent an economically viable and investment-resilient solution for the development of distributed energy systems in Russia. Their key advantages include a low levelized cost of electricity, extended service life, moderate capital expenditures, and minimal operating and maintenance costs. Locating SHPPs in close proximity to end-users helps reduce the load on trunk transmission infrastructure and enhances the reliability of local energy supply. These projects are particularly relevant for remote and isolated areas, where SHPPs can effectively replace costly diesel-based power generation. In addition to their economic benefits, SHPPs generate positive social and environmental impacts by promoting regional development and reducing greenhouse gas emissions. Government support measures and investment incentives in this sector have proven effective but require long-term institutionalization and adaptation to regional conditions. In the long term, SHPPs are poised to occupy a central role in Russia's energy strategy as a key component of a sustainable, decentralized, and low-carbon power system.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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CLIMATE CHANGE: INTERNATIONAL AID FOR DEVELOPMENT OF ADAPTATION IN THE GLOBAL SOUTH

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Abstract

This article explores the novel role of international aid for development of adaptation to climate change impacts and disaster risk reduction in the global South, and particularly, in climate vulnerable least developed and small islands states. Development aid is regarded as an instrument, both for enhancing their domestic resilience against disasters, safety of livelihoods and infrastructure, and for compliance with the norms and provisions of the climate change international regime with its Paris agreement. The research innovation is in tracking the new features and trends in multilateral assistance to development of adaptation systems in the recipients, and in analysis of changes in approaches and stronger positions of developing countries in climate diplomacy and multilateral North-South negotiations on adaptation development cooperation. Our focus is on identifying the climate specifics and core drivers in design of multilateral adaptation aid in comparison with the global development cooperation in general. The system of adaptive governance is approached from the polycentric perspective, which is characterized by a diversity of actors involved and broadening interactions between them. This study concludes that adaptation development aid could be more effective when climate finance is packaged together with transfer of technology and competences. Research is based on mixed methods and multidisciplinary approaches to aggregate findings from analysis of risks and climate impacts on society, results of international climate negotiations, UNFCCC documents, national reporting and case-studies on disaster risk reduction.

Keywords: adaptation to climate change, disaster risk reduction, international development aid, North-South climate diplomacy, polycentric governance, new collective quantified goal, multilateral fund for loss and damage

I. Introduction

Most climate change impacts and risks for society are attributed to a combination of drivers - both to destructive effects of disasters as a result of growing global climate variability, and to failures in human adaptation to disaster risks through response actions worldwide, which are not sufficient enough to address challenges posed by hazards [1][2]. Although the disaster risk reduction and adaptation to climate change impacts are among the top priorities on the global risks agenda, and multiple measures to enhance the resilience of society are undertaken at national and international levels, the trend towards escalating disaster damage is increasing as climate variability intensifies. According to the recent data of the World Economic Forum, in 2025 the annual loss and damage

costs of climate attributed disasters are expected to reach USD 145 billion, while by 2050 they are projected to increase between USD 1.7 - 3.1 trillion.

Global climate change affects all countries around the world in highly heterogeneous ways, depending on nation's geography and level of development [3]. The question about which states are best prepared for adverse climate impacts is among the top issues within the current international discourse. The countries of the global South, and particularly climate vulnerable least developed and small islands states, are disproportionally at risk as their resilience to adverse hazards impacts faces a challenge. It is explained by a set of factors, including their geographical exposure, climate vulnerability, socio-economic and institutional context, limited domestic capacity and resources for adaptation and disaster response to emergences.

Climate hazards like floods, sea-level rise, storm surges, wildfires and other extreme events might have particularly serious consequences for lives, livelihoods and infrastructure in the global South [4]. They stress infrastructure, causing damage to buildings and destruction of transport systems, telecommunications, power grids and result in costly replacements and repairs; livelihoods are affected and population might be displaced. Socio-economic and institutional issues, high poverty rates and limited financial resources hinder their ability to implement climate resilience measures like protective infrastructure upgrades, disaster preparedness, early warning, emergency response and post-disaster recovery. As a result, they bear significant consequences, with some estimates suggesting that countries of the global South, and especially least developed among them, could encounter a 12-13 percent annual increase in infrastructure costs in the near future. Adaptation costs grow simultaneously with response actions, including building protective seawalls, relocation of infrastructure and livelihoods, constructions upgrades to make them disaster-prone: it requires additional investments and technical capacities. Today, the developing countries experience significant adaptation gaps, while their adaptation needs are about a dozen times higher than their actual capacity to deal with climate risks.

Addressing climate vulnerabilities requires stronger international development cooperation, financial and technical assistance, and the implementation of sustainability strategies that prioritize climate resilience and disaster risk reduction. Multilateral framework for climate aid, incorporating mitigation and adaptation, has been under active formation during the last two decades, and since recently, particularly dynamic has been its segment on development assistance for the global South in adaptation to adverse climate change impacts and related hazards. While official development assistance (ODA) traditionally is among the key forms of international cooperation between developed and developing countries, the climate aid, and especially adaptation support, is a new and important strand, and it clearly reflects the climate specifics, the new factors defining its design, and peculiarities of contemporary North-South climate diplomacy.

The developing states had acquired stronger roles and stance in climate international cooperation and in dynamic international climate regime under the United Nations Convention on Climate Change (UNFCCC), including its provisions and norms on multilateral assistance. Today, active discourse within the international community is underway on selection of effective aid instruments, which could promote fast-track and easier access to transfers of multilateral climate funding, technology, and competences between donors and recipients. Adaptation aid functions through partnerships between donor and recipient countries, and it prioritizes the support for reduction of climate vulnerability, especially in case of disaster emergencies, along with consolidation of sustainability pathways and improvement of living standards.

The main *goal* of this study focuses on understanding and mapping the roles and limitations of international climate aid as a tool for enhancing resilience against climate hazards and adaptation capacity of its recipients in the global South. The study is aimed at analysis of (1) new features and trends of international aid to development of adaptation systems, (2) 'climate' specifics within the recently dynamic North-South development cooperation and main drivers shaping its design, and (3) how and to what extent the emerging multilateral framework of adaptation aid fits into the global climate change international regime under the UNFCCC.

II. Methods

The research results are based on application of a mixed methods approach, which combines qualitative analysis and case-studies. They allow to explore the major attitudes and perceptions about the role of international climate adaptation aid, its possible instruments and limits in consolidating the resilience and safety of climate vulnerable developing countries and their infrastructure against adverse climate consequences and disaster risks.

Qualitative methods are used to define the scope of the emerging international system of development cooperation in climate change and North-South adaptation aid, as well as to explore major trends and features of its architecture; evidence from recent results in multilateral coordination of adaptation aid transfers between the donors and recipients derives from extensive qualitative assessments. Research is based on analysis of documents of the UNFCCC annual conferences of the parties, their regular national communications and reporting. Transcribes of the official approaches of participants allow tracking their diversity within the North-South climate dialogue. The results show that selection of a particular aid instrument, technology, or finance product appears to be in the core of international climate negotiations and bargaining between donors and beneficiaries. It is supplemented and verified by analysis of international assessments recently undertaken in this field by the prominent international agencies.

Interdisciplinary approaches are applied. They are involved to combine the results of social and natural sciences in order to identify and assess possible adaptation governance options and instruments for effective problem-solving in enhancing resilience and safety of livelihoods and infrastructure against disasters. Set of selected options depends on observed climate change impacts and risks of related hazards for particular groups of countries depending on their natural vulnerability and geographical exposure. Assessment of local socio-economic, institutional factors and response capacities are equally important within such analytical exercise. Multidisciplinary methods allowed to reconfirm that results and variations in the structure of adaptation aid are highly context-dependent. They also helped in our inquiry about possible means for transfer of adaptation technology and competences, about their structure and limitations. Multidisciplinary approach enables to conclude that climate finance aid packaged together with transfer of technology and competences is among effective tools for problem-solving.

Attribution analysis, including assessment of drivers and factors in shaping the design of international development aid for climate adaptation in the global South, contributes to identifying its role in domestic adaptation capacity building and in implementation of national obligations under the UNFCCC climate regime. We distinguish between group of factors defined by natural, geographical, climate specifics of the recipients, and a set of drivers rooted into their socio-economic contexts: it allows identifying the results and effectiveness of particular aid instruments for enhancing resilience, domestic capacities in climate vulnerable least developed states. It shows that the latter group of factors is crucial particularly in disaster risk reduction and enhancing safety of critical infrastructure.

Case studies focus on disaster risk reduction in climate vulnerable developing coastal and small islands states in the South-East Asia with the emphasis on floods and sea level rise and related risks response to enhance safety, resilience and adaptation of livelihoods and infrastructure. Possible multilateral adaptation governance instruments for problem-solving are explored on the example of the recently established multilateral Fund on responding to loss and damage from climate disasters.

This study represents the next consequent step in our broader research exploring the major features and trends in global climate change, innovations in adaptive governance, implementation and effectiveness of the international climate change regime and challenges in domestic performance by its parties, groups of states and their different actors. We consider that the instrument of international climate development aid promotes for adaptation problems-solving

both within domestic and international contexts, although a number of serious problems and gaps associated with its application exists. Research methods applied and results gained are planned to be tested and verified within our current research project on assessment of *polycentric governance* of global climate risks and sustainable development.

III. Results

The following research results contribute to exploring the role of international aid for development of adaptation to adverse climate change impacts and for disaster risk reduction in climate vulnerable least developed countries and small islands states, and to meeting their national obligations under the UNFCCC. They reveal new features and trends in multilateral assistance to development of adaptation systems in the global South through focusing on climate specifics and drivers in design of adaptation aid as an important component of international development cooperation.

Today, we observe a number of novel features and trends in formation of the *global framework for climate aid*, and particularly, in its dynamic segment of international support for development of domestic adaptation systems in the least developed and small islands states of the global South. The growing role of adaptation aid instruments is perceived as an input into building resilience of their livelihoods and infrastructure facing adverse climate consequences and into disaster risk reduction; in a broader sense it contributes to meeting the key goals of climate ODA and sustainability. Adaptation aid is also becoming an important attribute for success in national implementation and compliance with the norms of the UNFCCC international climate regime by the developing parties; climate aid regime is heavily nested into the provisions of the latter. We conclude that currently the role of aid in the North-South climate negotiations and in climate development cooperation is consolidating. Recently, in the context of global adaptation gaps and insufficient international transfers to meet the adaptation needs of climate vulnerable states, the aid up-scaling is pledged, i.e. the tripling by 2035 up to USD 300 billion of annual climate development assistance to most vulnerable countries of the global South with more ambitious general goal of getting up to USD 1.3 trillion.

Our analysis indicates shifts not only in *quantitative* parameters of international support, but *qualitative* as well. Recent innovations in the architecture of adaptation development aid are observed, and to a high extent they reflect the specifics of climate development cooperation. Its design is characterized by changes in: 1) structure and sources of international aid; 2) institutional frameworks for resilience capacity building; 3) broader range of sources and actors sources involved; 4) consolidation of their networks and interactions; 5) diversity of donor-recipient linkages and partnerships, 6) finance products and technology transfers packaged together; 7) instruments and tools for enhancing easier and fast-track access to international aid; 8) means for concessional and preferential support for climate vulnerable beneficiaries. Research results show that from now on a wider range of sources and channels for international aid would be mobilized to secure the targeted increase in global climate finance flows to vulnerable states and their local communities. In contrast to earlier preferential emphasis on public sources for climate ODA, multiple public and private flows would be combined, and consequently public and private donors - be involved. Such new diversity is coupled with broadening contributions from international climate funds and development banks, and bilateral assistance. Not only developed countries listed in Annex II, UNFCCC with their special responsibility and commitment to international climate aid, but also rapidly developing economies are promoted to be partners in this global mission: South-South adaptation development cooperation is a novelty. We conclude that such newly emerging design is based on *polycentric approaches,* and it might effectively contribute to solving the key challenges for adaptation development aid - both for consolidation the domestic capacity of recipients in building resilience against adverse climate consequences and for implementation of their international climate obligations.

There is growing variety in the *structure* and *instruments* of climate adaptation aid. Selection of a particular tool is increasingly based on promoting faster and easier direct access of recipients to adaptation funding and technologies. Today, there are several types of adaptation finance instruments available to least developed countries. The major include multilateral/bilateral public grants, concessional sovereign loans, debt coverage, concessional and non-concessional blended bonds, climate finance from international institutions; but each has different consequences for the society and citizens of a recipient. This set also reflects the differences in the parties' positions within North-South climate diplomacy; selection of a particular aid instrument, or finance product is a part of negotiations and donor-beneficiary bargaining. Grants are mostly favored by recipients because they allow generating maximum public benefits for the society and do not require the financial return; usually they are small and short-term and might not be highly effective for creating disaster proof infrastructure, or stable institutional settings. On the contrary, the climate transfers from international finance institutions, or financial markets in the form of non-concessional loans/bonds envisage full repayment by the beneficiary to be generated through accumulated domestic revenues, charges, taxes, and often results in a burden for the citizens, financial debt, or crisis in a recipient. Choice of instruments is highly dependent on the local context, i.e. the specifics of climate vulnerability of a possible beneficiary and its local socio-economic potential. Recent establishing of the multilateral Fund for Responding to Loss and Damage (FRLD) is an interesting case to analyze international practices which intend to select instruments promoting faster and easier access to adaptation aid; our findings are presented for discussion in the following sections.

Analysis indicates at changes in *North-South climate diplomacy* interactions with a drive towards a stronger new role of the developing countries - as a result of their pressures and bargaining in a course of multilateral climate negotiations during the last two decades. The major outcome is not only in introduction of the higher targets for adaptation development aid to climate vulnerable developing states. The other part of their success is in further refining the design of international adaptation aid regime based on the UNFCCC norms, which define the leading role of the developed states and their commitment for assistance to the global South. Recently, the prominent efforts have been undertaken to balance the conflicting approaches of the parties in climate negotiations, and breakthrough results were adopted to provide further institutionalization of the new North-South *climate deal* within the international climate aid framework. The key among them include: (1) increase in annual donor-recipient flows of adaptation finance fixed by the New Collective Quantitative Goal with increase in climate finance; (2) combination of transfers of finance, technology, and competences for capacity-building via establishing the special support program for implementation of National Adaptation Plans (NAP) by 2030; (3) variety of novel instruments and conditions promoting access of recipients to funding and technologies; (4) stronger emphasis on enhancing allocations to support local institutions and locales in their adaptation action; (5) demand-led capacity building, technologies and know-how transfers; application of multi-year programmatic approaches defined by recipient's specifics and context. However, some issues of climate negotiations still remain open, and particularly the North-South climate *responsibility, compensation* **and** *justice* with its direct links to climate disasters *loss* and *damage* reduction; it remains on the agenda of adaptation aid, and its possible beneficiaries intend to use it further as an argument in climate negotiations.

We conclude that *climate finance, technology transfer* and *capacity building* packaged together are the key cornerstones in international climate development aid to the global South. Initially, the currently emerging system of adaptation development aid was associated mainly with mobilization of multilateral climate finance, and was strongly promoted by the developing countries. Later it was expanded to incorporate international support for transfer of technology and competences to cover the adaptation needs, which are usually articulated now in national adaptation plans. The evidence from case studies clearly indicates that to be effective the adaptation development cooperation is to be based on coordination and packaging the financial assistance with transfer of technology, competences, institutional support for adaptation capacity

building. As a single instrument the finance transfers might not be able to fully solve the complexity of adaptation development problems in the recipients. Research shows that adaptation development finance allocated for technology transfers increased during 2018-2022 by two-fold; technology aid is concentrated in such climate sensitive sectors as water, agriculture, and coastal zones. Important trend is the growing flows of technology and competences for wider involvement of vulnerable regions in international climate data exchange to overcome the existing gaps in global networks of disasters early warning and climate forecasting. We consider that application of such triangle-package of international aid might be particularly challenging for enhancing resilience of livelihoods and safety of infrastructure in climate vulnerable least developed states and for consolidating their future sustainability pathways.

IV. Discussion

I. Adaptation aid: State-of-the-art

Multilateral framework for climate aid has been under formation in close interaction with development of the UNFCCC international regime. Especially dynamic progress has been noted during the last decade - after the global goal to annually mobilize USD 100 billion for climate support of the developing countries, including their mitigation and adaptation efforts, was agreed. This target was finally enacted until 2025, and during this period the coordination of international aid for adaptation to adverse impacts of climate change had been underway. It is based on the finance mechanism of the UNFCCC, art.11 with its norms to assist the developing country-parties to establish their domestic adaptation systems. The OECD industrialized countries and economies in transition from Annex I, UNFCCC are encouraged to take part in climate assistance and international development cooperation. Also, the twenty four developed states listed in its Annex II[1] are designated with a stronger mission – to provide financial and technological support to address the climate change impacts: they are obliged to mobilize resources both for mitigation and adaptation, and to contribute to covering the climate costs in the developing countries to reduce their climate vulnerability.

During this period, the global climate finance mechanism combined the three major multilateral *specialized funds*, including the *Special Climate Change Fund (SCCF)*, administered by the Global Environmental Facility, the *Least Developed Countries Fund (LDCF)*, and the *Adaptation Fund (AF).*This system aggregating finance mostly from the governments, was actively used to channel the mobilized funding to developing countries. Recently it was enlarged to include the new multilateral *Fund for Responding to Loss and Damage* established in 2023 to assist climate vulnerable least developed states in averting, minimizing, and addressing damage and risks. International climate funding is also secured through *multilateral development banks*, and it targets particularly the low-income nations, small island states, and indigenous communities. The third source is the *bilateral* state-by-state transfers. According to some estimates the structure of sources for climate aid in 2022 looked as follows: the leading roles were shared almost in equal proportion by the multilateral development banks (44%) and bilateral development cooperation channels (43%); multilateral climate funds accounted for about 3% in total climate aid, with the rest mobilized from other international sources. Despite relatively modest contributions from climate funds in comparison with other sources, their role is important as they aim at promoting direct access to climate aid and tend to scrupulously take into account the local contexts of those recipients who are in urgent need in case of climate emergencies.

Recent international assessments indicate that currently there is a significant global adaptation gap, and it has acquired quite grotesque dimensions in the global South. They unanimously confirm that climate adaptation remains 'underfinanced and unprepared'. There is a

1 Annex I parties include the developed and economies in transition (EITs) states; Annex II parties are a subset of Annex I parties, specifically the OECD states (excluding the EITs), who are required to provide financial and technological support for mitigation and adaptation in the countries of to the global South.

discrepancy between climate finance flows and needs for climate adaptation in climate vulnerable least developed states. According to the UNEP Adaptation Gap Report the adaptation finance gap ranges from about USD 215 billion to USD 387 billion annually [5] depending on the sources of data and assessment methods applied. Today annual adaptation finance flows to recipients appear to be about 8-14 times lower than their adaptation needs. This data is aggregated and verified from two different sources – from national climate reporting of the parties to the international climate regime, and from global adaptation costs modeling. International assessments consider that currently the developed countries fall short to their earlier commitment on funding support for adaptation actions, and it is among the reasons for adaptation gaps and slow progress on the issue. For example, gradually increasing international public adaptation finance flows to developing countries in 2022 accounted for about USD 28 billion [1]. We believe that such state-of-the-art and adaptation failures are attributed also to certain gaps in knowledge about how to effectively perform the available adaptation options, and how to prioritize among implementation instruments in order to reduce disaster risks and enhance the resilience in the climate vulnerable states.

Today, impressive shifts in dynamics and structure of global adaptation aid are noted, and they signal at significant innovations in the international climate aid regime. In 2024, the multilateral climate finance deal was sealed via setting a *tripled finance* goal to protect livelihoods, infrastructure and lives against climate disasters in the vulnerable least developed countries and small island states. The new climate finance goal was adopted to mobilize USD 300 billion per year by 2035 for the developing countries: it envisages the 3-fold increase in annual international climate funding to be secured by the developed states, and it replaces the previous annual target of USD 100 billion. Its mechanisms were fixed in 2024 during the climate conference of the parties (COP-29), Baku by the so called *New Collective Quantified Goal* (NCQG) [6], which also suggests a broader global perspective to enable USD 1.3 trillion annually in climate finance for developing countries during the same period.

As a part of the new North-South climate finance deal it envisages more ambitious and comprehensive format, which reflects the growing needs of the developing countries to realize their climate action. In order to meet them, it intends to encompass contributions from a broader range of actors, including the combination of public and private finance, and involve a wider variety of sources worldwide. To a high extent, it is the result of international climate diplomacy and negotiations to coordinate the conflicting interests of the parties: till the last moment at COP-29 the final quantitative goal remained un-fixed, and it reflected significant variation in positions of donors, recipients and alliances of the states. Importantly, this process was accompanied by the strong bargaining and pressures from the developing countries. The climate finance deal with its NCQG could be regarded as a marker of the new role of the global South and its climate diplomacy in formation of multilateral climate aid framework. It also envisages important tools for implementation of the Paris agreement with its provisions towards enhancing climate resilience and adaptation capacity through climate aid; realization of the new finance deal is associated with stronger national climate plans, formulated in Nationally Determined Contributions, NDCs of the parties, to become due from 2025.

II. Approaches to adaptation aid: Recent shifts

Currently, the dynamic global discourse is reflecting a variety of approaches to the role of international climate finance, which is commonly perceived as North-South international aid, particularly to climate vulnerable and least developed countries. Usually it targets the long-term development of their domestic systems both in climate mitigation and adaptation, rather than short-term emergency humanitarian relief. Our discussion focuses on peculiarities of adaptation aid, as one of the types of broader international development support (recently more often termed as ‘development cooperation’), and measured by governmental ODA. It could be either bilateral

given by one country to another, or multilateral and channeled by donors through international organizations and development banks. Climate aid usually comes from the developed countries listed in the UNFCCC Annex II. However, since recently some of the rapidly emerging economies from the non-Annex I group, like for example, China, UAE, India have been also increasing their contributions to international climate flows to vulnerable developing states. It becomes one of the new features in the structure of international climate development cooperation.

Today, a variety of conceptual approaches to typology of international adaptation aid are in place, including, for example: (1) global development cooperation, which includes a variety of actors, linkages and bonds between donor-recipient states, activity types, coordination between governmental, profit-making and humanitarian actions, sources, investment flows; it is relatively new approach usually rooted in polycentric concepts; (2) climate ODA provided by the donor governments primarily to least developed climate vulnerable countries, and aimed at building their climate governance systems and implementation of international norms; (3) international aid associated with disaster emergencies, humanitarian relief, and voluntary funding; it could indirectly relate to climate infrastructure, but cover broader socio-economic challenges. We share the polycentric approach in adaptation governance which presupposes new trends in the structure, diversity of participants and interacting networks, multiple sources, cross-level interaction and coordination, and consolidation of regional development cooperation [7]. Among the novel illustrations, for example, is the recently broadened framework of climate development assistance to include not only public aid as it has been earlier envisioned by the UNFCCC regime, but also climate investment flows - with clear signals for possible climate investors from the COP-29; possible option of climate South-South aid is another innovation.

New approaches to typology of adaptation development assistance have direct links to introducing the new 'climate specifics' into the general system of international development cooperation. It is important not only for advances in theoretical discourse, but for practice as well – enhancing the effectiveness of international climate regime, removing gaps in its implementation and national compliance with its norms by the member states. Besides, the global climate diplomacy and recently dynamic negotiations are covering inter alia the coordination of conflicting positions and interests within the North-South dialogue, including the design of international climate development cooperation, forms and terms of financial flows to the recipients, their access to funding, eligibility criteria, links between adaptation and emergency relief. Our research results presented above indicate that new frameworks for international development cooperation clearly demonstrate the climate specifics, including a combination of such innovations as increase in the level of annual international adaptation funding, collectively set quantified goals, package of finance, technology, capacity building aid, assistance for designing domestic adaptation plans, new instruments for fast-track access to aid and others.

Refinement of climate aid architecture involves the system of norms, regulations and their application in practice. During the last three decades of climate negotiations the significant deviations in approaches of donors and recipients of climate aid had been registered. They are based on differences not only in their interests and perceptions, but also in positions within groups and alliances of states. For example, during the COP-29 a number of concerns were expressed by the developing countries and their groups about the major principles and design of adaptation aid within the new multilateral climate strategy with its NCQG. Bangladesh and the group of Small Islands Developing States (SIDS)[2] was insisting on incorporating the guaranteed minimum allocation floor for this group, while the Less Developed Countries (LDC) called for the NCQG to include a special annual allocation to them of USD 200 billion. The latter also rejected the investment goal as they intended to secure guaranteed funding for their budgets and instruments of local control versus private interests, because they consider that private standards cannot contribute to high integrity of adaptation finance flows. Similar suggestion was introduced by the

[2] SIDS – group of 39 UN member states and territories in the Caribbean, Pacific, Atlantic, Indian oceans and the South China Sea regions characterized by similar socio-economic and climate vulnerabilities.

St Vincent and the Grenadines, who opposed the investment component of the NCQG, underlying that 'relying on private sector to pick up the bill will not do'. Some others introduced quite exaggerated requests. The Marshall Islands noted that specific national allocation targets need to be fixed, as for example, for its national adaptation plan with domestic needs estimated at USD 35 billion; they also accused parties of 'playing with peoples' lives'. Tuvalu urged for recognizing within the collective goal the special circumstances of LDCs a SIDS. At the same time China called for all decisions to reflect common but differentiated responsibilities: it highlighted that the category of voluntary support provided by the developing countries is different from developed countries' responsibilities under the international climate regime, and it should not be considered as a component of the NCQG. Israel stressed that while broadening the donor base, there is no need in renegotiating the obligation of responsibility of the developed countries; Sierra Leone characterized the NCQG as the payment of the '*climate debt*' developed countries owe to the developing. The issue of common, but differentiated responsibility often emerges in international climate negotiations.

The problem of North-South climate *responsibility, compensation and justice* with related issues of loss and damage reduction still remains unresolved, and it might add certain controversies into the donor-recipient climate diplomacy regarding implementation of the global climate finance deal. Until recently it has been among the core impediments in international dialogue and bargaining between two groups of states. Still, this item remains on the agenda of climate adaptation and development assistance: developing countries would like to keep it for later use as a strong argument in climate negotiations, and also as a possible tool of control over realization of the international finance deal in practice. Some experts underline that selection of particular international funding instruments has direct links to this issue: they suggest that multilateral loss and damage coverage could not be qualified as international development aid, but should be regarded as climate responsibility of the global North, and thus it should be provided as grants, but not as non-concessional funding, loans and finance return-focused instruments, favored particularly by the EU.

III. Adaptation aid: Structure and instruments

Recent shifts in design and structure of climate adaptation aid reflect the specifics of climate development cooperation. To a high extent they are driven by results of the emerging South-North international climate deal, which is accompanied by donor-recipient coordination of preferences in selection of aid instruments. *First*, international adaptation development finance may be now secured from a variety of public and private sources, and by multilateral and bilateral donors. But, the resulting problem is that aid instruments could have very different profiles and impacts at the sub-national level in the recipients, and particularly - on most climate vulnerable groups of society. *Second,* since recently not only the donors from industrialized states could be sources of international adaptation aid. Some non-Annex I developing countries with the relevant capacities are encouraged to voluntary contribute to climate development aid. *Third,* a variety of aid instruments are tested to promote fast-track and easier access to adaptation funding. A number of incentives and normative options are discussed, including, for example, the reduction of constraints for direct access to funding, application of co-financing, non-debt-inducing instruments, increased concessional finance, especially in case of vulnerable LDC and SIDS with limited domestic capacity.

Today, there are several types of adaptation finance instruments available to less developed countries. Among the major of them - multilateral/bilateral public grants, concessional sovereign loans, debt coverage, concessional and non-concessional blended bonds flowing from multilateral and bilateral public sources, climate finance from international institutions. Such structure defines not only the dynamics of climate aid flows, but also a diversity of parties' positions in South-North climate negotiations. In the core of the discourse is "*who ultimately pays for*

adaptation, and who benefits from it" as it is formulated by the UNEP [1]. Indeed the major conditions that accompany each type of finance instrument are associated with the level of its concessionality, and resulting benefit/burden for the society and citizens of a beneficiary, as well as with the funding burden and preferences of a donor. Selection of a particular instrument is always in the focus of international climate negotiations and bargaining.

Adaptation grant project is usually favored by a beneficiary of adaptation aid, because it allows generating maximum public benefits for the society and citizens in a recipient, and does not presume the financial return. On the contrary, the aid flows from international finance institutions, or financial markets in the form of non-concessional loans/bonds envisage full repayment by the beneficiary, and needs to be generated through accumulated domestic revenues, charges, taxes. As a result, simple grant model, where the international funder bears all costs of adaptation, and the most vulnerable communities in the LDC receive all the benefits, is the most appealing for recipient. But, its approval is inevitably is accompanied by debates and controversies. Grants public finance accounts for about two thirds of the total concessionary public funding. They are considered as useful financial instrument for adaptation actions where it is hard to generate a financial return. Usually they are small and short termed, but might not be highly sufficient in creating, for instance, the disaster proof infrastructure and stable institutional settings. Often they are destined to adaptation capacity-building, development of competences, piloting adaptation innovations and institutions, where there are significant non-financial benefits [8].

In contrast, *loans* and other *debt* instruments could support larger investments, for example, by embedding adaptation and resilience into general development schemes. Currently, a large portion of international climate finance for adaptation in developing countries, especially in the Sub-Saharan Africa and Oceania, has been grant based, sourced from the OECD public funds, indicating that financing via loans is considered either too risky by commercial investors, or it has been hard to demonstrate sufficient return on investment. Concessionary finance at lower interest rates in contrast to commercial markets might benefit to domestic adaptation, but unless revenues are generated it would result in growing government borrowing, or require additional taxation or charges; the burden of repayment is still on the recipient. As a result, besides grants, the aid finance instruments could contribute to increase in adaptation finance, promote resilience and reduce loss and damage, but the impacted groups of the population finally bear the adaptation costs.

Selection of particular aid instruments was reflected in the debates during the COP-29. Varieties in positions of donors and recipients, and also among the beneficiaries of adaptation aid were demonstrated. For example, India along with its pledge for general up-scaling the global climate finance has requested to re-structure the aid format with the emphasis on grants and concessional instruments; it insisted that at least half of the allocated international finance under the NCQG should be mobilized in a form of grants and equivalent resources. Senegal and Nepal outlined the importance of grant-based finance for adaptation, and particularly when dealing with the loss and damage issues. Columbia pointed at the importance of leveraging the efforts in the international community beyond the UNFCCC, and to aim at debt cancellation. Negotiation positions of LDCs suggest that domestic finance should be excluded from the NCQG finance (Palau), and multilateral climate funding should not depend on available domestic resources (Mexico).

IV. Institutions to address loss and damage

In 2023 the multilateral *Fund for Responding to Loss and Damage* was established under the UNFCCC: it represents an interesting case for featuring the peculiarities of adaptation aid. Its aim is to channel international aid to protect lives, settlements and infrastructure in climate vulnerable least developed countries affected by disasters and to consolidate their adaptation capacity. Primary mission – mobilization of funding to support actions for climate hazards loss and damage

reduction, and regulating easier and faster access of the recipients to external resources. In order to consolidate its specific commitment to fast-track support and to avoiding complicated bureaucratic procedures, it plans to refine operational modalities for recipients' access. The Fund is an institutional innovation, introduced as a result of three decades of dynamic North-South climate negotiations. Mobilization of multilateral funding to particularly cover the growing costs of loss and damage from emergencies is critical for its success. It is governed by the Board which is hosted in Philippines, and it balances the membership from the developed and developing states[3] [9]. It is at the final stage of its operationalisation, and it is supposed to start pilot financing for climate adaptation projects in 2025.

At the beginning of 2025 a total of USD 741 million has been pledged by its 27 potential contributors. The European countries are leading among them: the main donors are France (104 million), Italy (104 million) Germany (96 million); the UAE (100 million) is the key contributor from Asia. Announced pledges of its other donors from Annex II, UNFCCC list are comparatively lower (in millions: the UK 49, the EU 26, Norway 25, the USA 18, Canada 11, Japan 10). Today, the contributions assembled by the FRLD account for about a half of the total pledged amount - USD 353 million. According to its procedures the donors' involvement is based on their voluntary commitments. The major question remains open to what extent the new Fund would be effective to provide sufficient support for actions to address loss and damage, and at least partially cover its beneficiaries' needs in consolidating their resilience against hazards. This question arises because according to recent assessments its transfers might be a dozen times lower than costs of constantly progressing loss and damage to livelihoods and infrastructure of its potential clients.

A number of important issues relating to FRLD success in climate adaptation and disaster risk reduction still remain open as there are certain impediments for its functionality. Uncertainties remain in methods and metrics for loss and damage evaluation attributed to climate change; the monetary value of loss and damage to settlements and infrastructure as a result of disasters. Existing loopholes in evaluation methods might be used by potential donors as an excuse for certain delays in realization of their financial commitments. Besides, despite the announced close start of pilot projects, the norms on enhanced access to funding via the fast-track and simplified modalities in case of emergencies remain not thoroughly clarified; the procedures for transfer of smaller grants to communities with destroyed infrastructure are still under discussion. The same relates to the eligibility criteria, i.e. who could be the main beneficiary of multilateral funding. These important operational details and the roadmap for practical action are still not finalized. The annual FRLD report, 2024 updates on administrative and structural procedures, but its operationalisation, programming and the eligibility criteria which could be considered as the key for its practical action, are limited in detail.

Despite these concerns, the FRLD creation could be regarded as a milestone in formation of the global climate adaptation institutional network representing the expanding assemblage of multilateral financial institutions to aggregate climate finance. Potentially it might turn into one of the key actors in international aid coordination, with its special focus on climate adaptation practice. For example, as a start, in 2025 the FRLD and the international Adaptation Fund[4] agreed on the Framework of collaboration to assist climate vulnerable countries to address the most pressing issues. It is based on collaboration and complementarity of two funds aiming at fostering the innovation, refining collective expertise and knowledge to address climate adaptation of communities and their infrastructures. Such joint mission illustrates the new trend towards building international constellations and coordination networks for climate adaptation.

[3] Among 26 members of FRLD, 12 represent the developed and 14 the developing states: 3 from the Asia-Pacific, 3 - Africa, 3 - L. America and the Caribbean, 2 - small islands developing states, 2 - least developed countries, 1- developing countries non—members of the regional groups.

[4] International Adaptation Fund established in 2010 mobilized adaptation grants of USD 1.25 billion; 183 adaptation projects are under implementation

V. Finance and technical assistance packaged together

Finance and technology transfers are the key cornerstones in international climate development aid. Our research shows that international development *finance* for climate adaptation packaged with transfer of *technology* and *competences* to support domestic capacity building and resilience of infrastructure is a promising tool. Application of adaptation development finance instrument as such, although being appealing and widely promoted by the global South, is not able alone to successfully solve the complexity of existing international and domestic adaptation problems in recipients. Technology transfer is an integral element of climate aid.

Today, there is broadening evidence about the diversity of international technology-oriented actions for domestic capacity building and disaster-proofing of infrastructure, including transfer of equipment and technical appliances, know-how and data to stakeholders and institutions It is supplemented by the recently increasing international adaptation funding. In 2018-2022 the climate adaptation development finance for *technology transfer* showed more than a double increase - from USD 5.7 billion to USD 12.7 billion, and its share in total climate-related development finance for technology grew from 26 percent in 2018 up to 35 percent in 2022 [1].

Below, we discuss *three* major aspects of international transfer of climate adaptation technologies - its implications for domestic, international and implementation frameworks.

First, despite high interest of the developing countries in promoting the international climate finance aid, the recent messages from their national climate adaptation strategies indicate at certain shifts in approaches, with increased preferences towards its combination with technical transfers. In 2024, the national climate reports from 56 developing countries put emphasis on technical development cooperation: about 43 per cent of their national plans cover different aspects of adaptation technologies and competences transfer. There is a wide variety of context-dependent technology priorities across regions and countries, and recent assessments show that according to aggregated data from developing countries during 2011-2023, the majority, i.e. about 88% of their adaptation technology needs are in three main sectors - water, agriculture and coastal zone management. These sectors are highly sensitive to climate risks and technologies for enhancing safety of local infrastructure and livelihoods are usually of a priority. They include, for example, construction of coastal storm surge barriers, dams, canals and installations for protection from sea level rise and flooding, water storage facilities, water harvesting technologies, etc.

Global funding portfolio under the UNFCCC, i.e. mobilized through the Adaptation Fund, Green Climate Fund, Global Environmental Facility, presents forty two adaptation technology-oriented projects realized during 2016-2023 with climate finance mobilized accounting for about USD 443 million. But it is more than ten-fold lower than domestic adaptation needs of the developing countries. There is also certain imbalance in international supply of technology aid across sectors, and it doesn't cover the risk-sensitive areas leaving safety of livelihoods and infrastructure under threat. Currently, its major focus is on agricultural sector which is getting support of about twice higher than aid to transport/storage and to water supply and sanitation, which are respectively ranking 2nd and 3rd in development finance for adaptation technology transfers.

Second, besides support for domestic adaptation the technical aid becomes an essential tool for strengthening compliance with the international norms and implementation of the UNFCCC regime by vulnerable developing countries. Particularly, it relates to meeting the standard international requirements for national reporting, formats for domestic compilation of adaptation data, establishing technology and information networks. Art. 10 of the Paris Agreement deals with the technology transfers, and it specifies norms for technology development cooperation. In 2023 the Technology Implementation Program was introduced to support formulation of adaptation technology preferences and to identify the major needs of climate vulnerable countries: they are invited to regularly report about their adaptation technology priorities, and its format is specified in detail.

Another urgent strand of technology development cooperation - consolidation of the global climate data networks, early warnings systems and disaster forecasting. Participation of climate vulnerable regions in international information supply and exchange is increasingly essential. Today, the global infrastructure for climate services and early warning systems is characterized by serious loopholes: only about one-third of the world is accountable for compatible climate data coverage. Regular collection and flows from the major areas of the global South to support the worldwide mapping, monitoring and services coverage remains insufficient. Their input into the Big Data centers becomes critical to synchronize systems of disaster early warnings and ensure better quality of emergency alerts to locales worldwide. Transfer of technology and competences, application of digital tools, performance of innovative education projects in the developing countries is a prerequisite for effective global climate infrastructure and services, and it is among the core segments in adaptation development cooperation.

Third, certain problems in domestic implementation of technology-oriented adaptation projects in recipients could occur; although in many cases the *planning* versus *implementation* issues within the adaptation cycle are also typical for the global North. The majority of the recently reported climate strategies from the National Adaptation Plans of the developing countries present a variety of targets aimed at enhancing climate resilience. National climate programs mostly focus on strategies and on climate risk assessment, without proportional attention paid to concrete implementation actions in disaster risk reduction. In many cases the adaptation plans are used as a kind of 'window-dressing' to substitute, or postpone the implementation under climate uncertainty. Major deviations in strategic adaptation planning versus implementation could result in further adaptation gaps. We believe that both phases should be closely intertwined, their major milestones packaged together, coherently realized and regularly verified in order to ensure effective performance within the integral adaptation chain. Among new directions of international coordination – development of indicators, methods and metrics to measure and compare the climate resilience across states, effectiveness in implementation of adaptation action and input of multilateral development aid. Today, standard formats for adaptation capacity data reporting by states are discussed, as well as indices for enabling factors and means for implementation depending on the local contexts for adaptation.

Among specific implementation quests - domestic performance of technology oriented adaptation projects in the beneficiaries after technical competences are transferred. Lack of technical expertise, services, infrastructure and information are typical factors hindering implementation of transferred technologies; ineffective domestic legal, regulatory and planning frameworks are also a constraint. According to rankings selected by the developing countries the economic and financial factors are regarded as the major barrier for success in application of adaptation technologies. Conditional aid is also among possible implementation concerns of recipients: sometimes donors tie technology transfers with conditions to purchase certain goods and services from the donor (that might be more expensive than locally), and it results in increase of project costs; another clause might relate to creating favorable conditions for investments from the donor country. Recipients also note that negative side-effects of ODA might include the corruption and short-term programs that are not sufficient for functioning of stable domestic adaptation systems.

CONFLICT OF INTEREST

Author declare that they do not have any conflict of interest.

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THE PETRO- AND HYDROTHERMAL POTENTIAL OF THE KARAGAN-CHOKRAKIAN DEPOSITS FOR THE CENTRAL PART OF THE TEREK-CASPIAN FOREDEEP

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Abstract

The article discusses the assessment of the thermal potential of the Karagan-Chokrak deposits of the Middle Miocene of the Terek-Caspian trough. The choice of research object is due to the fact that these deposits are the most studied in terms of lithological, stratigraphic, and thermophysical properties. These deposits are characterized by high temperatures, low mineralization, relatively shallow depths, accessibility of known groundwater deposits to potential consumers, and the presence of a significant number of drilled wells. To assess the resource potential of thermal energy, a large amount of available geological and geophysical data on known geothermal fields and oil field wells was summarized and analyzed. Using this data, digital models were created: the depth of the bottom of the deposits; the thickness of the formations; the distribution of average temperatures in the formation across the area, the material composition of the rocks, etc. For the formation conditions, calculations were made of the specific heat capacity of the rock skeleton and formation water, as well as an assessment of the radiogenic component of the heat flow. An area analysis of the distribution of thermal field parameters created by factors of various nature shows that the peculiarities of temperature distribution across the area and section may be due to: in the first case, by the elevated or depressed position of the deposits; in the second case, by the degree of infiltrative "cooling," i.e., the presence of "heat-resistant" rocks (e.g., clay deposits in Maykop); in the third case, the warming effect of rocks within disturbed folds, which we see in areas of modern geodynamic activity, and lastly, the material composition of rocks differing in the presence of long-lived isotopes of uranium, thorium, and potassium. The assessment of the thermal resource potential of the studied object shows that this type of renewable energy source has enormous reserves. The task of their comprehensive development lies solely in the development of modern geotechnological technical solutions and environmentally sound methods of their use.

Keywords: geothermal field, heat capacity, sedimentary deposits, porosity, formation water, radiogenic heat generation.

I. Introduction

According to materials from the International Geothermal Congress in Reykjavik, geothermal energy is used in 88 countries around the world, and its use increased by 52% by 2020 compared to 2015. Installed capacity reached 10.7 GW, with an average annual growth rate of 8.73%. Heat energy consumption is 283.58 TWh/year, which is 72.3% more than in 2015, and is increasing at an average annual growth rate of 11.5% [8].

The use of this amount of geothermal energy leads to savings of up to 81.0 million tons of oil equivalent per year, which prevents the emission of 78.1 million tons of carbon and 252.6 million

tons of CO_2 into the atmosphere. By 2025, the installed capacity of geothermal energy is projected to reach 19.3 GW with consumption of up to 480 TWh/year [12].

In Russia, the use of geothermal resources is most developed in the Kuril-Kamchatka region, Dagestan, Krasnodar Krai, the Chechen Republic, and to a much lesser extent in other regions. Thermal water is used for industrial purposes, centralized heat supply, individual space heating, greenhouse heating, bathing and balneological purposes, drying agricultural crops, and fish farming. Currently, about 1,000 geothermal heat pumps are in operation in the regions of Russia. According to V.D. Svalova's estimates, by 2020, the use of geothermal energy in Russia amounted to 433 MW of installed capacity and energy production of 8.475 TJ/year [11].

The plans for the development of geothermal energy until 2030, as part of the implementation *of the Strategy for Scientific and Technological Development of Russia* (approved by Decree of the President of the Russian Federation No. 145 of February 28, 2024), envisage capital investments of 15 billion rubles.

There are 15 known thermal water deposits in the study area, of which only 9 are currently in use. One deposit is in conservation and 4 deposits are in the state reserve. Thermal waters are used industrially only at the Khankalsky thermal deposit, where a geocirculation system (GCS) is used to maintain reservoir pressure, and in 2014, a 1 MW geothermal power plant was commissioned, also operating in GCS mode [15].

This study aimed to investigate and evaluate the petrothermal and hydrothermal resources of the Karagan-Chokrakian sandy-clay deposits of the Middle Miocene in the central part of the Terek-Caspian foredeep, with a view to assessing the prospects for further development of thermal energy use.

The choice of deposits is due to the fact that they are the most studied in terms of thermophysical parameters and known lithological and stratigraphic structure. The formation waters of these deposits are characterized by high temperatures, low mineralization, and relatively shallow depths. In general, both in terms of lithology and physical properties, the Karagan and Chokrak deposits in this area differ little.

II. Methods

To assess the resource potential of thermal energy, a large amount of available geological and geophysical data on known geothermal fields and oil field wells was summarized and analyzed. Using this data, digital models were created: the depth of the base of the deposits; the thickness of the formations; distribution of average temperatures in the formation across the area, material composition of rocks, etc. For formation conditions, calculations were performed for: water density, specific heat capacity of rock matrix and formation water, radiogenic component of heat flow, and overall area distribution of the petrothermal and hydrothermal potential of the studied deposits.

All calculations and subsequent constructions were performed in the Quantum GIS system, which has open code, allowing for the management of geodata and the maintenance of a unified database.

III. Data

The Karagan-Chokrakian deposits of the Terek-Caspian foredeep are represented by interlayers of sandy-aleuritic, clayey, and clayey-carbonate rocks. At the same time, clayey carbonate rocks "... play an extremely subordinate role and constitute on average 2-3% of the entire section and in rare cases reach values of 11-13% in limited, local areas ..." [6].

Karagan deposits are thin, up to 50-100 m thick, and usually lie on top of Chokrak deposits, often with erosion. They are divided into two suites: the lower - Sunzha suite and the upper -Manas

suite. Both suites are composed of sandy-aleuritic and clayey rocks with interlayers of clayey-carbonate formations.

Chokrakian deposits are divided into two parts: the lower - Makhachkala suite, predominantly clayey with interlayers of marl; and the upper - Sernovodsky suite, sandy-clayey. In some cases, the thickness of the chokrak reaches 700 m.

Rock density. The sedimentary rock matrix consists mainly of three basic components: sandy-aleuritic, carbonate, and clayey, which have different mineralogical densities. The sandy-silty component is represented by quartz (65...85%) with an admixture of feldspars, glauconite, and siliceous rocks. The mineralogical density of quartz is $2.65 \cdot 10^3$ kg/m^3, glauconite – $3.05 \cdot 10^3$ kg/m^3, and feldspars and siliceous rocks $(2.3 \div 2.6) \cdot 10^3$ kg/m^3. Overall, the average mineralogical density of the sandy-silty component is $2.67 \cdot 10^3$ kg/m^3.

Carbonate deposits are represented mainly by calcite with a mineralogical density of $2.71 \cdot 10^3$ kg/m^3 and, much less frequently, by dolomite with a density of $2.87 \cdot 10^3$ kg/m^3. As a rule, Chokrak rocks are characterized by low carbonate content, and only a few compacted interlayers have a carbonate content of more than 2-3%. The average density is 2.72×10^3 kg/m^3.

Clay deposits are represented by hydromicas, sometimes mixed with montmorillonite and glauconite. The mineralogical density of these minerals varies from $2.85 \cdot 10^3$ to $3.05 \cdot 10^3$ kg/m^3 and averages $2.87 \cdot 10^3$ kg/m^3, which significantly exceeds the density of quartz and calcite.

According to petrophysical and geophysical studies, the porosity of the deposits varies on average within a narrow range, mainly from 16 to 22%, with more than 75% of samples characterized by a porosity of 18-22%. The work [3] presents data on the correlation of core data with well logging data (density gamma-gamma, neutron and acoustic logging) for the Khankala deposit, where the average porosity value was 19.6%. The weighted average value for the core was slightly lower at 19.4%. According to the author, the slightly lower porosity value for the core was due to incomplete (82%) rock removal during sampling.

The mineralogical density of the rock matrix of these deposits, based on core and well logging samples, shows that it is not very dependent on the degree of lithification and varies within a narrow range, mainly from 2.65 to $2.70 \cdot 10^3$ kg/m^3, with 50% of samples at $2.66 \cdot 10^3$ kg/m^3.

Water saturation. The bulk density d_p of water-saturated rocks based on well logging data, using the results of core analysis, sampling, and testing of productive formations, is determined by the formula:

$$d_p = d_{sk} \cdot (1-K_p) + d_v \cdot K_p. \quad (1)$$

from which the total porosity of rocks is:

$$K_p = (d_{sk} - d_{p.}) / (d_{sk} - d_v). \quad (2)$$

where d_{sk} - the matrix density, kg/m^3;
d_v – formation water density, kg/m^3.

The formation water of the Karagan-Chokrakian deposits has low mineralization, h.e., the mineralization of water for known thermal deposits in the territory is $(1.65 \div 3.7) \cdot 10^{-3}$ kg/m^3 [5]. Taking into account reservoir temperatures of 80÷110°C and reservoir pressures of 2.0÷3.0 MPa, the estimated density of reservoir water is determined by the average value of $0.98 \cdot 10^{-3}$ kg/m^3.

Specific heat capacity and thermal conductivity. The thermophysical parameters of sedimentary rocks, including those of Karagan-Chokrak, have been studied repeatedly and are given in numerous works of Dagestan region scientists. These works provide typical values of the thermophysical parameters of rocks, including the specific heat capacity for the studied Karagan-Chokrak and other sedimentary deposits. [1, 4, 7, et all].

To analyze and evaluate thermal potential, the geothermal field must first be divided into stationary and non-stationary components: radiogenic and "tectonothermal," associated with the

processes of heat transfer from the subsurface during limited periods of tectonic and magmatic activity [2]. Accordingly, the thermal conductivity of the medium is the sum of conductive heat exchange and the radiation component.

For lithological and stratigraphic conditions similar to those under study, Mammaev O.A. et al. performed thermal conductivity calculations to account for both components. Based on his research, it was concluded that "... with a quasi-stationary geothermal field, the most satisfactory results in calculations created by mantle heat sources are obtained by solving a one-dimensional stationary heat conductivity equation" [9, 10].

At the studied geothermal fields of the Dagestan, it was found that the share of the radiogenic component of the sedimentary thickness up to 5 km in the heat flux observed at the surface reaches an average of 10% or 6-7 mW/m^2 [9].

For a homogeneous lithological-stratigraphic layer, the potential petrothermal energy of the rock keleton is determined by the formula:

$$Qc.n. = C \cdot t \cdot V(1-K) \cdot p. \quad (3)$$

where Qc.п. - the potential thermal petrothermal energy of dry rock in J;
C - the specific heat capacity of the rock, J/kg·°C;
t - the average temperature in the formation, °C;
V = a·b·h – volume of rock together with pores, m^3;
p =2.66 ·10^3 kg/m^3 – specific density of rock;
K = 0.19 – porosity coefficient, units.

The potential thermal energy of formation waters in sedimentary strata, taking into account mineralization, temperature, and pressure, is determined by the following formula [13]:

$$Q_{пв} = C_в \cdot t \cdot V \cdot K \cdot ϱ. \quad (4)$$

where $C_в$ = 4.1868 ·10^3 J/(kg· ^{0}C - specific volumetric heat capacity of formation water at the surface.

Under reservoir conditions, the specific heat capacity of bound water changes smoothly with increasing pressure and temperature [7]. With increasing pressure, the heat capacity also decreases and, with increasing temperature, taking into account mineralization, temperature, and pressure [2], is:

$$C_{пв.} = C_в \cdot 3.1 \cdot 10^{(-3)} G = 4.09 \cdot 10^{(-3)} J/(кг \cdot {}^0C. \quad (5)$$

where G - the mineralization of water in reservoir conditions, kg/m^3

Radiogenic component. To calculate the amount of radiothermal generation in rocks due to the decay of isotopes of naturally occurring radioactive elements (^{238}U, ^{232}Th, and ^{40}K), the following formula from [2], is used:

$$A = 0.132 (a \cdot U + b \cdot Th + c \cdot K) \cdot p. \quad (6)$$

where A - heat generation, mW/m^3;
p - the specific density of rocks, kg/m^3;
^{238}U, ^{232}Th, ^{40}K – content of radioactive elements uranium, thorium, and potassium in rock in % by weight;
a, b, c – conversion factors.

The calculations use the coefficient values proposed by M.D. Khutorsky [14]: a=0.718·10^{-4} μW/m^3; b=0.193·10^{-4} μW/m^3; c= 0.262 μW/m^3. The results of the calculation are shown in Table 1 below.

Table 1: Value of radiothermal generation per unit volume in the Karagan-Chokrakian deposits for the central part of the Terek-Caspian foredeep

Age of deposits	Lithological composition	Rock density, kg/m³	Average values			Average value relative to volume, %	A, μW/m³
			^{238}U, n·10^{-4} %	^{232}Th, n·10^{-4} %	^{40}K, %		
N_2 kg + N_2 ch	Sand fraction	2050	3.0	5.1	2.1	53.0	0.998
	Silt fraction	2250	5.1	11.2	2.3	23.5	4.36
	Clay fraction	2540	2.0	5.8	2.5	3.5	3.07
Total radiogenic heat generation per unit volume							1.585

Note: 1) rock volume values are taken into account with a porosity coefficient K_{por}=19.6%;
2) other inclusions constitute an insignificant volume of ~ 0.4%.

The distribution of the radiogenic component of the heat flux was calculated for the area of the corresponding elementary cell, as used in previous calculations. The results of the calculations of the values of the radiogenic component of the heat flux are shown in Figure 3.

IV. Results

The general pattern of the observed field is an increase in thermal potential in the northern and northwestern directions from the minimum values in the south of the territory, in the strip where the sediments emerge on the surface, and further, as the thickness of the sedimentary layer increases, to maximum values in the axial part of the deflection and further north to the zone separating the foredeep from the Skifian Plate. There is a dependence of the increase in temperature and, accordingly, thermal potential as the Karagan-Chokrak sediments sink and the crystalline basement rises. This may be due to an increase in rock density (and a corresponding decrease in thermal resistance) and low absorption of conductive flow. The lowest potential is observed in areas of sedimentary deposition (the Chechen and Ossetian depressions).

In general, a consistently high potential is observed in known fault zones with inherited and modern geodynamic activity. These are the Krayevoy, Tersky, and Sunzhensky faults (seam zones) of sublatitudinal extension and the Benoy-Eldarovsky and Kazbeksky faults of meridional and submeridional extension, which complicate the overall temperature distribution pattern.

The nature of the change in hydrothermal potential generally follows the pattern of petrothermal energy distribution. At lower potential, it shows a more differentiated character, which is probably primarily related to the distribution of temperatures and the thickness of the deposits.

These are the Kraevoy, Tersky, and Sunzhensky faults (seam zones) of sublatitudinal extension. Complications in the overall temperature distribution pattern are associated with intersections between sublatitudinal faults and transverse submeridional faults, namely the Kazbek and Benoy-Eldarov faults. According to deep seismic sounding data, all these faults are characterized by mantle underthrusting.

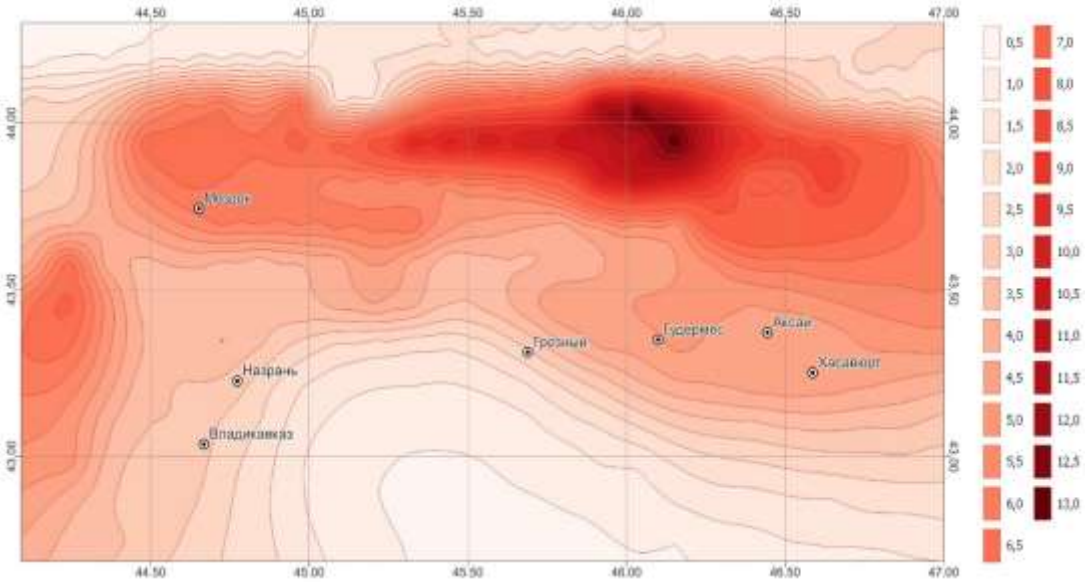


Figure 1: *Map of the areal distribution of the petrothermal potential of the Karagan-Chokrakian deposits for the central part of the Terek-Caspian foredeep, (in* $n \cdot 10^{15}$ *J)*

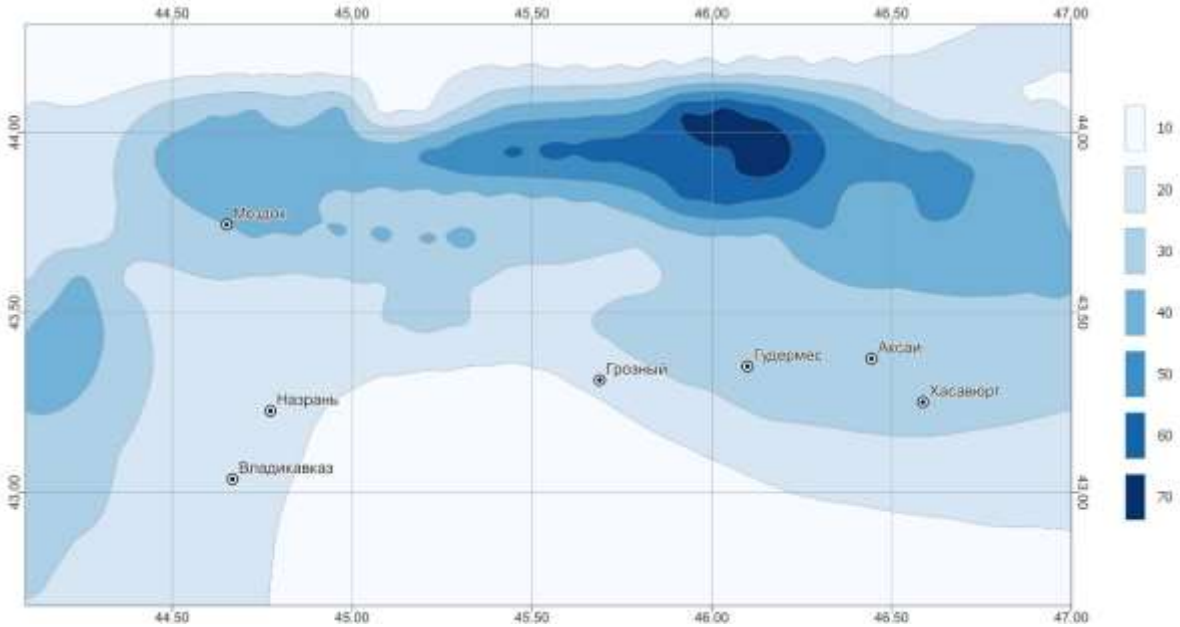


Figure 2: *Map of the areal distribution of hydrothermal potential of the Karagan-Chokrakian deposits for the central part of the Terek-Caspian foredeep, (in* $n \cdot 10^{14}$ *J)*

The nature of the change in hydrothermal potential generally follows the pattern of petrothermal energy distribution. At lower potential, it shows a more differentiated nature, which is primarily likely related to temperature distribution, stratigraphy, and sediment thickness.

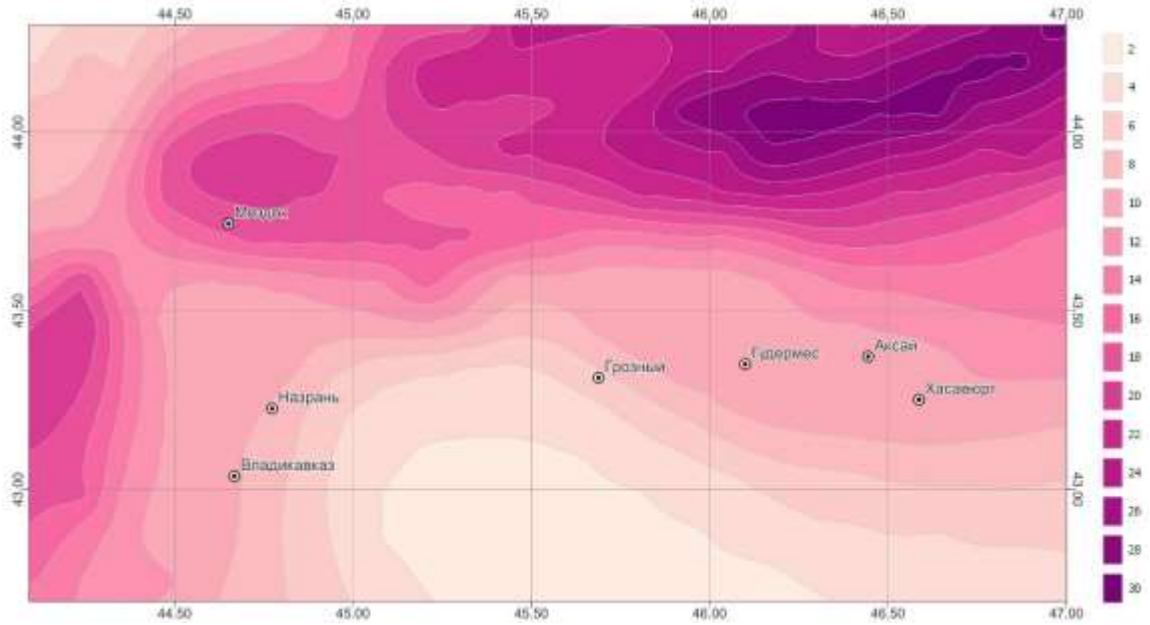


Figure 3: *Map of the areal distribution of radiogenic heat release potential of the Karagan-Chokrakian deposits for the central part of the Terek-Caspian foredeep (in* $n \cdot 10^5 W$*)*

It should be noted that the Middle Miocene complex is distinguished by the overlap of the heat-insulating (low thermal conductivity) strata of the Upper Miocene from above and the Maikop clay deposits from below. Such a differentiated picture of the thermal field distribution shows a significant contribution to the thermal field of the radiogenic component of the decay of long-lived isotopes. This component is significant for terrigenous sedimentary rocks, which are the Karagan-Chokrakian deposits.

V. Conclusion

Thus, the assessment of the thermal resource potential of the Karagan-Chokrak deposits in the central part of the TKP shows that this type of renewable energy source has enormous reserves. The task of their comprehensive development lies solely in the development of modern geotechnology technical solutions and environmentally sound methods for utilizing both hydrothermal and petrothermal potential.

The peculiarities of temperature distribution across the section in the region may be due to: 1) the elevated or depressed position of the sediments; 2) the degree of infiltrative "cooling," h.e., the presence of "heat-resistant" rocks (e.g., clayey sediments of Maikop); 3) the warming effect of rocks within disturbed folds, which we see in areas of modern geodynamic activity; 4) the material composition of rocks differing in the presence of long-lived isotopes of uranium, thorium, and potassium.

One promising area is the use of petro- and hydrothermal energy from oil wells. The study area has a significant number of wells drilled in oil fields that have been decommissioned due to waterlogging of deposits but are technically suitable for operation.

The absence of the need to drill wells will significantly reduce the cost of implementing geothermal projects.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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COMPREHENSIVE STUDY OF CERTAIN THERMAL WATERS IN ADJARA FOR THE MANAGEMENT OF NATURAL RESOURCES

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Abstract

A comprehensive study of certain thermal waters in the Autonomous Republic of Adjara was carried out. In order to study the vegetation of the landscapes surrounding the study sites, cenotype identification and analysis of structural characteristics were carried out in the areas of Daba Makhinjauri (Khelvachauri Municipality) and the villages of Akhalsopeli and Leghva (Kobuleti Municipality). The organoleptic properties of the waters were also assessed. The studies revealed that the highest concentrations of Ca^{2+}, Mg^{2+} and Cl^- ions were found at the Leghva site. Analysis of nitrates, nitrites, ammonium ions, phosphates and sulphates confirmed that the thermal waters are free from chemical contamination. The Makhinjauri thermal water is characterised by a hydrogen sulphide--sulphide composition, while the Akhalsopeli thermal water has a chloride--sodium ionic composition with elevated levels of fluorine and boron. Makhinjauri thermal water (temperature 37.62°C) is not classified as mineral, while Akhalsopeli water is classified as mineral-thermal (temperature 37.63°C and mineralisation > 1g/L). Leghva water is highly mineralised (mineralisation ≈ 2.1 g/L). No traces of Cd, As, Hg, Pb, V, Ti, Tl, Cu, Co, Cr, Mo, Ni or Zn were detected in the waters. The Akhalsopeli water contains insignificant amounts of Mn, Sb, Se and Ba, while low concentrations of B, Li, Mn, Sb and Ba were found in the Leghva water. Sanitary-microbiological analysis confirmed that the waters are free from contamination. The hydrocarbon composition of the accompanying gases showed a 100% methane content at all three sites. In addition, a thermal water map was produced using geo-information systems, highlighting the buffer zones of the thermal waters.

Keywords: thermal water, formations, chemical content, associated gases, map

I. Introduction

In the XXI century, amidst global warming, irreversible atmospheric pollution and the depletion of fossil fuels, the search for alternative, renewable and cost-effective energy sources have become increasingly important. Utilizing such sources can mitigate environmental harm, conserve resources and address the global energy crisis. Alongside solar and wind energy, thermal waters are recognized as an alternative energy source that is economical, environmentally sustainable, reliable and inexhaustible.

Thermal waters, as a renewable energy resource, offer numerous undeniable advantages, making them competitive not only with traditional thermal energy sources but also with other renewable options. Traditional sources often have high costs and significant environmental impacts, while many renewable sources, such as solar and wind, are subject to fluctuations depending on the time of day or weather conditions. In contrast, thermal waters provide a stable and reliable energy supply, unaffected by weather or seasonal changes. Their utilization requires no energy carriers or dams and does not release harmful substances into the environment.

The issue of water resources is highly relevant today, as global warming has led to a reduction in water availability in many countries, significantly impacting their economies. Addressing Georgia's strategic and tactical challenges - spanning sectors such as the economy, agriculture, resort management, energy, balneology and more - requires up-to-date and comprehensive information on the water resources of specific regions and their anticipated changes [1, 2]. In the context of modern climate warming, it is essential to examine the factors influencing the formation of groundwater as a natural resource and to predict potential changes [3, 4]. Georgia, with its varied tectonic, lithological, geochemical, geothermal, and hydrogeological conditions, is abundant in fresh, mineral, and thermal groundwater. This richness is largely attributed to the substantial atmospheric precipitation the country receives (93.3 km^3 annually). Of these reserves, 63% are located in Western Georgia, 24% in Eastern Georgia and 13% in Southern Georgia. Georgia's hydromineral resources are notably diverse, with over 2,000 mineral water sources identified. Among them, more than 1,700 emerge naturally, while over 300 are extracted through wells. The chemical and physical properties of the aforementioned mineral waters highlight the therapeutic benefits of many of these sources [5, 6]. Additionally, Georgia is home to numerous thermal springs, which represent a renewable and environmentally friendly energy resource.

The country possesses abundant high-temperature thermal water resources, yet, out of 250 known deposits, only 44 geothermal water wells have been registered, with temperatures ranging from 30°C to 112°C. The total flow rate of naturally occurring thermal waters, with temperatures between 20°C and 1000°C, exceeds 1,000 L/s. Georgian thermal waters display a wide range of chemical compositions, from fresh hydrocarbonate-calcium to highly mineralized chloride-sodium. Generally, the deeper the water, the hotter it is upon emergence; however, some sources are highly mineralized, which complicates their extraction. The Adjara-Trialeti folded system is regionally known for its favorable geothermal conditions, which contribute to the prevalence of thermal water sources in the area. Many of these water sources have been utilized for balneological and hygienic purposes for centuries. As a result, the region is home to numerous geothermal water deposits, whose heat is applied in balneology and various sectors of the national economy. The waters of this region are renowned for their diversity, offering both low and high mineralization and are well-suited to meet a wide range of consumer needs. It is important to note that geothermal heat is 5-6 times more cost-effective than heat generated by other methods, and the payback period for properly invested funds is relatively short. While thermal waters are primarily used for balneological purposes today, they have the potential for broader applications across many sectors of the national economy. Georgia represents an inexhaustible source of

affordable, deep energy, with its thermal waters offering healing properties, high temperatures, low mineralization and a rich content of chemical elements [7, 8].

The use of groundwater as a subsoil resource is governed by the "Law on Subsoil," which was adopted by the Parliament of Georgia in 1996. According to this law, Georgia's subsoil is considered state property and its management aims to ensure the rational use of subsoil and mineral resources. This is done while considering natural processes, environmental potential, the needs of current and future generations, and the principles of sustainable development [9, 10]. A significant portion of Georgia's thermal and mineral waters remain untapped. Our ancestors recognized the unique properties of this resource and have been using it for the treatment of various ailments since ancient times. Active research and development in this area continued until the 1980s and 1990s. However, since the early 1990s, no systematic state hydrogeological studies have been conducted in Georgia. As a result, the available information on the quantitative and qualitative characteristics of groundwater is based on previous studies.

The relevance of this issue is primarily driven by the need for each region in Georgia to have its natural resources assessed at a modern scientific level, particularly in the context of regional management. There is also significant potential for utilizing thermal water resources for heat and energy purposes, although this potential has been minimally tapped so far. In light of ongoing global warming and the resulting transformation of various natural landscapes, conducting a comprehensive study of groundwater in the Adjara region is timely. This study is crucial for assessing the potential of water resources, ensuring their effective and rational use, and supporting the sustainable development of the region's economy, agriculture, energy, and other sectors.

Given the strategic importance of thermal waters for the development of the national economy, the goal of this research is to conduct a comprehensive study of thermal waters at various locations in the Autonomous Republic of Adjara. The aim is to evaluate these waters and identify potential directions for their future use. The study focused on the thermal waters of three locations in the Autonomous Republic of Adjara: Makhinjauri (Khelvachauri Municipality), Akhalsopeli (Kobuleti Municipality), and Leghva (Kobuleti Municipality). It is important to note that modern, comprehensive studies have not been conducted on these waters, the extent of their bacteriological contamination remains unknown and there is a lack of up-to-date geographical data on these sources. The research objectives included: studying the vegetation in the landscapes surrounding the study sites; analyzing the chemical and microbiological characteristics of the thermal waters; examining the gases associated with the thermal waters; conducting multielement analysis of the thermal waters using plasma atomic emission spectrometry (ICPE-9820, Szimadzu); and creating a map of the water locations using a GIS system [11].

II. Research Materials and methodology

For the research, literature sources related to the natural resources and physical-geographical conditions of the Autonomous Republic of Adjara were used. These sources provided valuable information on geothermal waters to assess their historical use. It was found that, to date, no comprehensive studies have been conducted on the organoleptic, physicochemical, and microbiological characteristics of the waters mentioned. Additionally, there has been no analysis of their ionic composition or multi-element content, nor has the composition of their accompanying gases been determined. These gaps highlight the need for complex studies to identify potential directions for the use of these waters.

To collect water samples from the aforementioned locations, a field scientific research expedition was organized. This expedition involved a field reconnaissance survey of the surrounding areas, a background study of the vegetation and measurements of various

parameters under field conditions, including temperature, air pressure, pH, electrical conductivity and salinity. Additionally, organoleptic indicators such as color, odor, taste, appearance and transparency were evaluated. In the laboratory, a multielement analysis of the thermal waters was conducted using ICPE-9820. A comprehensive analysis of the organoleptic, physical, chemical, and microbiological properties of the waters was performed using titrimetric, photometric, potentiometric, and plasma atomic emission spectrometry methods. The hydrocarbon content was determined through gas chromatography.

Water samples were collected in chemically clean containers with screw-on stoppers. To ensure accurate measurements of physicochemical parameters, the containers were filled to the top, minimizing the possibility of air under the stopper and reducing the risk of shaking the contents during transportation. For microbiological analysis, separate, pre-sterilized 0.5-liter glass containers were used, which were not filled completely to prevent accidental contamination and to allow for light mixing of the sample before analysis [12]. The total volume of water collected at each location was 2 liters. Upon placement in the water container for analysis, each sample was labeled with relevant details, including the sample number, description, sampling location, environmental and climatic conditions, and the study's purpose.

The determination of variable physicochemical parameters and microbiological analysis of the samples was conducted within 6-8 hours of collection. For other cases, samples were stored according to the technical regulations, which involved cooling them to 2-5°C with a storage period of up to 24 hours. Once cooled, analysis began when the sample temperature reached room temperature. In the field, the following parameters were measured using the Combo Water Quality Meter AZ 86031 device: water temperature, air pressure, pH, electrical conductivity, and salinity. Immediately after collecting the water samples, organoleptic indicators such as color, odor, taste, appearance, and transparency were evaluated, as these properties can change over time in the water [13]. A comprehensive laboratory analysis of the thermal waters was conducted, focusing on the determination of several key parameters: The pH was measured potentiometrically using a laboratory pH meter (Mettler Toledo) [14]. The concentrations of HCO3-, Ca2+, Mg2+ ions, and carbonate hardness were determined through titrimetric methods [15, 16, 17]. The concentrations of ammonium, nitrate, nitrite, fluoride, sulfate, phosphate ions, and hydrogen sulfide were assessed using photometric methods [18, 19, 20, 21, 22, 23, 24]. Multielement analysis of the thermal waters was performed using plasma atomic emission spectrometry with an ICPE-9820 instrument [25]. For microbiological analysis, saprophytic microorganisms were identified, including mesophilic, saprophytic aerobes, and facultative anaerobes, which are capable of forming colonies on nutrient agar and are visible under 2x magnification. The primary indicator of fecal contamination in water is lactose-positive Escherichia coli, which consists of gram-negative, non-spore-forming rods capable of fermenting lactose into acid and gas at 37°C within 24 hours. The number of saprophytic microorganisms and the quantity of lactose-positive Escherichia coli bacteria were determined using microbial cultivation methods followed by titration [26]. The hydrocarbon content in the thermal waters was analyzed using gas chromatography. The analysis was performed on a Thermo gas chromatograph with an aluminum ionization detector (model Focus GC, S/N 20032872), equipped with the automatic program Chrom-Card/PIANO and a Supelco DH 100 quartz capillary column (100 m in length, 0.25 mm internal diameter, stationary phase methylsiloxane). Chromatography was conducted in constant pressure mode at 345 kPa, with helium as the mobile phase. The test sample was injected using a microsyringe, with a volume of 5 μl. The injector temperature was set to 250°C, and the sample introduced into the column was split in a helium flow at a 1/13 ratio. Chromatography was performed in a single stage with a temperature gradient. The process began at 35°C, which was maintained for 13 minutes. The quantitative content of hydrocarbons was determined by internal normalization of the peak area, with accuracy to 0.001% [27].

III. Results and Discussion

Main vegetation formations of the study locations and their conservation value. To study the vegetation of the landscapes surrounding the study locations in Makhinjauri and Kobuleti municipalities, coenotypes were identified and structural features were examined. The diversity of relief, climatic conditions, soils, and anthropogenic factors contributes to the mosaic nature of the vegetation, with clear evidence of vertical zonation and exposure. The buffer zones around the study sites are predominantly covered by forest vegetation (Table 1). These forests consist of oriental beech, Caucasian linden, chestnut, alder, and Caucasian hornbeam, forming mixed coenoses. Alder forest formations, with the presence of elm, larch, willow, and other species, are found near river valleys. The majority of the forest areas are utilized for agricultural crops and subtropical introduced woody species. In forests impacted by anthropogenic activities, there is a high potential for the invasion of non-native species, and the conservation value of the natural ecosystems is considered moderate.

Table 1: *Main vegetation formations of the study locations*

Object	Buffer zone formations	Category	Conserva-tion value	Anthropoge-nic influence quality	Note
Kobuleti (Akhalsofeli) X 732420.5559 Y 4633694.242 Z 8.178	Alder forest with fern-willow; Alder forest with evergreen Colchian undergrowth; Hornbeam forest with birch undergrowth; Hornbeam-chestnut forest with birch undergrowth, etc. (Alnus, Betula, Populus, Salix, etc.)	Natural / Modified	Average	Agricultural lands	High in Invasive potential of foreign species: Pueraria ; Acacia, crypto-meria. River Achkva is present
Legva X 742433.8613 Y 4638118.757 Z 83.4	Hornbeam-beech forest; Chestnut-beech forest; Hornbeam-chestnut-beech forest; Chestnut-hornbeam-alder forest; Alder-alder-alder forest.	Natural / Modified	Average	Soviet period Tea and citrus fruits were developed; today Corn fields are drawn	Widespread subtropical Plants, there are many advents . River Skura is present
Makhinjauri X 725075.2039 Y 4616596.988 Z 28.294	Typical formations of Colchian forests: Hornbeam-beech forest; Hornbeam-chestnut forest; Hornbeam-alder forest; Chestnut-hornbeam-alder forest; Chestnut-hornbeam-beech forest; Hornbeam-beech-alder forest	Natural/ Modified . Bordering Mtirala National Park	Average	Settlement; Botanical garden is established nearby	It is high in foreign species Invasive potential (trees, shrubs, herbs). River Sakalmakhe is present

Field Measurements: Field measurements taken at the study locations revealed that the waters of Makhinjauri and Akhalsopeli are warm (37.62°C to 36.99°C), while the water in Leghva is cooler (18.34°C). The atmospheric pressure at the thermal water sites ranged from 1012.4 to 1016

mbar (Table 2). The pH of Makhinjauri thermal water is alkaline, Akhalsopeli's is moderately alkaline and Leghva's is weakly alkaline. Leghva water exhibits the highest electrical conductivity (9717 μS/Sm), while Makhinjauri water has the lowest (495 μS/Sm). Correspondingly, the salinity is highest at Leghva (9717 mg/L) and lowest at Makhinjauri (247 mg/L).

Table 2: *Evaluation of Physicochemical Parameters of Thermal Waters under Field Conditions*

Location	Physical and Chemical Parameters				
	Water Temperatures °C	**Air Pressure, mbar**	**pH**	**Electrical Conductivity of Water, μS/Sm**	**Salinisty, mg/L**
Makhinjauri	37.62	1014.2	9.0	495	247
Akhalsopeli	36.99	1016.0	8.3	1232	6165
Leghva	18.34	1012.4	7.4	1942	9717

Organoleptic Parameters. In contrast to the waters of Makhinjauri and Akhalsopeli, Leghva water has a yellowish color. Makhinjauri water had a distinct hydrogen sulfide odor (Table 3). The taste of the waters from Makhinjauri and Akhalsopeli was mildly brackish, while Leghva water was strongly brackish. All three water sources appeared similar, free from foreign impurities, with a natural sediment of mineral salts. However, Leghva water was slightly turbid, unlike the clear waters of Makhinjauri and Akhalsopeli.

Table 3: *Organoleptic Parameters of Thermal Waters*

Indicator	Location	Description
Color	Makhinjauri	Clear liquid
	Akhalsopeli	Clear liquid
	Leghva	Yellowish liquid
Odor	Makhinjauri	Distinct odor of hydrogen sulfide
	Akhalsopeli	characteristic of complexes formed by substances dissolved in water
	Leghva	characteristic of complexes formed by substances dissolved in water
Taste	Makhinjauri	Weak saline
	Akhalsopeli	Weak saline
	Leghva	Strong saline
Appearance	Makhinjauri	Free from foreign impurities, containing a natural sediment of mineral salts
	Akhalsopeli	_ʻʻ_
	Leghva	_ʻ_
Transparency	Makhinjauri	Transparent
	Akhalsopeli	Transparent
	Leghva	Weak turbidity

Water chemical content and bacteriological analysis. Leghva thermal water is classified as highly hard, Akhalsopeli water as moderately hard, and Makhinjauri water as soft (Table 4). The highest concentrations of Ca^{2+}, Mg^{2+} and Cl^- ions were observed at the Leghva location. Analysis for nitrates, nitrites, ammonium ions, phosphates, and sulfates confirmed that the thermal waters

are free from chemical pollution. Ionic analysis revealed that these waters do not belong to iron or silicon water categories. Makhinjauri thermal water is characterized by a hydrogen sulfide-sulfide composition. Akhalsopeli thermal water likely has a chloride-sodium ionic composition, with elevated levels of fluorine and boron. Leghva thermal water also exhibits a high Mg^{2+} content. Makhinjauri thermal water (temperature - 37.62°C) is non-mineral. Akhalsopeli water is mineral-thermal (temperature - 37.63°C, mineralization > 1 g/L). Leghva water is highly mineralized (≈2.1 g/L).

Through multielement analysis, the following order of macroelements was identified:

At Makhinjauri location - Na > Si > K > Ca > Al > Mg > P. Water does not contain iron; at Akhalsopeli location - Na > Ca > K > Al > Si > Mg > P. Water does not contain iron; At Leghva location - Na > Ca > Mg > K > Al > Si > Fe > P (Tale 5). There were no traces of heavy metals - Cd, As, Hg, Pb, V, Ti, Tl, or microelements - Cu, Co, Cr, Mo, Ni, Zn. There was insignificant level of Mn, Sb, Se, Ba in Akhalsopeli water. Low levels of Li, Mn, Sb, Ba were detected Leghva water. In this regard, the waters fall under the following studies.

Assessment of fecal contamination in the studied waters confirmed that they are not contaminated (Table 6). The total count of saprophytic microorganisms is as follows: Makhinjauri - 8/1 ml, Akhalsopeli - 18/1 ml and Leghva - 12/1 ml, all within the permissible limit of no more than 100/1 ml. The total count of Escherichia coli bacteria is <300/1 L at all three locations.

Table 4: *Ionic Content of Thermal Waters*

Parameter Unit of Measurement	**Location**			**Standard**
	Makhinjauri	***Akhalsopeli***	***Leghva***	
pH	9.5	8.5	7.8	6-9
HCO_3^-, mg/L	73.2	54.9	30.5	400
Hardness , mg-eq/l	0.3	6.8	30.0	7-10
Ca^{2+}, mg/L	4.0	132.3	420.8	140
Mg^{2+}, mg/L	1.22	2.4	109.5	85
Cl^-, mg/L	33.65	1250	1538.4	250
NH_4^+, mg/L	0.028	0.098	-	2.0
NO_2^-, mg/L	-	-	-	0.2
NO_3^-, mg/L	4.31	2.1	2.25	50
PO_4^{3-}, mg/L	0.069	0.045	0.066	3.5
F^-, mg/L	0.414	2.62	-	0.7
SO_4^{2-}, mg/L	-	-	-	250
H_2S, mg/L	6.8 Hydrogen Sulfide	-	-	0.03

Table 5: *Multielement analysis of thermal waters using plasma atomic emission spectrometry. Macroelements (mg/L)*

Location	**Al**	**Fe**	**K**	**Ca**	**Mg**	**Na**	**P**	**Si**
Makhinjauri	1.42	-	12.1	9.19	0.184	394	0.0775	18.2
Akhalsopeli	18.6	-	98.4	>271	0.182	5976	0.0484	7.52
Leghva	24.9	0.162	93	> 854	>136	3998	0.0861	9.38

Microelements (mg/L)							
Location	**B**	**Li**	**Mn**	**Sb**	**Se**	**Be**	**Ba**
Makhinjauri	0.17	-	-	-	-	<0.0002	-
Akhalsopeli	>14.8	-	0.0058	<0.0117	<0.0012	-	0.0093
Leghva	2.75	0.0538	0.236	<0.0170	-	-	0.0003

Table 6: *Microbiological analysis of thermal water quality*

Parameter, Dimension	**Lotation**			**Limit**
	Makhinjauri	**Akhalsopeli**	**Leghva**	
Total number of saprophytic microorganisms, units per 1 mL	8	12	Total number of saprophytic microorganisms, units per 1 mL	8
Lactose-positive Escherichia coli bacteria count (Coli index), units per 1 L	< 300	< 300	Lactose-positive Escherichia coli bacteria count (Coli index), units per 1 L	< 300

Hydrocarbon Composition of Waters and Mapping. Gas-liquid chromatography analysis revealed the presence of methane in the hydrocarbon composition based on retention time (Fig. 1). The accompanying gases at all three locations showed 100% methane content. Based on peak areas, the methane concentration increases in the following order: Makhinjauri < Leghva < Kobuleti. Therefore, in terms of gas composition, these are classified as methane waters.

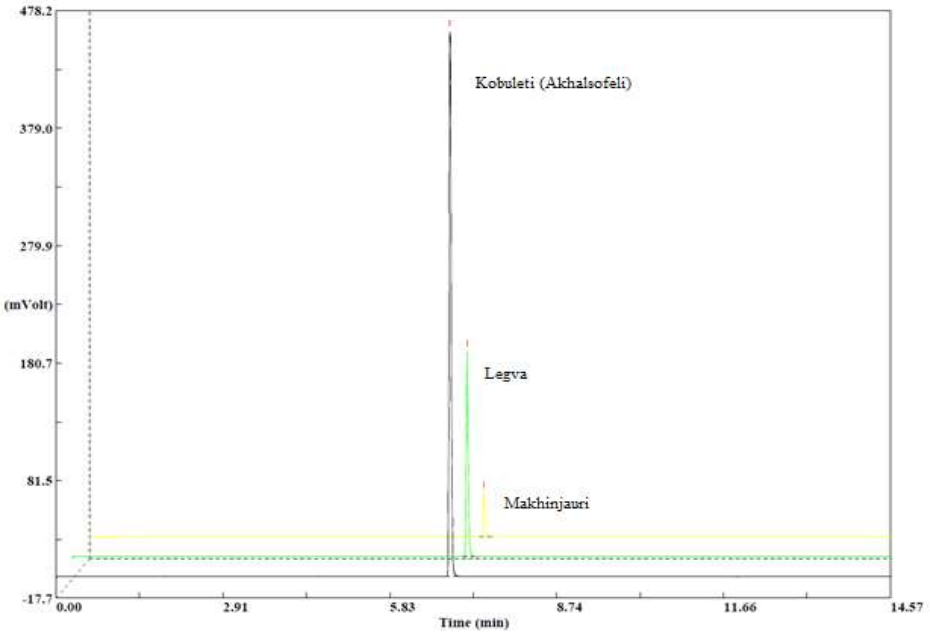


Figure 1: *Hydrocarbon profile of thermal waters*

During the research, a map of the aforementioned thermal waters was created using geoinformation systems, enabling a visual representation of their locations (Fig. 2). GPS coordinates of the selected sites were recorded and mapped.

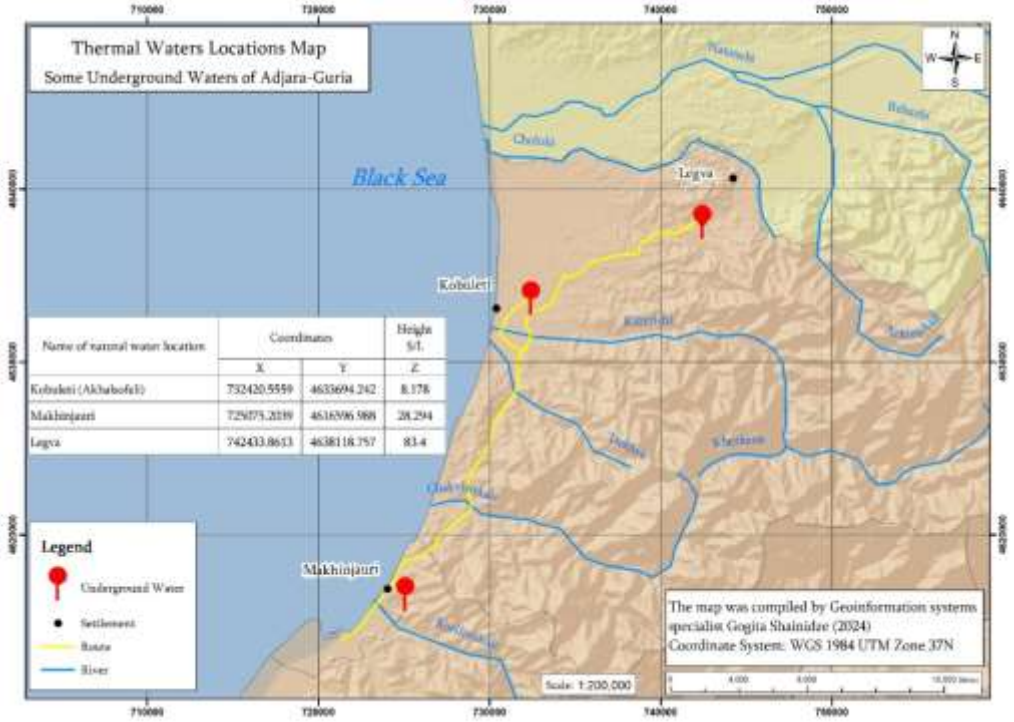


Figure 2: *Location maps of thermal waters*

IV. Conclusion

A significant portion of the thermal waters in the Autonomous Republic of Adjara remains unexplored, with their locations not marked on current maps. Their classification (mineral, thermal, or mixed) and potential uses (balneological, drinking, cosmetic, or energy) have not been studied. As a result, these waters are often used indiscriminately by the local population, which could pose serious risks instead of offering benefits. Furthermore, the gases associated with these waters have not been studied, yet they could play a crucial role in improving the living conditions of the Adjara region's residents, particularly in terms of gas supply. Research is ongoing in the field of comprehensive thermal water studies. Based on the final experimental results, relevant recommendations will be provided, which will be crucial for addressing the needs and interests of the local population. We also hope that the findings will enable the proper utilization of the studied waters for their intended purposes, including balneological, medical-preventive, and energy-related applications. Upon completion of the research, modern geodatabases of thermal waters will be developed using geoinformation systems (GIS), incorporating classifications based on the chemical analysis results of geothermal waters. These maps will be accessible to anyone interested, and the geodatabases can be shared and integrated into various maps. Given that thermal water resources are also abundant in other regions of Georgia, the findings from our research in Adjara will serve as an impetus for similar studies in other areas, helping to identify previously unexplored natural thermal water resources and make them available for public use.

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CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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EXOGENOUS GEOLOGICAL PROCESSES AND RISKS IN THE CHECHEN REPUBLIC: THEORETICAL AND PRACTICAL ASPECTS

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Abstract

This article examines exogenous geological processes and their influence on relief formation and sediment accumulation in the Chechen Republic. The main types of exogenous processes are considered: weathering, slope processes, aeolian, fluvial, and karst processes. Attention is paid to the physical and chemical processes of weathering, as well as the formation characteristics of slope, aeolian, and fluvial landforms. Particular attention is paid to karst processes, the formation of specific landforms, and karst deposits. The geological and geomorphological characteristics of the Chechen Republic include a description of its physical, geographical, and climatic features, as well as a detailed analysis of the distribution and activity of landslides and mudflows in mountainous areas. The relief, hydrological, hydrogeological, lithological, petrographic, and climatic characteristics of the study area favor the development of exogenous geological processes. The diversity of geological, orohydrographic, and climatic conditions has led to the prevalence of various types of exogenous processes here.

Keywords: exogenous processes, weathering, slope processes, landslides, aeolian processes, fluvial processes, geomorphology, karst deposits.

I. Introduction

Exogenous geological processes play a key role in shaping the Earth's modern landscapes and relief. These processes include rock weathering, water, wind, and other factors that alter the shape and composition of the earth's surface. This study examines various types of exogenous processes, such as weathering, slope, aeolian, fluvial, and karst processes, and their influence on relief formation in the Chechen Republic. Particular attention is paid to landslides and mudflows, which have a significant impact on the region's landscape and infrastructure. It also examines the geological and geographical features of the Chechen Republic, including its physical location and climatic conditions, which determine the intensity and distribution of exogenous processes.

II. Methods

The studies utilized modern methods for determining the dynamics of landscape-landslide complexes, including both ancient stages of landslide formation and modern movements, as well as instability states (visual interpretation of optical images, multispectral image analysis, radar data, etc.). Vegetation and the stages of successional recovery after each landslide activation often serve as indicators of short-term states. Advances in the application of high-resolution Earth

remote sensing data and the frequency of monitoring make it possible to approach the identification of landslide dynamics as an integral part of landscape dynamics. Thus, the concepts of spatiotemporal image resolution [19] and multi-temporal imaging allow for a systematic approach to the selection of images for the analysis of landslide landscapes and their dynamics. Images were needed that physiognomically reflect the characteristic states of landscapes [17, 18]. For low-mountain forest landscapes, spring images are the most physiognomic, reflecting the lateral structure of natural complexes containing landslide bodies: cracks, breakaway walls, delayed or early onset of vegetation in moist areas, small erosional incisions, etc., with reference to natural complexes of a certain rank and type. Laser scanning (LiDAR) from a quadcopter offers significant potential, allowing for the identification of relief without the "noise" introduced by vegetation. The use of digital elevation models allows for a detailed analysis of the contribution of morphometry to slope stability or instability. Currently, more than 100 geomorphometric characteristics are calculated for various tasks based on the projected grid of a Digital Elevation Model.

III. Results

The North Caucasus is one of the most dangerous regions in terms of natural and man-made emergencies. Landslides are the most common type of slope process in the Chechen Republic, posing a threat to life in this part of the North Caucasus. Over the past century, the active development of the republic's territory, primarily as a result of the development of the oil industry, has increased the pressure on natural landscapes, compromising their stability. At the same time, the population, the length of roads and infrastructure lines, new buildings have been constructed, and land use patterns have changed (from extensive to intensive). Economic development has been accompanied by a constant threat of landslides. Recurring landslides within villages, destroying vital communications and roads, have necessitated scientifically based approaches to landslide monitoring and the justification of measures to protect vital infrastructure.

Based on landforms and genetic types of sediments, the following types of exogenous processes are distinguished: weathering, slope, aeolian, fluvial, and karst.

Weathering processes. This group includes the processes of rock alteration and destruction under the influence of external agents—the atmosphere, hydrosphere, and biosphere—with the formation of the crust and weathering products. Two types of weathering products are distinguished: eluvium and coluvium. The former are weathering products of rocks lying in place where they formed, while the latter are displaced downslope by gravity. Depending on the factors affecting the rocks and the results of these actions, weathering processes are divided into two types: physical and chemical weathering. Physical weathering results in the sequential fragmentation of rocks into smaller fragments without changing their chemical and mineral composition. It occurs more actively at high latitudes, in high mountains, and in hot deserts. Chemical weathering leads to changes in the chemical and mineral composition of rocks or to their complete dissolution. The most important factors here are water, as well as the oxygen, carbonic acid, and organic acids it contains.

Slope processes. These include rockfall-slide, desiccation-solifluction, landslide, complex polygenic processes, and others. Their formation is determined by a combination of lithological, geomorphological, and climatic conditions predetermined by the recent endogenous development of the relief. One important condition for the development of these processes is a significant slope steepness (more than 350). Slope processes are associated with weathering. For example, the formation of scree is associated primarily with physical weathering.

Landslide processes are the most common. Landslides involve the displacement of a monolithic rock block. Landslide processes are largely determined by geological and hydrogeological features. The main geological conditions for their occurrence are the underlying

permeable rocks beneath a horizon of impermeable rocks and the coincidence of the dip of the roof of the impermeable rocks with the direction of the surface slope. During landslides, rocks are partially crushed and transformed into a structureless mass. Accumulations of landslide masses at the foot of slopes are called delapsions [1, 2, 10]. Landslide processes form a specific complex of relief forms: landslide cirques, landslide blocks, landslide terraces, landslide embankments, etc.

Aeolian processes. These processes are associated with the geological action of wind. The end results are the accumulation of aeolian deposits of sand, silt, and, less commonly, clay composition, and the formation of certain landforms—dunes, barchans, aeolian ridges, cumulus sands, hummocky sands, etc. All aeolian forms are characterized by a gentle windward slope and a steep leeward slope.

Fluvial processes. These processes and the associated landforms are caused by the activity of sheet runoff (rainwater, melted snow, streams), permanent and temporary surface watercourses. During heavy rainfall and snowmelt, water flows in a continuous stream or a dense network of small streams downslope, picking up and transporting fine particles from higher ground. The geological material deposited at the bottom of the slope is called deluvial deposits.

Among the fluvial processes associated with permanent watercourses, erosion and corrosive processes are distinguished. Erosion refers to the process of channel deepening (deep erosion) or channel widening at the expense of banks (lateral erosion), while corrosive processes refer to the process of grinding and polishing rocks by moving masses of detrital material carried by water.

The predominant landforms associated with fluvial processes are erosive furrows and ruts, gullies, ravines, gullies, and river valleys, from which detrital material is transported to lower areas and accumulates there. Within these negative landforms, accumulative landforms are also present in smaller quantities as microrelief elements.

The debris deposited in river valleys by permanent streams (rivers) is called alluvium, consisting of sorted particles of varying sizes.

Temporary streams in the mountains form a mudflow after heavy rainfall and snowmelt. At the foot of the slope, the mudflow spreads, forming a debris flow fan. Such debris flows are called proluvium, which differ from alluvium in that they are less sorted and contain larger particles of debris.

Karst processes. Karst is a combination of processes involving the dissolution and leaching of rocks, followed by the erosion of accumulated material, resulting in unique landforms that arise in areas where rocks are relatively easily soluble in water. Karst is characterized primarily by negative landforms. Based on morphological characteristics, the following surface and underground forms are distinguished: carrs, wells, shafts, sinkholes, sinkholes, ponors, karst ravines, valleys, polyas, karst caves, underground karst channels, dry valleys, and karst bridges.

The main conditions for the development of karst are: a flat or gently sloping surface, a significant thickness of water-soluble rocks, the presence of aggressive groundwater and conditions that ensure their movement.

Karst deposits (formations) include stalactites, stalagmites, calcite curtains, draperies, and other dripstone formations in limestone caves.

Based on the lithological composition of soluble rocks, the following types of karst are distinguished: carbonate karst (limestone, dolomite, chalk, marble); Salt or halide karst (rock salt, sylvinite) and sulfate karst (gypsum, anhydrite).

Landslide processes. The greatest landslide activity in the republic was observed in 2016-2017. The peak number of activation events occurred in the spring and summer and was primarily due to heavy precipitation. The conditions, causes, activity, and danger of landslide events on the republic's roads are characterized. During the study period, approximately 70 such events (involving material damage) were recorded on roads running through the Vedensky, Itum-Kalinsky, and Shatoisky administrative districts of the republic. Information is provided on the

activity and scale of landslide deformations and roadbed destruction in these districts during the study period. The highest activity of landslides and slides was observed on the roads of the Shatoi district (more than 40 manifestations). It was noted that the volumes of landslides and slides on the roads of the republic generally varied within the range from 100 m3 to 17.5 thousand m3. Landslides and slides were most developed in the areas of mid-low mountain relief and high mountain relief of the Greater Caucasus Meganticlinorium. Activation of individual manifestations is expected in April-May in the Shatoi and Itum-Kalinsky districts of the republic. In the Shatoi district, activation of landslides and slides is possible along the following roads: v. Yarysh-Mardy - v. Zony, v. Zony - v. Shatoi. In the Itum-Kalinsky district, activation of landslides and slides is likely along the following roads: v. Veduchi - v. Itum-Kale. The main factor causing the activation is hydrometeorological.

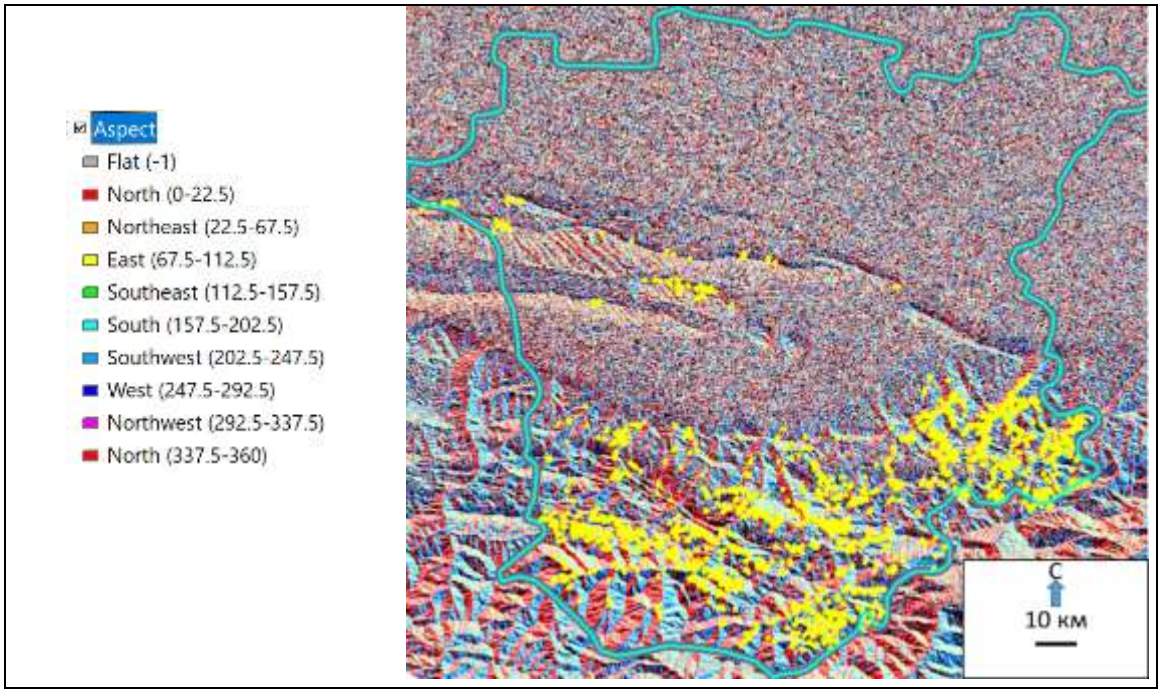
Landslides and mudflows. In general, low activity of dangerous EGP is predicted in the Chechen Republic. The landslide process is most widespread in the mid-low mountain relief of the Greater Caucasus Meganticlinorium, where the highest landslide activity is expected, namely in the Nozhai-Yurtovsky, Vedensky, Kurchaloevsky and Shatoysky districts of the republic. Activation of the landslide process is likely in April-May in the Shatoysky district within the highways of the village of KhalKiloy - the village of Nizhniy-Dai and the village of Yarysh-Mardy - the village of Zony. In May-June, with continuation of residual activity in July-August in the event of heavy rainfall, there is a high probability of activation of the landslide process: - in the Nozhai-Yurtovsky district within the highways: the village of Shovkhal-Berdy - the village of Alleroy; the village of Shuani - the village of Sayasan; Betti-Mokhk village – Sovragi village, Ayti-Mokhk village – Biltı village, Benoy village – Ayti-Mokhk village; - in the Vedensky district within the following highways: Tsa-Vedeno village – Pervomayskoye village, Pervomayskoye village – Agishbatoy village, Vedeno village – Dargo village, Marzoy-Mokhk village – Pervomayskoye village; - in the Kurchaloevsky district within the highways: Yalkhoy-Mokhk village – Enikali village; Koren-Benoy village – Biltı village; Dzhaglargi village – Regita village. The main factors of activation are hydrometeorological and man-made.

Mudflows and landslides are quite active in the mountainous part of the Chechen Republic. Here, as in some other regions, a synergistic effect of these processes is observed. Heavy rainfalls lead to rising river water levels and, consequently, to the erosion of banks composed of easily eroded rocks, which contributes to the sliding of coastal areas (mudflow material) and the formation of mudflows [3,4,12]. Landslides, most typical for low-mountain forest-steppe landscapes, occur near the village of Belgatoy. The landslide develops on Neogene deposits, represented by interbedded sandy argillites with multiple aquifers.

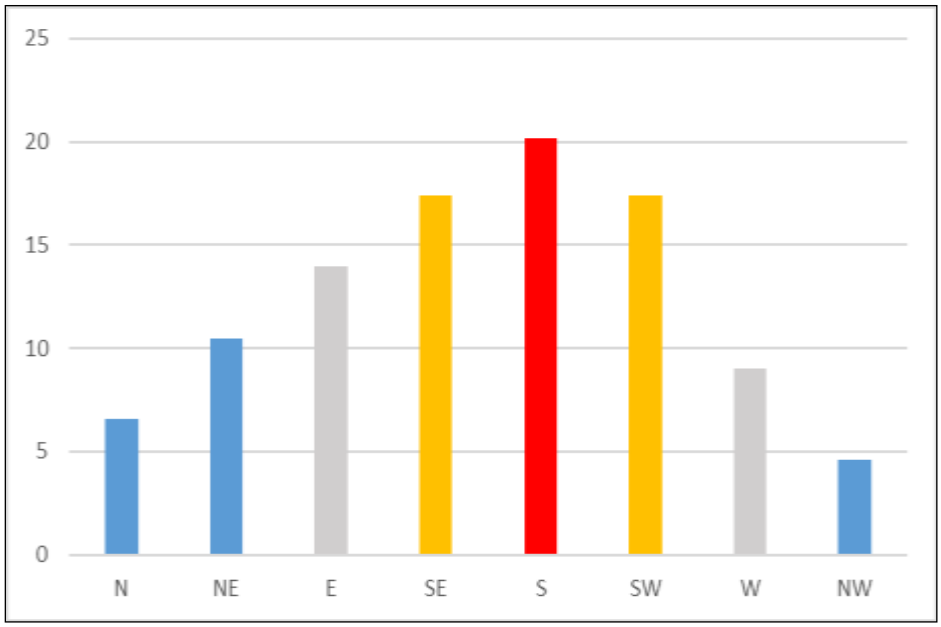
The Belgatoy landslide begins at an altitude of approximately 766 meters and ends on an alluvial fan superimposed on a river terrace, which steeply drops off to the Belgatoy River channel (water level is approximately 608 meters above sea level). The landslide extends for approximately 800 meters. Landslide processes are active in the upper part (above 700 m); in the transit zone, they are combined with erosion processes, while in the discharge zone, the accumulation of both landslide and erosion material predominates. In the southern, treeless areas of the lower part of the erosion-landslide cirque, talus is common [20].

The landslide develops on Neogene deposits consisting of interbedded sandy mudstones with multiple aquifers. These aquifers are exposed as the landslide deepens, forming a temporary watercourse in the thalweg portion of the erosion-landslide cirque, which, passing the alluvial fan at its base, incises to a depth of up to 5 meters.

Overall, the integration of the Belgatoy landscape-landslide complex into the landscape structure depends heavily on geomorphological features and moisture conditions. Long-term anthropogenic activity has significantly transformed both the topography and the moisture conditions of the soils and grounds. The construction of "heavy" housing and roads in the 1960s and the intensification of agriculture led to an increase in landslide phenomena, culminating in the catastrophic landslides of 1989 [5,6,11].



A.



B.

Figure 1. Distribution of the number of landslides in the Chechen Republic by exposure on the map (a) and on the graph below (b)(The y-axis shows the number of landslides as a percentage of the total. The x-axis shows slope exposure) (Compiled by the authors).

Landslide processes are most prevalent in the eastern and southeastern parts of the Black Mountains region, where landslides periodically intensify in the spring and fall due to increased precipitation and snowmelt. Given the rugged topography and significant amounts of precipitation, much of which filters into the mountain massif, clayey rocks become vulnerable to landslides, mudflows, and other processes. In the Black Mountains, landslides develop on the northern slopes of the mountains in a continuous band 15-25 km wide. Their activity increases significantly on the slopes of mountain river valleys, where mudflows can also occur.

Landslide activity is primarily determined by geological features. The region is characterized by widespread clayey rocks, predominantly of Sarmatian age, against a monoclinal structure complicated by a number of anticlines. In the area of the towns of Mekhdettankort, Amir-Kort, and the villages of Baitarki, Mazhgar, Tatay-otar, and elsewhere, Chokrak layers, consisting of sandstones with rare clay interlayers, surface. Lower and middle Sarmatian deposits, primarily clayey rocks, extend in a narrow band from the border of the Chechen Republic and the Republic of Dagestan in the east to the village of Sayasan and further west. These same deposits are also found near the villages of Benoy and Alkhan-otar. Their cross-sections can be observed along numerous small rivers and gullies – the B. Yaryksu, M. Yaryksu, Doku-ein, Yaman-Su, Erzumbere-ein, Sheren-ein, and others [7,9,13]. In places with significant channel slopes, the presence of loose material or clayey, easily eroded rocks, small alluvial mudflows are formed, caused by high-intensity rainfalls [8,14,15].

To the north of the described deposits, a thick layer of Upper Sarmatian rocks is exposed, composed in the lower part of dark gray clays with a thickness of over 300 m. The villages of Gilany, Zandak, Rogun-Kazha, Aiti-mokhk, and others are located in the zone of their outcrop. Thus, the dependence of the manifestation of landslide processes on the material composition (lithology) of geological horizons is clearly visible here. In the southern part, Chokrak sandstone beds and Upper Cretaceous carbonate rocks outcrop, while in the northern part, Quaternary Akchagyl-Apsheron layers, represented by sandy-siltstone rocks, are exposed. All of these rocks are classified as highly permeable. Landslide processes are either virtually absent or weakly manifested here.

Despite many years of experience in researching and predicting landslide processes, their periodic activation causes significant material damage and poses challenges to the future development of infrastructure in populated areas and the entire study area. Therefore, the development of scientifically sound methods for predicting these processes, as well as the improvement of existing and the development of new landslide control methods, remain highly pressing.

Eolian Processes. A wide variety of eolian landforms are common in the Chechen Republic. The most common sandy landform is ridged sands, which are relict landforms inherited from other physical and geographical conditions. In the northern and northeastern parts of the lowland, there are areas of open sand dunes, formed due to improper plowing and excessive grazing.

Aeolian processes affect the semi-desert and desert landscapes of the Trans-Terek Plain of the Chechen Republic. The total area of land subject to wind erosion is 1,603 km2 (36.9% of the total area of semi-desert and desert landscapes). Areas most susceptible to wind erosion occupy 301 km2 (6.9%), while moderately susceptible areas occupy 1,302 km2 (30.0%).

Karst processes. One of the main conditions for the development of karst processes, as noted above, is the presence of rocks readily soluble in groundwater. The nature of changes in the intensity of erosion processes plays a significant role in the formation of karst relief. It is well known that karst regions are characterized by weak erosional dissection. Here, erosion processes are reduced due to the rapid infiltration and influx of atmospheric precipitation into the subsurface of karst massifs. One interesting area with regard to karst is the interfluve of the Yaryk-Su and Benoy-Yassy rivers in the southeast of the Chechen Republic. This region is composed of Lower Cretaceous limestones and is heavily karstified. Most karst sinkholes are

located near the summits of the slopes of watersheds. Sinkholes here are typically small in size: diameters range from 3 to 15 meters, and depths from 1 to 4 meters. In karst areas, the conditions for the formation of soil and vegetation cover change. In some areas, karst development leads to the formation of new soil types, primarily due to changes in soil moisture levels. The drying influence of karst in the interfluve of the upper reaches of the Benoy-Yassy and Yaryk-Su rivers has led to the predominance of meadow-steppe soils here, which act as a kind of blot in the mountainous zone of brown earth-forest soil development [7,16].

Karst formation processes lead to significant changes in the soil cover and transformations, which can lead to the creation of inter-type differences. Karst also has a significant impact on vegetation. Certain environmental factors in karst areas often present a sharp contrast to zonal ones, leading to the emergence of plant communities uncharacteristic of the zone and an overall increase in the diversity of vegetation. As atmospheric precipitation passes through the forest cover, it feeds karst waters and becomes enriched with organic acids, resins, and essential oils.

IV. Conclusion

Thus, the topographic, hydrological-hydrogeological, lithological-petrographic, and climatic features of the study area favor the development of exogenous geological processes. It is the diversity of geological, orohydrographic, and climatic conditions that has led to the spread of various types of exogenous processes here. The presence of clayey carbonate and gypsum-bearing rocks soluble in groundwater, increased rock fracturing, highly dissected topography, and a dense hydrographic network in the mountainous region facilitate the widespread development of erosion processes (karst, landslides, mudflows, and karst) with the accumulation of eluvial and deluvial-proluvial deposits. Karst processes predominate in the mid-mountain part of the area, where limestone (limestone belt) and gypsum-anhydrite rocks are widespread. Landslides and talus processes are observed in the highlands. Landslide processes are common in areas with thick clay strata (the southeastern and other parts).

Fluvial processes (primarily lateral erosion of permanent streams) are more characteristic of the low-mountain and flat zones of the central part. Aeolian processes are typical in the northern semi-desert zone, where strong winds prevail.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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STUDY OF REVERSE OSMOSIS DESALINATION TECHNOLOGY FOR CASPIAN SEA WATER WITH PRELIMINARY NANOFILTRATION SOFTENING

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Abstract

The article presents the results of a study of the technology of reverse osmosis desalination of Caspian water with preliminary nanofiltration softening, carried out using the computer program "ROSA". At the NF stage, the possibilities of the most perfect membrane, NF90-400, were studied. To prevent carbonate scale formation, acidification with sulfuric acid was provided with a decrease in pH to 6,4÷6,6 and with control according to the Stif-Davis criterion. It has been established that when the permeate yield exceeds 55% of the initial water, precipitation of sulfate scale on the membranes is predicted, which, in accordance with the recommendations of the program, makes it necessary to increase the induction period for the crystallization of this salt by introducing antiscale. The possibility of reliable exclusion of the formation of calcium deposits on the membranes of the reverse osmosis stage is substantiated. It is shown that this purification system makes it possible to obtain additional water from the water of the Caspian Sea for heating networks and power boilers of thermal power plants with a pressure of up to 9,8 MPa inclusive. For boilers with a pressure of more than 13,4 MPa, additional cleaning is required in mixed-bed filters or electrodeionization modules.

Keywords: seawater, thermal power plants, desalination, reverse osmosis, nanofiltration, scale formation

1. Introduction

Desalination of saline water is an effective means of solving the problem of ever-increasing shortage of natural fresh water. Of the known desalination methods, the reverse osmosis (RO) method is currently the most widely used: up to 69.2 per cent of desalinated water. The shares of the other methods are: 17.1% - multistage instantaneous evaporation; 6.9% - multistage surface evaporation; 2% - electrodialysis; 1.9 - others [1]. This circumstance makes it urgent to further improve the RO method, including by developing more reliable ways to prevent scaling on membranes, compared to the currently practised methods. According to the publications of recent years, innovative ways of solving this problem include preliminary softening of saline water by nanofiltration (NF) method [2].

In [2] a review of the main works in the field of NF-RO technology integration is given. It follows from the review that most of the studies were carried out on the example of ocean water (35 g/dm^3). According to [3] this system allows desalination process at relatively low pressure (22 bar) compared to single-stage RO using SWRO brand membranes - (60 bar). As a result, the cost of desalinated water is reduced by 27%. High selectivity of nanofiltration membranes for divalent ions is noted: from 89.4% for Ca^{2+} to 97.8 - for SO_4^{2-}. The paper [4] presents data on reconstruction

of the operating RO unit by connecting NF. It is shown that in this case the ocean water hardness is reduced to 220 mg/dm^3, which eliminates the danger of calcium deposits formation on RO membranes, allows increasing the desalinated water yield at this stage from 28% to 56% and reducing the power consumption from 9.6 kW·h/m^3 to 5.9 kW·h/m^3. According to [5], on the example of desalination of brackish water of one of Iranian cities, comparative studies of three purification technologies were carried out: nanofiltration with NF270 membrane, reverse osmosis with BW30 membrane and their hybridisation. It was found that the hybrid system requires fewer membrane elements than RO purification. The specific energy consumption is also reduced. The authors of the study [6] have studied the possibilities of NF-RO hybrid system on the example of water with salt content 28.2÷28.7 g/dm^3. It was found that under the traditional scheme of RO with BW-30 membranes and operating pressure of 30 bar it is possible to reduce the salt content of permeate to 3.13 g/dm^3, and under the hybrid scheme this index is reduced to 0.76 g/dm^3. It was recommended to use this water for soil irrigation.

The analysis of the above and a number of other publications shows that the efficiency of the NF-RO system depends to a large extent on the quality of the source water. Studies in this area were mainly empirical in nature. Therefore, quantitative regularities obtained on individual water types cannot be extrapolated to waters of arbitrary composition, including Caspian Sea water. The authors are not aware of any studies on NF-RO treatment of Caspian water, one of the peculiarities of which is a high potential of calcium sulphate deposits formation on membranes. Meanwhile, this technology is of great interest for the Caspian republics in terms of obtaining desalinated water for technical purposes, including supplementary water for thermal power plants (TPS).

The aim of the present research is to evaluate the efficiency of reverse osmosis desalination technology of Caspian Sea water with preliminary nanofiltration softening for the preparation of supplementary water for TPS.

II. Technological scheme of hybrid NF-RO desalination system and research methodology

The technological scheme of the investigated NF-RO desalination system is presented in Fig.1.

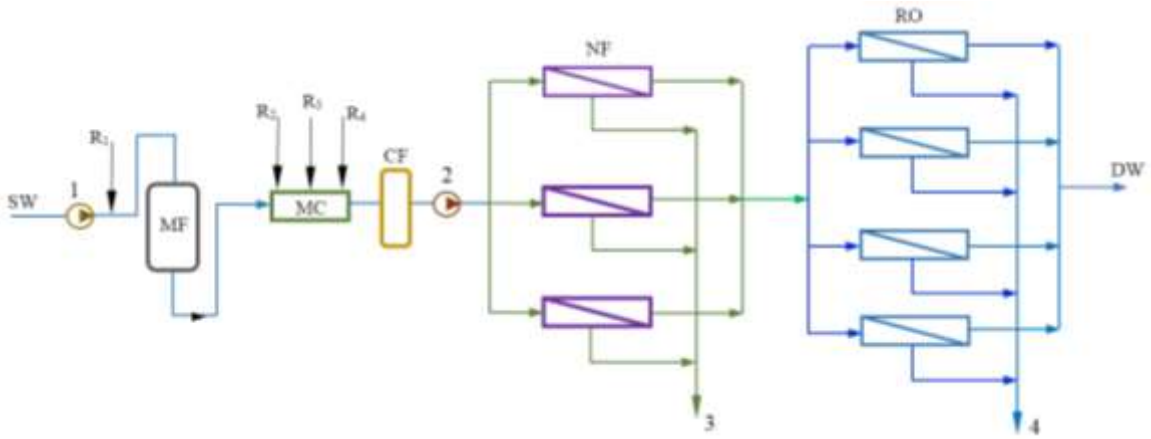


Figure 1: *Technological scheme of hybrid NF-RO seawater desalination system*
SW - sea water; MF - mechanical filter; MC - mixing chamber; CF - cartridge filter; DW - desalinated water; R$_1$-R$_4$- tanks for reagents; 1 and 2 - pumps; 3,4 – discharge concentrates.

According to this scheme seawater (SW) after preliminary treatment with sodium hypochlorite ($R_{1)}$ is fed by pump (1) to mechanical filter (MF) where it is cleaned from mechanical impurities. The clarified water enters the mixing chamber (SC), into which three reagents are fed: calcium sulphate solution (R_2), antiscale (R_3) and sodium bisulphide (R_4). The purpose of using each of these reagents is described in detail in the literature, in particular in [7]. The combined goal is to reduce the intensity of organic and calcium fouling on membranes.

After the mixing chamber, the water enters the cartridge filter (CF) with a mesh size of 5 μm for deep cleaning from mechanical impurities, then by a high-pressure pump (2) is fed to nanofiltration modules where it is divided into two streams: permeate passed through the membranes and residual concentrate (3). The latter is discharged or discharged to the wastewater tank of the power plant, and the permeate is fed to the RO modules, where it is also divided into two streams: permeate (desalinated water), used as a target product and concentrate (4). The latter can be discharged or, for reuse, fed to the high pressure pump intake (2).

The work was carried out on the example of Caspian water with qualitative indicators characteristic of the Apsheron coast of the Republic of Azerbaijan: pH=8.2 and ion concentration (mg/dm^3): $S_{Ca^{2+}}$=320.9; $S_{Mg^{2+}}$=729.9; S_{Na^+}=3174.9; S_{Na^+}=5034.3; $S_{SO_4^{2-}}$ =3264.0; $S_{HCO_3^-}$ = 244,0; TDS = 12768.

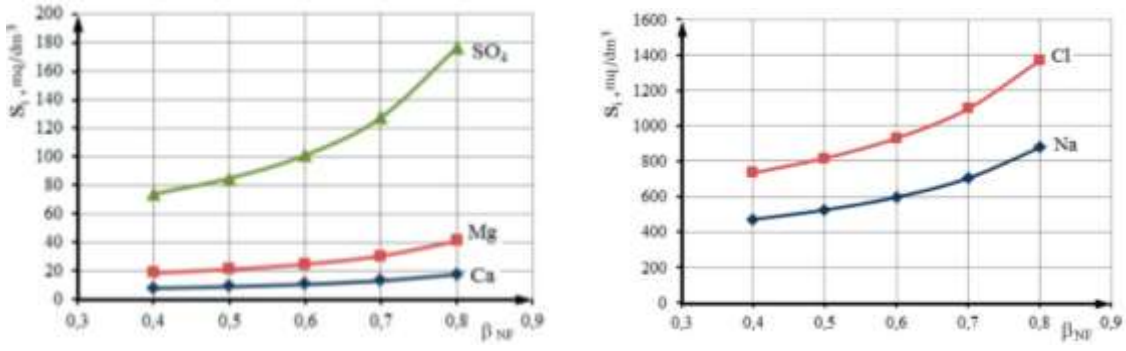
The calculation and analytical method of research with the use of the computer programme "ROSA" (Reverse Osmosis System Analysis) was used in the research. At the NF stage, the capabilities of the most perfect membrane, NF-90, included in the programme package were studied. To prevent carbonate scaling, acidification with sulphuric acid was envisaged with pH reduction to 5.4÷6.6 and control by Steef-Davis criterion. The values of permeate yield -β_{NF} (conversion, hydraulic efficiency), as well as temperature (10÷40^{0}C) were varied within 0.4÷0.8. In the RO stage, the capabilities of two types of membranes, BW30 and SWHR-380, were investigated. Temperature and permeate yield were also varied at this stage -$\beta_{RO.}$

III. Research results.

According to calculations at variation β_{NF} within 0.4÷0.8 there is a significant decrease in concentration of ions in NF permeate, and in the greatest degree - of scale-forming divalent ions. Thus, the concentration of calcium ions decreases to 8.1÷17.8 mg/dm^3, magnesium - to 18.8÷41.2 mg/dm^3, sulphates - to 74.1÷176.5 mg/dm^3 respectively with minimum and maximum values β_{NF}. The investigated membrane is characterised by lower values of selectivities on univalent ions Na^+ and Cl^- that causes relatively high residual concentrations of these ions in the NF permeate: on the average 630 and 920 mg/dm^3, respectively. The character of influence of β_{NF} on the residual concentrations of ions can be judged from the data of Fig. 2. These dependences are close to parabolic. Increase of ion concentrations with growth of β_{NF} is caused by corresponding decrease of concentrate fraction and increase of its salt content.

The result of the decrease in ion concentration is a significant decrease in the salt content of the permeate: from 1.3 to 2.5 g/dm^3, i.e., on average by 85%. Increase of NF leads in the specified range to approximately three times increase of osmotic pressure of concentrate, and working pressure from 12.5 to 21.1 bar.

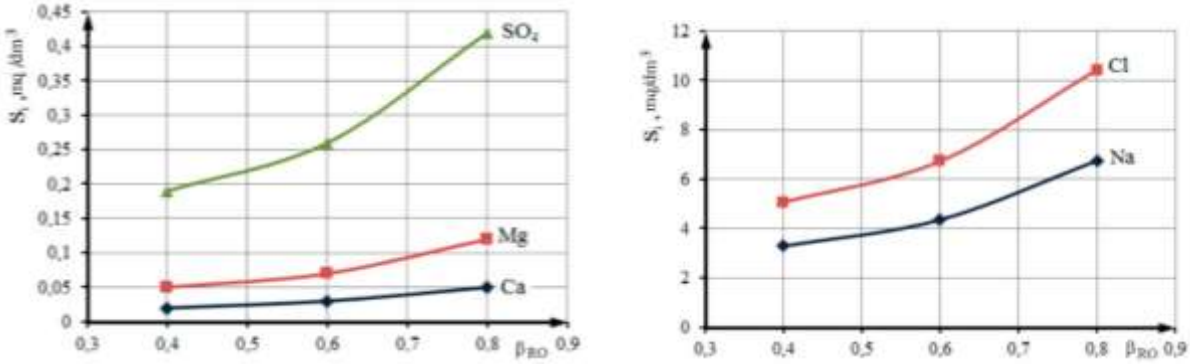
Such deep desalination of Caspian water on one stage of NF using NF-90 membranes creates real prerequisites for obtaining drinking water with salt content less than 1 g/dm^3 in two-stage plants. This issue is the subject of a separate study. As for power boilers of TPS, it is known that to ensure scale-free operation much deeper desalination of sea water is required, and in some cases - complete desalination. The latter is traditionally carried out in mixed action filters, and in modern technologies - in special electrodeionisation modules. To increase the efficiency of such finishing treatment, it is required to minimise the salt content in the source water, which can be achieved by reverse osmosis.



a) b)

Figure 2: *Effect of NF permeate yield on ion concentrations.*
a) for divalent ions; b) for monovalent ions.

At computer simulation of the RO stage, the conditions of feeding this stage with nanofiltration permeate with different values of β_{NF} were modelled. At the same time, the yield of permeate of the RO stage was varied - β_{RO}=0.4÷0.8. Fig.3 shows graphs of dependence of ion concentrations in permeate of OO stage at feeding with NF permeate corresponding to β_{NF} = 0.8.



a) b)

Figure 3: *Effect of the permeate yield of RO and on ion concentrations at β_{NF}=0.8.*
a) for divalent ions; b) for univalent ions.

As follows from the graphs, the character of dependences remains the same, the average concentrations of calcium, magnesium and sulphate ions are 30, 70 and 260 μg/dm³, respectively; sodium and chloride - 4.4 and 6.6 mg/dm³, and total salt content - 11.4 mg/dm³. At minimum acceptable conversion values equal to 0.4 the cation concentrations are 10, 20, 70 μg/dm³ and salt content is 3.9 mg/dm³ respectively.

The influence of permeate outputs on the salt content of the permeate and specific consumption of electrical energy can be judged from the data of Fig. 4.

As can be seen from the graph, the increase in outputs leads to an increase in the salt content of permeate RO from 3.9 to 8.2 mg/dm³, at β_{NF}=0.4 and from 8.8 to 18 mg/dm³, at β_{NF}=0.8. At the same time, increasing β_{RO} reduces energy consumption almost twofold: from 1.35 to 0.62 kW·h/m³ on average.

In the process of research it was found that at β_{NF}>0.55 precipitation of $CaSO_4$ is expected on NF membranes in connection with which the programme recommends the use of antiscaling. The possibility of precipitation of this salt on SO membranes is completely excluded at any values of β_{RO}: at the permissible degree of concentrate saturation <100%, the actual value of this indicator was less than 1%.

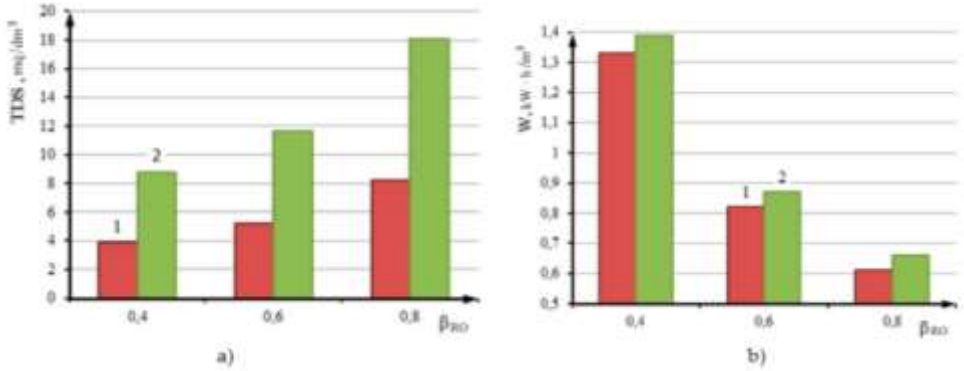


Figure 4: *Effect of RO permeate yield on its salt content (a) and specific energy consumption (b). (1-β_{NF}=0.4; 2-β_{NF}=0.8)*

It is known, that at TPS treated water can be used as make-up water of heating networks and boiler make-up water of various parameters. Each of these systems imposes certain requirements to the quality of treated water. Comparison of these requirements with the quality of water obtained from the Caspian under the investigated scheme shows that the NF stage permeate can be used for heating network make-up water, as it is characterised by a very low value of carbonate index. Assuming the condition that the quality of boiler make-up water should be not worse than the quality of feed water, the permeate of the RO stage satisfies the norms of feed water quality for boilers with pressure up to 9.8 MPa inclusive. For boilers with pressure of 13.8 and 23 MPa the required quality is not provided by hardness and specific electrical conductivity.

Using more selective membranes SWHR-380 reduces calcium concentration to almost zero values, magnesium - to 8÷10 μg/dm^3. In other words, the limitations on hardness of supplementary water for boilers with pressure of 13.8 MPa are removed. However, salt content of permeate remains rather high: 2÷3 mg/dm^3, against standardised 0.15 mg/dm^3 according to TPS technical operation rules. Changing the temperature of treated water within the range of 10÷ 40^{0}C leads to a 5-6-fold increase in ion concentrations in the NF permeate and a 30 % decrease in specific power consumption, which is obviously explained by an increase in the membrane pore size (Table 1).

Table 1: *Effect of temperature on nanofiltration performance (β_{NF}=0.6)*

Indicators	t=10^{0}C	t=20^{0}C	t=40^{0}C
Ca, mg/dm^3	3,1	5,92	17,87
Mg, mg/dm^3	7,2	13,74	41,39
Na, mg/dm^3	189,7	344,7	875,89
Cl, mg/dm^3	295,6	537,52	1367,9
SO_4, mg/dm^3	27,9	53,38	162,9
HCO_3, mg/dm^3	5,0	9,1	25,61
TDS, mg/dm^3	528,6	964,4	2491,5
W, kWh/m^3	1,16	1,04	0,82

The character of temperature influence on the RO process parameters is similar regardless of the type of membrane used (Table 2).

It is noteworthy that despite the possibility of deeper purification, the use of high-pressure SW membranes is associated with a twofold increase in specific energy consumption.

Table 2: *Effect of temperature on reverse osmosis performance (β_{RO}=0.6)*

Indicators	t=10^{0}C	t=20^{0}C	t=40^{0}C
Ca, mg/dm^3	0,01/0	0,02/0	0,05/0,01
Mg, mg/dm^3	0,02/0	0,04/0,01	0,12/0,02
Na, mg/dm^3	1,18/0,56	2,26/0,98	7,26/2,74
Cl, mg/dm^3	1,82/0,85	3,48/1,51	11,2/4,22
SO_4, mg/dm^3	0,06/0,01	0,12/0,01	0,39/0,04
HCO_3, mg/dm^3	0,13/0,12	0,15/0,12	0,27/0,15
TDS, mg/dm^3	3,23/1,54	6,06/2,64	19,2/7,19
W, kWh/m^3	1,52/3,96	1,01/2/57	0,53/1/33

Note: Numerator - BW; Denominator - SW.

However, even in this case the salt content of permeate considerably exceeds the permissible one for feeding boilers with pressure of 13.8 MPa and higher, i.e. there is still a need for additional additional desalting, for example, in mixed action filters, although there is a possibility to reduce the consumption of acid and alkali for regeneration of ionite mixture. In this connection the necessity of optimization studies is not excluded.

IV. Conclusions

1. Using the computer programme "ROSA" the conditions of preparation of additional water of TPS by reverse osmosis desalination of water of the Caspian Sea with preliminary nanofiltration softening excluding calcium deposits on membranes of the reverse osmosis stage are established. On the example of NF-90 membrane it is shown that by acidification of initial water the calcium carbonate deposits are excluded, and the most problematic calcium sulphate deposits can be formed on nanofiltration membranes at the value of permeate yield exceeding 55% of initial water. For operation modes with higher yields, in accordance with the programme recommendations, the use of antiscaling agents is suggested.

2. Along with scale-forming ions, the possibility of a sufficiently deep reduction in the salt content of Caspian water has been demonstrated: to 1.3÷2.5 g/dm^3, against the initial level of 12.8 g/dm^3. It has been shown that, according to such indicators as the hardness and salt content of feedwater for thermal power plant boilers, the NF-RO hybrid system allows obtaining water for boilers with a pressure of up to 9.8 MPa inclusive. For boilers with higher pressure, additional desalination in mixed-action filters is required.

3. The main directions of further, more in-depth research of the considered system of supplementary water treatment include study of possibilities of bypassing and recirculation between NF and RO stages, as well as issues of optimisation of the system as a whole and assessment of technical and economic efficiency of hybridisation.

4. We believe that the results of the above studies may be of interest to engineers and researchers engaged in research and design of water treatment plants of thermal power plants located on the Caspian coast.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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STATISTICAL ANALYSIS OF ATMOSPHERIC PRECIPITATION IN THE RACHA-LECHKHUMI AND KVEMO SVANETI REGION OF GEORGIA IN 1936-2023

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Abstract

Atmospheric precipitation is one of the most important components of the climate. Therefore, its study in Georgia, as in other countries, is of great importance, particularly in light of global climate change. Given that Georgia is a mountainous country with extremely heterogeneous terrain, the study of climate change in its individual regions is of particular scientific and practical interest. This study presents the results of research into the precipitation regime and its variability in the Racha-Lechkhumi and Kvemo Svaneti region, based on observational data from the Ambrolauri, Lentekhi and Shovi stations between 1936 and 2023. A detailed statistical analysis was carried out on the sum of monthly, annual and seasonal (cold and warm periods of the year) precipitation for individual stations, as well as for all stations combined. Linear correlations were established between the specified parameters for different months and seasons of the year. Regression equations were obtained for the intra-annual variation of the specified parameters' monthly values, which are of the form of a polynomial of the eighth degree. The variability of the precipitation regime from 1984 to 2023 was studied in comparison to the period from 1936 to 1974. It was found that the variability for individual points is ambiguous. In Ambrolauri, there is a tendency for precipitation to increase in the year and in the warm half-year. In Lentekhi, there is a tendency for precipitation to decrease in the year and in the cold half-year. In Shovi, annual and seasonal changes in the precipitation regime are of little significance. Trends in the annual and seasonal sums of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at the three stations between 1936 and 2023, were found to follow a third-degree polynomial trend. Data on the average rate of change over eight decades for the specified parameters is presented.

Keywords: climate change, atmospheric precipitation, statistical analysis, trend

I. Introduction

The problem of climate change is very relevant for many countries of the world, including Georgia, which has a significant diversity of climatic regions on its territory [1]. Considering that atmospheric precipitation is one of the most important components of the climate, special

attention has always been paid to its study in Georgia [1-3]. Over many decades, a large number of studies have been conducted on the climatology of annual, seasonal, monthly and daily precipitation amounts [1-5]; identifying the role of excess and deficit of precipitation in provoking landslides [6], mudflows [7], floods [8], droughts [9], as well as their impact on the agricultural sector [10], bioclimatic conditions of territories [11], etc. A number of studies have compared data from satellite and ground-based measurements of precipitation regimes [12,13]. Work has begun on long-term precipitation forecasting using modern models [14].

The accumulation of new information allows us to constantly update data on the variability of the precipitation regime in various regions of Georgia [1,4,8] against the background of climate change. Below are presented some results of the studies of the precipitation regime and its variability in the Racha-Lechkhumi and Kvemo Svaneti region based on observations at the Ambrolauri, Lentekhi and Shovi stations in the period from 1936 to 2023.

II. Study area, material and methods

Study area – Racha-Lechkhumi and Kvemo Svaneti region of Georgia, three meteorological stations (Fig. 1): Ambrolauri (42.52° N, 43.15° E, height H = 544 m a.s.l.), Lentekhi (42.78° N, 42.73° E, H = 760 m a.s.l.) and Shovi (42.70° N, 43.68° E, H = 1507 m a.s.l.). Data of the Georgian National Environment Agency about monthly sum of precipitation in the period from 1936 to 2023 are used. The analysis of data is carried out with the use of the standard statistical analysis methods of random events and methods of mathematical statistics for the non-accidental time series of observations [15-17]. The following designations will be used below: Mean – average values; Min – minimal values; Max - maximal values; St Dev - standard deviation; σ_m – standard error; R^2 - coefficient of determination; R – coefficient of linear correlation; C_v – coefficient of variation, %; K_{DW} – Durbin-Watson statistic; α - level of significance; P – sum of precipitation, mm (monthly; seasonally: October - March, April – September, January – December – P_{cold}, P_{warm}, P_{year}). Ambrolauri – Am, Lentekhi – Len, Shovi – Sh, Av – data, averaged over three stations. Distance between meteorological stations: Ambrolauri - Lentekhi: 45 km, Ambrolauri - Shovi: 48 km, Lentekhi - Shovi: 78 km. Missing observational data using standard methods were recovered [15]. Comparison of mean values of precipitation in two forty -year periods of time (1936-1975 and 1984-2023) was produced with the use of Student's criterion with the level of significance α not worse than 0.25. The degree of correlation was determined in accordance with [16]: very high correlation ($0.9 \le R \le 1.0$); high correlation ($0.7 \le R < 0.9$); moderate correlation ($0.5 \le R < 0.7$); low correlation ($0.3 \le R < 0.5$); negligible correlation ($0 \le R < 0.3$). The curve of trend is equation of the regression of the connection of the investigated parameter with the time at the significant value of the determination coefficient and such values of K_{DW}, where the residual values are accidental. The dimension of atmospheric precipitation (mm) and word "correlation" are often omitted from the text below.



Figure 1: *Location of meteorological stations Ambrolauri, Lentekhi and Shovi.*

III. Results

Results in Table 1-4 and Fig. 2-5 are presented.

In Tables 1,2 statistical characteristics of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations, from January to June and July to December in 1936-2023 are presented.

Table 1: *Statistical characteristics of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations, from January to June in 1936-2023.*

Month	Jan				Feb				Mar			
Location	Am	Len	Sh	Av	Am	Len	Sh	Av	Am	Len	Sh	Av
Mean	85	114	80	93	72	91	69	77	77	109	90	92
Min	0	10	0	9	0	0	0	7	0	5	0	9
Max	452	556	444	484	199	269	212	200	251	341	258	283
St Dev	62.5	86.7	62.5	65.6	43.3	56.9	41.3	42.1	46.8	63.9	53.1	46.9
σ_m	6.7	9.3	6.7	7.0	4.6	6.1	4.4	4.5	5.0	6.9	5.7	5.0
C_v,%	73.9	76.3	78.5	70.8	60.5	62.6	59.4	54.5	60.6	58.6	58.7	50.8
	Correlation Matrix				Correlation Matrix				Correlation Matrix			
Am	1	0.76	0.86	0.93	1	0.59	0.70	0.84	1	0.66	0.69	0.90
Len	0.76	1	0.78	0.93	0.59	1	0.79	0.91	0.66	1	0.48	0.86
Sh	0.86	0.78	1	0.93	0.70	0.79	1	0.92	0.69	0.48	1	0.82
Av	0.93	0.93	0.93	1	0.84	0.91	0.92	1	0.90	0.86	0.82	1
Month	Apr				May				Jun			
Location	Am	Len	Sh	Av	Am	Len	Sh	Av	Am	Len	Sh	Av
Mean	80	108	107	98	94	98	122	105	95	106	124	108
Min	10	18	10	15	20	19	25	37	23	21	0	36
Max	259	272	242	217	203	229	235	196	228	269	225	215
St Dev	39.4	56.0	47.7	41.8	41.0	41.7	43.4	35.9	41.5	55.8	41.2	36.4
σ_m	4.2	6.0	5.1	4.5	4.4	4.5	4.7	3.8	4.5	6.0	4.4	3.9
C_v,%	49.0	51.8	44.7	42.5	43.8	42.7	35.5	34.3	43.6	52.4	33.3	33.6
	Correlation Matrix				Correlation Matrix				Correlation Matrix			
Am	1	0.68	0.70	0.88	1	0.57	0.55	0.83	1	0.45	0.57	0.82
Len	0.68	1	0.59	0.88	0.57	1	0.65	0.87	0.45	1	0.30	0.79
Sh	0.70	0.59	1	0.86	0.55	0.65	1	0.87	0.57	0.30	1	0.75
Av	0.88	0.88	0.86	1	0.83	0.87	0.87	1	0.82	0.79	0.75	1

In particular, as follows from these tables, the range of changes in the mean, minimum and maximum monthly values of P for individual points and their amounts averaged over three stations is as follows.

Mean values - Am: 72 (Feb) - 112 (Oct), Len: 88 (Sep) - 119 (Dec), Sh: 69 (Feb) - 124 (Jun), Av: 77 (Feb) - 112 (Oct).

Min values - Am: 0 (Jan-Mar, Jul, Aug, Oct-Dec) - 23 (Jun), Len: 0 (Feb) - 21 (Jun), Sh: 0 (Jan-Mar, Jun, Nov, Dec) - 25 (May), Av: 6 (Oct) - 37 (May).

Max values - Am 198 (Aug) - 452 (Jan), Len: 229 (May) - 556 (Jan), Sh: 212 (Feb) - 444 (Jan), Av: 196 (May) - 484 (Jan).

The range of changes in the coefficient of variation is as follows.

Am: 43.6 % (Jun)- 73.9% (Jan), Len: 42.7% (May) - 76.3% (Jan), Sh: 33.3% (Jun) - 78.5% (Jan), Av: 33.6% (Jun)- 70.8% (Jan).

The range of change in the correlation coefficient between meteorological stations for the monthly sum of precipitation by month is as follows.

Jan: 0.76 (Pair: Am - Len, high) - 0.86 (Pair: Am - Sh, high), Feb: 0.59 (Pair: Am - Len, moderate) - 0.79 (Pair: Len - Sh, high), Mar: 0.48 (Pair: Len -Sh, low) - 0.69 (Pair: Am - Sh,

moderate), Apr: 0.59 (Pair: Len - Sh, moderate) - 0.70 (Pair: Am - Sh, high), May: 0.55 (Pair: Am-Sh, moderate) - 0.65 (Pair: Len - Sh, moderate), Jun: 0.30 (Pair: Len - Sh, low) - 0.57 (Pair: Am - Sh, moderate), Jul: 0.30 (Pair: Len - Sh, low) - 0.65 (Pair: Am -Sh, moderate), Aug: 0.60 (Pair: Len -Sh, moderate) - 0.71 (Pair: Am - Sh, high), Sep: 0.44 (Pair: Am - Len, low) - 0.61 (Pair: Am - Sh, moderate) , Oct: 0.70 (Pair: Len - Sh, high) - 0.85 (Pair: Am - Sh, high) , Nov: 0.63 (Pair: Len - Sh, moderate) - 0.75 (Pair: Am - Sh, high) , Dec: 0.73 (Pair: Len - Sh, high) - 0.83 (Pair: Am - Sh, high).

Table 2: *Statistical characteristics of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations, from July to December in 1936-2023.*

Month	Jul				Aug				Sep			
Location	Am	Len	Sh	Av	Am	Len	Sh	Av	Am	Len	Sh	Av
Mean	76	101	106	94	75	100	105	93	86	88	99	91
Min	0	13	23	19	0	1	21	20	11	2	12	8
Max	209	506	218	225	198	258	306	222	202	281	235	217
St Dev	41.9	69.0	45.8	40.7	43.8	66.6	55.5	48.3	39.1	50.1	43.5	36.3
σ_m	4.5	7.4	4.9	4.4	4.7	7.1	6.0	5.2	4.2	5.4	4.7	3.9
C_v,%	55.4	68.6	43.1	43.3	58.7	66.6	53.0	51.9	45.5	57.2	44.1	40.0
	Correlation Matrix				Correlation Matrix				Correlation Matrix			
Am	1	0.33	0.65	0.77	1	0.63	0.71	0.87	1	0.44	0.61	0.81
Len	0.33	1	0.30	0.79	0.63	1	0.60	0.88	0.44	1	0.48	0.81
Sh	0.65	0.30	1	0.77	0.71	0.60	1	0.87	0.61	0.48	1	0.84
Av	0.77	0.79	0.77	1	0.87	0.88	0.87	1	0.81	0.81	0.84	1
Month	Oct				Nov				Dec			
Location	Am	Len	Sh	Av	Am	Len	Sh	Av	Am	Len	Sh	Av
Mean	112	109	115	112	90	107	80	93	97	119	76	97
Min	0	1	7	6	0	17	0	15	0	9	0	10
Max	283	275	338	254	252	301	242	250	390	346	288	341
St Dev	60.7	66.3	64.1	58.5	57.1	69.6	51.8	53.2	64.8	75.8	51.2	59.4
σ_m	6.5	7.1	6.9	6.3	6.1	7.5	5.6	5.7	6.9	8.1	5.5	6.4
C_v,%	54.0	61.0	55.6	52.2	63.3	64.8	64.4	57.4	67.0	63.7	67.3	61.1
	Correlation Matrix				Correlation Matrix				Correlation Matrix			
Am	1	0.76	0.85	0.94	1	0.72	0.75	0.91	1	0.82	0.83	0.95
Len	0.76	1	0.70	0.89	0.72	1	0.63	0.90	0.82	1	0.73	0.93
Sh	0.85	0.70	1	0.92	0.75	0.63	1	0.87	0.83	0.73	1	0.90
Av	0.94	0.89	0.92	1	0.91	0.90	0.87	1	0.95	0.93	0.90	1

The range of change in the correlation coefficient between meteorological stations for the monthly sum of precipitation and their amounts averaged over three stations, by month is as follows.

Jan: 0.93 (Pair: Av - All Stations, very high), Feb: 0.84 (Pair: Av -Am, high) - 0.92 (Pair: Av - Sh, very high), Mar: 0.82 (Pair: Av -Sh, high) - 0.90 (Pair: Av - Am, very high), Apr: 0.86 (Pair: Av - Sh, high) - 0.88 (Pair: Av- Am, Len, high), May: 0.83 (Pair: Av - Am, high) - 0.87 (Pair: Av - Len, Sh, high), Jun: 0.75 (Pair: Av - Sh, high) - 0.82 (Pair: Av - Am, high), Jul: 0.77 (Pair: Av - Am, Sh, high) - 0.79 (Pair: Av - Len, high), Aug: 0.87 (Pair: Av - Am, Sh, high) - 0.88 (Pair: Av - Len, high), Sep: 0.81 (Pair: Av - Am, Len, high) - 0.84 (Pair: Av - Sh, high), Oct: 0.89 (Pair: Av - Len, high) - 0.94 (Pair: Av - Am, very high), Nov: 0 0.87 (Pair: Av - Sh, high) - 0.91 (Pair: Av - Am, very high), Dec: 0.90 (Pair: Av - Sh, very high) - 0.95 (Pair: Av - Am, very high).

In Table 3 statistical characteristics of annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations for 1936-2023 are presented.

In particular, as follows from table 3, the range of changes in the mean, minimum and maximum seasonal values of P between individual points is as follows.

Mean values. Year: 1038 (Am) - 1249 (Len), Cold Season: 511 (Sh) - 649 (Len), Warm Season: 506 (Am) - 662 (Sh).

Min values. Year: 550 (Len) - 700 (Sh), Cold Season: 73 (Am) - 242 (Len), Warm Season: 161 (Len) 354 (Sh).

Max values. Year: 1443 (Am) - 1989 (Len), Cold Season: 942 (Am) - 1243 (Len), Warm Season: 765 (Am) - 1034 (Len).

The range of changes in the coefficient of variation is as follows.

Year: 16.8% (Sh) - 24.0% (Len), Cold Season: 27.7% (Am) - 32.2 (Len), Warm Season: 16.9% (Sh) - 28.1% (Len).

Table 3: *Statistical characteristics of annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations for 1936-2023.*

Season	P_{year}				P_{cold}				P_{warm}			
Location	Am	Len	Sh	Av	Am	Len	Sh	Av	Am	Len	Sh	Av
Mean	1038	1249	1173	1154	533	649	511	564	506	601	662	589
Min	621	550	700	792	73	242	222	230	245	161	354	345
Max	1443	1989	1816	1732	942	1243	1026	1070	765	1034	1018	845
St Dev	185.5	300.1	197.4	195.8	147.8	208.7	141.6	148.0	102.7	168.8	111.8	106.3
σ_m	19.9	32.2	21.2	21.0	15.8	22.4	15.2	15.9	11.0	18.1	12.0	11.4
C_v,%	17.9	24.0	16.8	17.0	27.7	32.2	27.7	26.2	20.3	28.1	16.9	18.0
	Correlation Matrix				Correlation Matrix				Correlation Matrix			
Am	1	0.57	0.73	0.85	1	0.65	0.79	0.89	1	0.52	0.65	0.82
Len	0.57	1	0.55	0.87	0.65	1	0.65	0.90	0.52	1	0.46	0.86
Sh	0.73	0.55	1	0.85	0.79	0.65	1	0.89	0.65	0.46	1	0.80
Av	0.85	0.87	0.85	1	0.89	0.90	0.89	1	0.82	0.86	0.80	1

The range of change in the correlation coefficient between meteorological stations for the seasonal sum of precipitation and their amounts averaged over three stations, by seasons is as follows.

Year: 0.55 (Pair: Len - Sh, moderate) - 0.73 (Pair: Am - Sh, high), 0.85 (Av - Am, Sh, high) - 0.87 (Av - Len, high).

Cold Season: 0.65 (Pair: Am - Len, moderate) - 0.79 (Pair: Am - Sh, high), 0.89 (Av - Am, Sh, high) - 0.90 (Av - Len, very high).

Warm Season: 0.46 (Pair: Len - Sh, low) - 0.65 (Pair: Am - Sh, moderate). 0.80 (Av - Sh, high) - 0.86 (Av - Len, high).

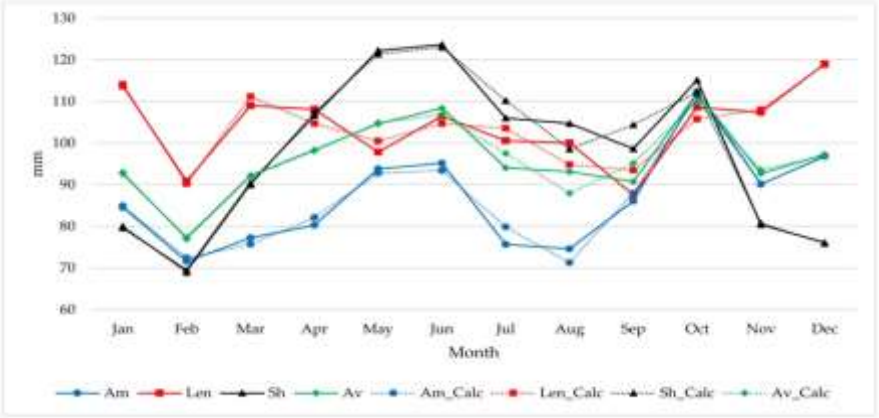


Figure 2: *Intra-annual variation of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations (measured and calculated data).*

In Fig. 2 intra-annual variation of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations (measured and calculated data) are presented. In Table 4 coefficients of the regression equation (polynomials of the eighth degree) for the intra-annual variation of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations, based on data from 1936 to 2023.

Table 4: *Coefficients of the regression equation for the intra-annual variation of monthly sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their amounts averaged over three stations, based on data from 1936 to 2023.*

Regression	$Y = a \cdot x^8+b \cdot x^7+c \cdot x^6+d \cdot x^5+e \cdot x^4+f \cdot x^3+g \cdot x^2+h \cdot x+i$, x – number of month, 1…12			
Location	Am	Len	Sh	Av
R^2	0.971	0.889	0.974	0.933
a	0.001072	0.00115	0.000957	0.001044
b	-0.05193	-0.06126	-0.04705	-0.05261
c	1.035133	1.361883	0.957919	1.101379
d	-11.0067	-16.3896	-10.5033	-12.4425
e	67.83332	115.7414	67.67775	82.51051
f	-247.312	-485.499	-262.678	-327.163
g	521.9025	1162.667	599.6971	751.7874
h	-582.249	-1419.7	-715.591	-896.207
i	334.7955	755.9773	400.5	493.4773

As follows from Fig. 2, all cases of intra-annual distribution of P have a multimodal form. The extreme and minimum values of P are as follows.

Am: Extremes: Jan (85), May (94), Jun (95), Oct (112), Dec (97); Min: Feb (72), Jul (76), Aug (75). Len: Extremes: Jan (114), Dec (119); Min: Feb (91), May (98), Sep (88). Sh: Extremes: May (122), Jun (124), Oct (115); Min: Feb (69), Dec (76). Av: Extremes: Jun (108), Oct (112); Min: Feb (77), Sep (91), Nov (93).

The correlation coefficient between meteorological stations for intra-annual distribution of P is as follows. R = 0.39 (Pair: Am – Len, low); R = 0.35 (Pair: Am – Sh, low); R = 0.80 (Pair: Am – Av, high); R = -0.14 (Pair: Len – Sh, negligible); R = 0.40 (Pair: Len – Av, low); R = 0.78 (Pair: Sh – Av, high). The intra-annual distribution of P for all cases, with a high degree of reliability, it is approximated by a polynomial of the eighth degree ($R^2 \geq 0.889$; Fig. 2, Table 4).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Cold	Warm
Am	12	-5	10	10.8	11.6	0	9	1	3	-1	12	-6	58.1	22	36.3
Len	-33.7	-19.1	-20.0	27.2	13.4	24.5	-4	-2	-24.5	-11	-4	-13	-66	-100.1	34
Sh	2	-10	7	14.9	0	12.1	8	-24.3	-6	-6	10	-1	7	3	4
Av	-6	-11.3	-1	17.6	8	12.3	4	-9	-9	-6	6	-6	0	-25	25

Figure 3: *Difference between monthly, annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi in 1984-2023 and 1936-1975 (ntegers without a comma refer to the difference with a level of significance α>0.25).*

In Fig. 3 data on difference between monthly, annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi in 1984-2023 and 1936-1975. The significant changes over two forty-year time periods for average monthly, annual, and seasonal values of P for individual stations and on average per station are as follows.

Am: increase in Apr (10.8), May (11.6), for the year as a whole (58.1), and in the warm season (36.3). Len: increase in Apr (27.2), May (13.4), and Jun (24.5); decrease in Jan (-33.7), Feb (-19.1), Mar (-20.0), Sep (-24.5), and in the cold season (-100.1). Sh: increase in Apr (14.9) and Jun (12.1); decrease in Aug (-24.3). Av: increase in Apr (17.6) and Jun (12.3); decrease in Feb (-11.3).

Fig. 4-6, as examples, show the trends of mean annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three stations in 1936-2023.

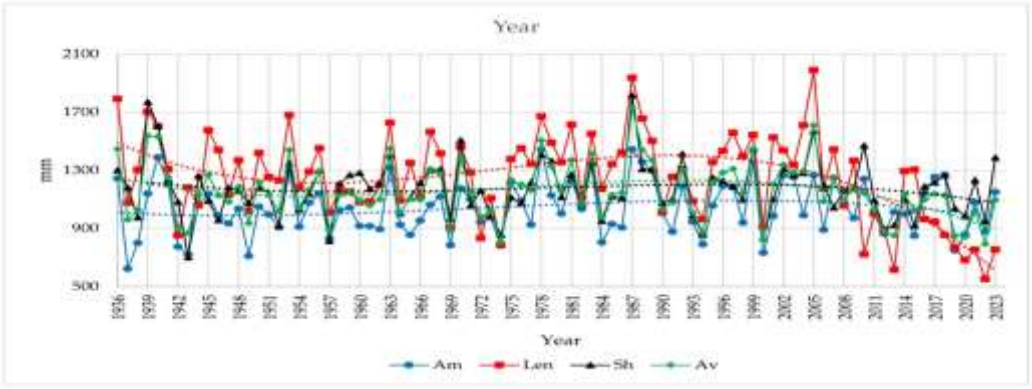


Figure 4: *Trends of mean annual sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three stations in 1936-2023.*

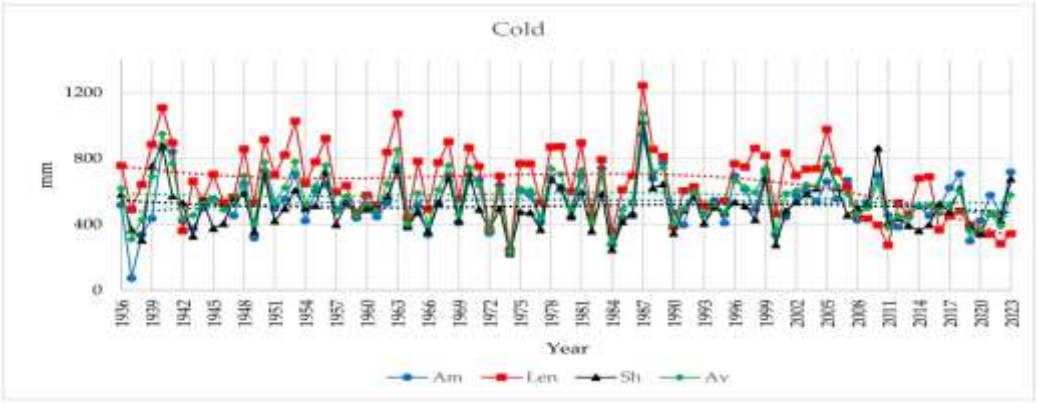


Figure 5: *Trends of mean sum of precipitation in cold season in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three stations in 1936-2023.*

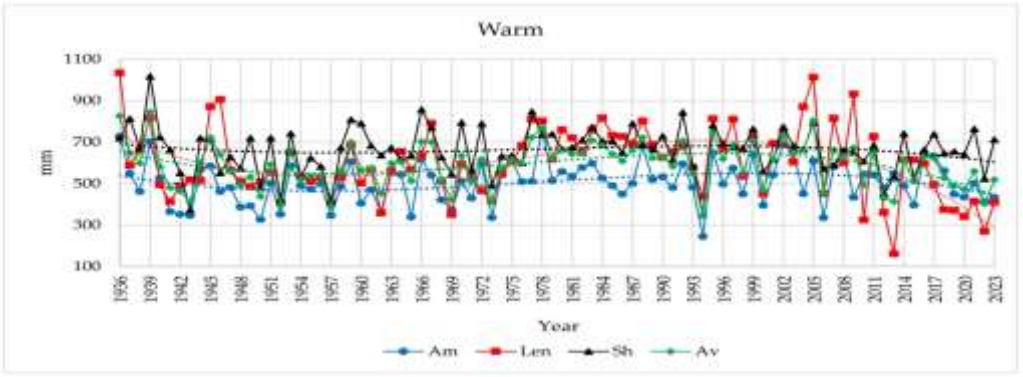


Figure 6: *Trends of mean sum of precipitation in warm season in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three stations in 1936-2023.*

In Table 4 the coefficients of the regression equation for the trend of annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three

stations in 1936 - 2023, are presented.

Table 4: *The coefficients of the regression equation for the trend of annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three stations in 1936 - 2023.*
x – number of year, 1…88; $\alpha(R^2) \leq 0.22$, $\alpha(K_{DW}) = 0.05$.

Parameter	R^2	K_{DW}	a	b	c	d
Regression	$Y = a \cdot x^3 + b \cdot x^2 + c \cdot x + d$					
Point/Season	Year					
Am	0.0434	2.15	-0.00173	0.1934	-4.023	1011.61
Len	0.337	1.89	-0.00916	1.0620	-32.816	1518.62
Sh	0.0221	2.00	-0.00210	0.2682	-9.270	1247.85
Av	0.141	1.98	-0.00433	0.5079	-15.370	1259.31
Point/Season	Cold					
Am	0.017	2.19	0.0004	-0.0799	4.666	465.53
Len	0.211	1.89	-0.0030	0.3121	-9.227	763.13
Sh	0.018	2.00	-0.0009	0.1191	-4.366	550.45
Av	0.056	2.06	-0.00117	0.1168	-2.967	592.96
Point/Season	Warm					
Am	0.092	2.19	-0.00213	0.2735	-8.685	546.01
Len	0.294	1.93	-0.00615	0.7486	-23.545	755.29
Sh	0.023	2.14	-0.00119	0.1487	-4.887	697.29
Av	0.178	2.05	-0.00316	0.3901	-12.368	666.17

Finally, in Table 5 data on ten-year average change rate (tenfold value of first derivative of the trend regression equation) for the specified parameters are presented.

Table 5: *Ten-year average change rate of annual and seasonal sum of precipitation in Ambrolauri, Lentekhi and Shovi, as well as their averaged amounts at three stations (mm/10 year).*

Season	Point	1936-1945	1946-1955	1956-1965	1966-1975	1984-1993	1994-2003	2004-2013	2014-2023	Mean
Year	Am	-2.1	0.7	2.4	3.1	1.7	-0.5	-3.7	-8.0	-0.8
	Len	-22.2	-6.7	3.2	7.7	1.9	-9.0	-25.5	-47.4	-12.2
	Sh	-6.6	-2.5	0.3	1.8	1.3	-0.7	-4.0	-8.5	-2.4
	Av	-10.3	-2.9	2.0	4.2	1.7	-3.4	-11.1	-21.3	-5.1
Cold	Am	3.8	2.5	1.4	0.5	-0.5	-0.7	-0.6	-0.3	0.8
	Len	-6.1	-1.8	0.8	1.5	-1.7	-6.0	-12.1	-20.0	-5.7
	Sh	-3.2	-1.3	-0.1	0.6	0.6	-0.2	-1.5	-3.4	-1.1
	Av	-1.8	-0.2	0.7	0.9	-0.5	-2.3	-4.7	-7.9	-2.0
Warm	Am	-5.9	-1.8	1.0	2.6	2.2	0.2	-3.1	-7.7	-1.6
	Len	-16.0	-4.9	2.5	6.2	3.6	-3.1	-13.4	-27.4	-6.6
	Sh	-3.4	-1.2	0.3	1.1	0.7	-0.5	-2.4	-5.1	-1.3
	Av	-8.4	-2.6	1.3	3.3	2.2	-1.1	-6.3	-13.4	-3.1

In particular, the analysis of Fig. 4-6 and Table 5 shows the following. In 1936-1945 in general, there are tendencies of decreasing annual and seasonal amounts of precipitation (with the exception of Ambrolauri in the cold half-year). A similar situation is observed for the periods 1946-1955 (except Ambrolauri, according to annual data and in the cold season) and 1994-2003 (except Ambrolauri, warm season).

From 1956 to 1993, a general tendency towards increasing precipitation was observed: 1956-1965 - except Shovi in the cold season, 1966-1975 - all points, 1984-1993 - except Ambrolauri and Lentekhi in the cold season.

From 2004 to 2023, a tendency towards decreasing annual and seasonal sum of precipitation were observed for all points. Moreover, the greatest tendencies towards a decrease in precipitation amounts are observed in Lentekhi.

IV. Conclusion

A detailed statistical analysis of time series of observations of monthly, annual and seasonal (cold and warm periods of the year) precipitation amounts for the Ambrolauri, Lentekhi and Shovi stations (Racha-Lechkhumi and Kvemo Svaneti region of Georgia) for the period from 1936 to 2023 was carried out.

It was found that the values of the linear correlation coefficient between the three points and average for these points monthly, annual and seasonal sum of precipitation are significant. At the same time, for monthly data, the values of the correlation coefficient are in the range of 0.30 – 0.95 (9.7 % of cases - low correlation, 19.4 % - moderate correlation, 52.8 - high correlation, 18.1 % -very high correlation; total 72 pairs of correlation coefficients). For annual and seasonal data, the correlation coefficient values are in the range of 0.46 – 0.90 (5.6 % of cases - low correlation, 33.3 % - moderate correlation, 55.6 % - high correlation, 5.6 % -very high correlation; total 18 pairs of correlation coefficients).

Intra-annual distributions of precipitation amounts have a multimodal form and are well approximated by an eighth-degree polynomial.

The variability of the precipitation regime in the specified time period was studied by comparing monthly, annual and seasonal data for 1984-2023 and 1936-1974, as well as analyzing the trends in annual and seasonal precipitation amounts. It was found that the specified variability for individual points is ambiguous.

In particular, the analysis of trends in annual and seasonal precipitation showed that in certain decades there were both decreasing and increasing tendencies in precipitation for different points. However, from 2004 to 2023, a tendency towards decreasing annual and seasonal sum of precipitation were observed for all points. Moreover, the greatest tendencies towards a decrease in precipitation amounts are observed in Lentekhi.

Acknowledgments

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE FORMATION OF THE HYDROGEOLOGY OF THE ABSHERON PENINSULA

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Abstract

The process of formation of hydrogeological conditions on the Absheron Peninsula is extremely complex. Geomorphological, tectonic, geological-lithological conditions, the activity of the Caspian Sea, climatic indicators, individually participate to a certain extent in the process of formation of groundwater. The distribution of geological stratigraphic units on the Absheron Peninsula, the heterogeneity of their lithological compositions in the area, and the geomorphological-tectonic structures of the territories confirm what is said. The general regularities for the studied areas include the uneven distribution of surface water, the almost absence of rivers, the scarcity of atmospheric precipitation and the fact that evaporation exceeds atmospheric precipitation by several times. Clayey facies predominate in stratigraphic units of different ages on the Absheron Peninsula. The fact that the collector layers participating in the intersection are in the form of layers, the presence of clay in the composition of the water-retaining rocks, the fact that the layers separating them consist of completely solid, thick-layered clays, the presence of salts of various compositions in the clay rocks, etc. have created conditions for the formation of fresh and weakly saline water horizons in these areas. The complexity of the tectonic conditions in the areas where the research was conducted also confirms what has been said. Thus, the replacement of anticlines and synclines consisting of rocks of different ages in the area, the presence of numerous tectonic faults and disturbances have led to the formation of completely unrelated water complexes. For many years, in some areas of the Absheron Peninsula, groundwater levels have approached the surface of the earth, their distribution areas have increased, and the process of decreasing the degree of mineralization in groundwater has been observed. In some areas, the opposite has been observed. All this has had a certain impact on the formation and change of hydrodynamic and hydrochemical conditions of the areas.

Keywords: groundwater, pressurized water, hydrodynamic indicators, degree of mineralization, hydrogeological exploration

I. Introduction

The geological structure of the Absheron Peninsula includes modern sediments from the Quaternary period to the Cretaceous sediments. The tectonic and geomorphological conditions of the area are very complex.

The Absheron Peninsula is divided into two parts according to its geological and lithological, tectonic and geomorphological, hydrogeological characteristics: Western Absheron and Eastern Absheron. The stratigraphic boundaries between Western Absheron and Eastern Absheron pass through the Productive layer, Agjagil and Lower Absheron layers. This boundary extends in the southeast direction through the villages of Goradil, Fatmai, Mammadli. Zabrat, Surakhani, and then in the south to Govsan [1-3,19,20].

The hydrodynamic conditions of the groundwater of the Absheron Peninsula are formed in very complex geological and geomorphological, tectonic and anthropogenic conditions.

Both soil and pressurized aquifers are widespread on the Absheron Peninsula. The water-retaining rocks in the aquifers consist of limestones, sandstones, sands, and gravels. Aquifers cover all stratigraphic ages from the Quaternary to the Productive layer [1,10-12].

According to tectonic zoning, the Western Absheron hydrogeological region covers the Western Absheron highland, the Haji Zeynalabdin Tagiyev Binagadi subsidence area, the Chuvaldagh and Guzdak plateaus. Here, a limited closed Baku depression and the eponymous groundwater basin are separated. Sediments of the Santon layer of the Cretaceous system to the Yunusdagh stratum are distributed in Western Absheron. The hydrogeological conditions of Western Absheron correspond to the hydrogeological conditions of Gobustan. Unlike Gobustan, artificial factors also participate in the formation of groundwater in Western Absheron. This process became even more active after the construction of the Jeyranbatan reservoir in 1956 [4,5,16-18].

When studying the hydrogeological conditions of the study object, the landscape indication method was used, whereby the recipient components of the landscape were studied through their physiognomic components. At points with easily traceable technogenic influences, appropriate study sites were selected, and the chemical composition and level of groundwater were studied using dug wells (Fig.1) [6-9].

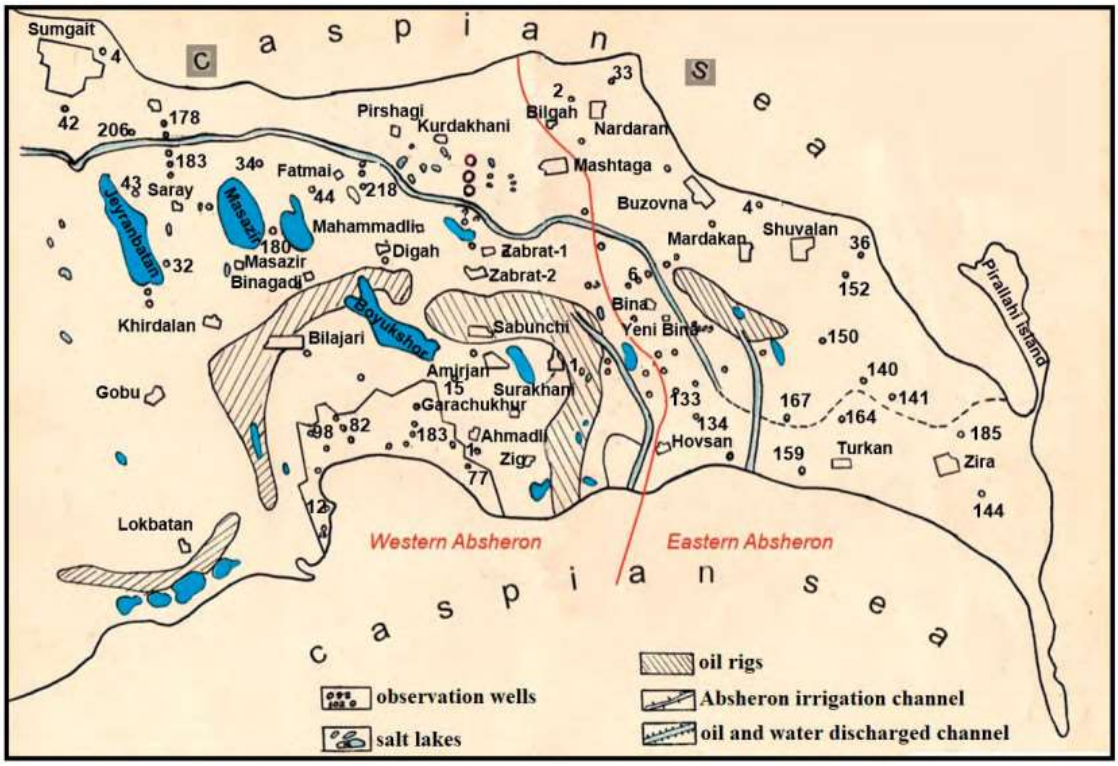


Figure 1: *Exploration wells drilled in the Absheron Peninsula*

In general, hydrogeological and exploration wells have been drilled for various purposes in the Absheron Peninsula over the past 30-40 years. The characteristics of the hydrodynamic conditions of the peninsula were compiled based on data from wells drilled over many years [13-15,21].

According to the tectonic zoning scheme, East Absheron covers the territories of the Kurdakhani-Mashtaga uplift, Bina-Govsan, Dubandi-Zira depressions. The geological and geomorphological conditions of East Absheron create favorable conditions for the formation of groundwater here. Sediments of the Modern Period - Absheron stratum are widespread in this area. Since the productive layer sediments lie under layers of great thickness, they are not

important from a hydrogeological point of view. In addition to natural factors, artificial factors also play a major role in the formation of groundwater in the East Absheron territory.

Groundwater in the East Absheron territory covers all the places we have mentioned. In order to analyze the hydrodynamic conditions of groundwater, a map of hydroisohypses, depth, mineralization and chemical composition was compiled for the territory of the Absheron Peninsula based on multi-year data.

The western borders of the area of undifferentiated stratigraphic classification of groundwater in the Absheron Peninsula extend from the Haji Zeynalabdin Tagiyev settlement to the Gumyamag Lake in the southeast direction. 3 km south of this, the border connects with the western shore of Jeyranbatan Lake. The border extends in this direction and reaches the city of Khirdalan. From here, the borders are slightly drawn to the east and extend to the sea in the direction of Lokbatan. To the west of these borders, groundwater is distributed sporadically.

The flow of groundwater is from west to southeast and east. In the north-west of Absheron, the direction of underground flow is north, towards the sea. Hydroisohypses are located here in a radial form, breaking between absolute heights of +30 m (-30 m). The absolute height of the groundwater surface detected by wells varies between 38.9 m and -27.5 m. The slope of the groundwater flow is 0.01 between the Jeyranbatan reservoir and Sumgayit city, 0.02 in the Novkhani gardens area, and 0.04 in the Goradil gardens district. In the Khirdalan district, the underground flow is towards the Jeyranbatan reservoir. Here, the absolute height of the level varies between 74.3 m and 31.4 m. In the Masazir and Mirzaledi lakes districts, the underground flow is towards the lake along the perimeter of the lakes. In the peripheral areas, groundwater has a sporadic distribution. In the Boyuk Shor lake district, the absolute height varies between -62.7 m and 43.2 m. From here, the hydroisohypses are located at +30 m in both directions. Between the city of Khirdalan and the settlement of Bilajari, the hydroisohypses are divided into two directions. The highest level of hydroisohypses to the north is +40m. The direction is towards Boyukshor Lake. In the south, the slope is towards Khojahasan Lake. Here, the direction of groundwater flow is from the Yasamal valley towards Gırmızı Lake, and from there towards the coastal settlement. The absolute height of groundwater in these areas varies from -25.1 m to 9.9 m.

In the Baku depression, groundwater is distributed in the sediments of all stratigraphic layers. Here, groundwater flow has a uniform radial flow form in the seaward direction.

The presence of Balakhani-Sabunchu-Ramani, Surakhani and Garachukhur-Zikh anticlines in the eastern part of the city creates conditions for changing the shape of groundwater flow. The flow of groundwater spreads radially from these structures in all directions. The slope of the hydrorelief in the city is variable. In the west and east, the slope varies between 0.01-0.1, in the north 0.06-0.01, and in the coastal strip in the south 0.014-0.1. On the Keshla plateau, the slope of groundwater flow varies between 0.003-0.08 [22,23].

Groundwater formed in the territory of Baku is used in the central parts of the city and along the sea coast.

Groundwater emerges to the surface in various areas of the city. The flow of groundwater formed in the territory of Baku city falls into a single general flow in accordance with geological and structural conditions.

The general flow of the groundwater basin on the Absheron peninsula is in the direction from Western Absheron to Eastern Absheron. The flow of groundwater along the entire perimeter of Eastern Absheron flows into the sea. In the central parts of the peninsula, the slope of the groundwater flow is 0.01, and along the sea coast - 0.0025. In the direction of the Bina settlement, the slope of the groundwater flow is 0.0001. The hydroisohyps of groundwater in Eastern Absheron is radially with a slight slope towards the sea.

II. Methods

In order to study the hydrodynamic properties of groundwater in the Western Absheron area, wells 60-73, 34-49 were drilled in accordance with the Middle and Upper Absheron and Productive layer sediments. Groundwater was detected in some of these wells, while in others it was not detected (Table 1).

Table 1: *Data from wells drilled into groundwater of the Middle and Upper Absheron sediments on the Absheron Peninsula*

№	Well №	Static level, m	Dynamic level, m	Level drop, m	Consumption, l/s	Special consumption, l/s·m	The permeability of water-retaining rocks, K_ϕ m/gün	Sukeçiricilik əmsalı, K_m, m²/day	Level and pressure transmission coefficient (a), m²/day	Irrigation coefficient, μ
1	60	1,2	36,7	35,5	0,4	0,011	0,07	1,33	$0,6 \cdot 10^2$	0,02
2	65	5,5	32,4	26,9	0,07	0,003	0,04	0,32	$0,16 \cdot 10^2$	0,019
3	68	6,8	32,4	25,6	0,3	0,01	0,11	1,32	$0,2 \cdot 10^3$	0,02
4	69	7,3	38,2	30,9	0,19	0,006	0,3	8,4	$0,4 \cdot 10^3$	0,025
5	70	18,2	40,3	22,1	0,015	0,0006	0,04	0,08	$0,05 \cdot 10^2$	0,02
6	71	17,2	37,2	20,0	0,02	0,001	0,03	0,12	$0,21 \cdot 10^2$	0,017
7	72	6,5	31,48	24,98	0,8	0,032	2,3	34,5	$0,8 \cdot 10^3$	0,05
8	73	7,5	31,65	24,15	1,2	0,05	0,7	9,8	$0,5 \cdot 10^3$	0,02

As can be seen from the table, although the data of the wells located in different areas of Absheron Peninsula are different, their hydrodynamic properties are characterized by very small dimensions.

The depth of the groundwater level is 1.2-17.2 m. The well flow rate during pumping is 0.015-1.2 l/s, the specific flow rate is 0.0006-0.05 l/s.m. The filtration coefficient of the water-bearing rocks is 0.03-2.3 m/day, the water permeability coefficient is 0.08-34.5 m²/day, the level permeability coefficient is 0.05.102-0.8.103 m²/day, the water permeability coefficient of the water-bearing rocks varies between 0.017-0.05. No groundwater was detected in other wells drilled into the sediments of this layer in Western Absheron.

Wells 34, 35, 36, 37, 38, and 39 were drilled to study the hydrodynamic properties of groundwater in the sediments of the productive layer in Western Absheron. Of these, groundwater was discovered in wells 34, 36, and 39 (Table 2).

Table 2: *Data from wells drilled into Balakhani (Productive layer) sediments*

№	Well №	Static level, m	Dynamic level, m	Level drop, m	Consumption, l/s	Special consumption, l/s·m	The permeability of water-retaining rocks, K_ϕ	Sukeçiricilik əmsalı, K_m, m²/day	Level and pressure transmission coefficient (a), m²/day	Irrigation coefficient, μ
1	34	7,5	32,0	24,5	0,7	0,03	0,5	3,0	$2 \cdot 10^2$	0,02
2	36	10,0	38,5	28,5	0,09	0,003	0,07	0,35	$0,2 \cdot 10^2$	0,017
3	39	8	38,0	30,0	1,2	0,04	0,62	4,34	$0,2 \cdot 10^3$	0,05

The hydrodynamic parameters of the pressurized waters of Western Absheron were studied using well No. 11. The well is located 1.5 km west of the Hokmali settlement. The piezometric level is 12.5 m. The consumption of the well during the drawing time is 0.8 l/s, the specific consumption is 0.028 l/s.m. percolation coefficient of water retaining rocks is 0.09 m/day, permeability coefficient is 3.15 m^2/day, level transfer coefficient is 0.8.102 m^2/day.

The depth of groundwater on the Absheron peninsula varies. In Western Absheron, the depth of groundwater varies from 1 m to 15.2 m (well No. 7). The lowest depth of groundwater is observed in the area between Sumgayit city and Jeyranbatan Lake. The groundwater depth interval in these areas is between 1-2 m. Around Lake Boyukshor, in the Yasamal Valley, in the southern parts of Lokbatan settlement, in the Red Lake district, in the Sahil settlement district, the groundwater depth is in the interval of 1-2 m.

According to the information received, the hydrodynamic parameters of groundwater in the areas where the wells are located are very weak. The well's flow rate during pumping is 0.03-1.2 l/s, the specific flow rate is 0.03-0.003 l/s.m. The filtration coefficient of the water-bearing rocks is 0.07-0.62 m/day, the water permeability coefficient is 0.39-4.34 m^2/day, the level permeability coefficient is 0.2.102-0.3.103 m^2/day, the water permeability coefficient of the water-bearing rocks varies between 0.017-0.05.

In the Masazir settlement district and in the surrounding lakes, the groundwater depth increases as it is separated from the lakes, reaching a depth of 16.5 m and more. In the territory of Baku city, the groundwater depth repeats the shape of the relief. On the edges of the Baku amphitheater, the depth - 10-12 m, and in some places 20-25 m and more. In the direction of the sea, the groundwater depth decreases to an interval of 1-2 m.

In the territory of Eastern Absheron, the groundwater depth varies from 0 to 30 m. In the territory of Central Absheron, the groundwater depth is close to the surface of the earth. The depth of groundwater in Kurdakhani, Pirshaghi, Mammadli, Nardaran, Mashtaga, Fatmai, Surakhani and other areas varies between 1-2 m. In the areas from Nardaran to Zira, the depth of groundwater varies between 10-20 m (Fig.2.).

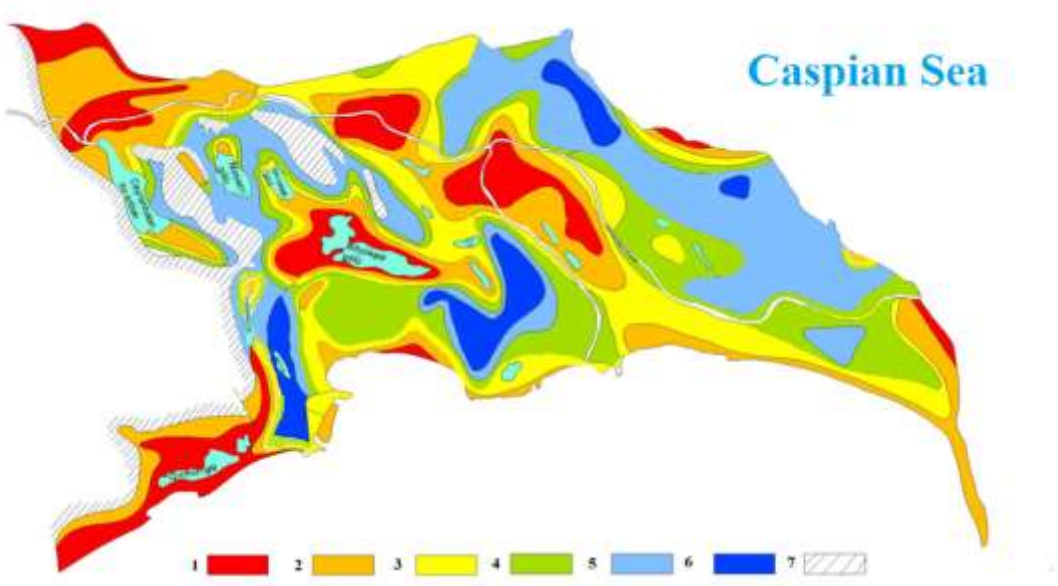


Figure 2: *Map of groundwater depth of the Absheron Peninsula*
The depth of the water: 1. 0-1 m; 2. 1-3m; 3. 3-5 m; 4. 5-10 m; 5. 10-20 m; 6. >20 m; 7. Areas of sporadic groundwater flow

The water content of the water-retaining rocks in Western Absheron varies in very low intervals. The water consumption during the pumping period of wells drilled between Sumgayit city and Novkhani gardens varies between 0.03-3.0 l/s. In the Jeyranbatan Lake region, the water consumption of wells is 0.4-0.9 l/s, and the specific water consumption is 0.05-0.3 l/s.m. The most common specific water consumption is 0.03-0.09 l/s.m. The filtration coefficient of the water-retaining rocks varies between 0.3-3.6 m/day. In the area between Mirzaledi, Masazir and Boyuk Shor lakes, the specific water consumption of wells is 0.06-0.12 l/s.m, and the filtration coefficient of the water-retaining rocks varies between 0.9-2.1 m/day. In the Khirdalan area, the flow rate of wells is 0.6 l/s, the specific flow rate is 0.05 l/s.m. The rock filtration coefficient is 0.7 m/day. The flow rate of wells drilled in the Khoja-Hasan Lake region is 0.2 l/s, the specific flow rate is 0.02-0.05 l/s.m, and the rock filtration coefficient varies between 0.1-0.7 m/day. The flow rate of wells drilled south of the lake is 0.5 l/s, the specific flow rate is 0.06 l/s.m, and the filtration coefficient is 3.1 m/day.

In the southwest of the Absheron Peninsula, the flow rate of wells increases to 3.5 l/s. The specific flow rate of wells in this direction varies between 0.01-0.09, 0.15-0.23 l/s.m. The permeability of water-retaining rocks varies between 0.03-1.0 m/day.

In the Baku depression, the rocks of the groundwater horizon are more watery. The thickness of the water horizons is variable. The flow rate of wells during the water withdrawal was between 0.2-5.9 l/s. The greatest water content is distributed in the Yasamal settlement. The reason for this is explained by the influence of Ganly Lake. The specific flow rate of wells is 0.02-0.3 l/s.m. The permeability of water-retaining rocks varies between 0.1-25.9 m/day. The permeability of water-retaining rocks in the central parts of the Baku depression varies between 0.2-9.2 m/day. The flow rate of wells is 0.2-5.0 l/s, and the specific flow rate is 0.02-0.3 l/s.m.

The flow rate of wells drilled into groundwater in East Absheron is up to 9.8 l/s. The flow rate of wells in the Nardaran and Zagulba zones varies between 2.0-10.0 l/s. The specific flow rate of wells in these areas is 0.2-1.1 l/s.m. The filtration coefficient of water-retaining rocks is 1.1-5.2 m/day. The thickness of the aquifer is 60-70 m. This thickness is observed everywhere in East Absheron. The flow rate of wells in the Mashtaga area is 0.8-1.5 l/s, and in the Mardakan-Shuvalan area it is 0.4-2.1 l/s. The specific flow rate of wells varies between 0.14-0.38 and 0.03-0.25 l/s.m. The filtration coefficient of water-retaining rocks varies between 0.2-2.3 m/day. The infiltration rate of the water-retaining rocks in the Bina-Govsan basin is 1.0-4.8 m/day. The flow rate of the wells is 0.9-3.0 l/s, and the specific flow rate is 0.06-1.2 l/s.m.

The pressurized groundwater distributed on the peninsula has a high degree of mineralization. Therefore, these waters have not been well studied due to their lack of practical significance.

Pressurized aquifers on the peninsula have been studied during hydrogeological, hydrogeological-ameliorative mapping, and exploration and exploration works for balneological purposes. Pressurized waters lying in deeper layers have been studied during oil exploration.

Unlike groundwater, pressurized waters on the Absheron Peninsula have created a single aquifer horizon and characterize separate stratigraphic units of the section. In these areas, pressurized aquifers have no hydraulic connection with other horizons.

In the western parts of the Absheron Peninsula, pressurized aquifers have developed in the sediments of the Productive layer. In the northwestern part of the peninsula, the ceiling of pressurized aquifers has been discovered at a depth of 49-70 m. In the southwest, this depth varies between 30-54 m. In the northwest, pressurized waters have been studied to a depth of 200-250 m, and in the southwest - up to 100 m. In the northwest of the peninsula, in the Sumgayit city district, in the west, in the Goradil village, in the Masazir Lake area, the piezometric levels of pressurized waters are at a depth of 3.4-18.7 m. The flow rate of wells during water withdrawal varies between 1-7 l/s. The specific flow rate of wells is 0.07-0.8 l/s.m. The filtration coefficients of water-retaining rocks are 0.2-1.9 m/day. In the Garadagh-Puta area, the piezometric level is at 1-2 m. The flow rate of wells during water withdrawal is 0.3-0.9 l/s, and the specific flow rate is 0.03-0.11 l/s.m.

The infiltration rate of water-retaining rocks is 0.03-0.11 m/day. Pressurized waters are sporadically distributed in Western Absheron.

Pressurized waters are found everywhere in the Baku Basin. Pressurized aquifers consist of several pressurized aquifer layers and were formed in the sediments of the Absheron-Quaternary period. The water-bearing rocks consist of sand, silt, sandstones and limestones. The feeding area of pressurized aquifers in the Baku Basin is the area where their collector rocks emerge to the surface. Such conditions are found everywhere in the Absheron Peninsula. The flow direction of pressurized waters everywhere repeats the flow direction of groundwater. In the central parts of the city, pressurized waters both feed groundwater and flow into the Caspian Sea. In the western and eastern parts of the city, groundwater feeds pressurized waters. The role of artificial factors in the feeding of pressurized waters is very low. As a result of the feeding of pressurized water horizons with different waters on the edges of the basin, the levels of both groundwater and pressurized waters increase in the central parts. This process is observed everywhere in the city. The depth of the top of the pressurized aquifer varies between 20-105 m. The lowest depth of pressurized water is observed in the coastal area. In these areas, the top of pressurized water is found at a depth of up to 36 m. In the central parts of the city, the top of pressurized water lies at a depth of 92-105 m. The general direction of groundwater flow is towards the sea. The direction of the flow is formed in accordance with the geological-tectonic and geomorphological conditions of the area. The piezometric level in these areas varies between 99.7 m (-22.7 m). The highest value of the piezometric level is observed in the Yasamal settlement, and the lowest values are observed along the coast. In areas after the "O" horizon, the piezometric level is above the ground surface in wells drilled for pressurized water. The flow rate of wells during pumping in these areas is 0.1-3.8 l/s. The seepage coefficient of water-bearing rocks is 0.1-1.2 m/day.

Pressurized aquifers are found everywhere in Eastern Absheron. Pressurized aquifers are widespread in the Khazar, Gurgan, Baku, and Upper Absheron sediments. The aquifers are sand, gravel, sandstone, and limestone. In Eastern Absheron, the Agjagil and Lower Absheron sediments are anhydrous.

There is no data to characterize the vertical section of the aquifers located in the Agjagil and Prodeuctive layer sediments in Eastern Absheron. There is no data to characterize the vertical section of the aquifers located in the Aghjagil and Mushkildar sedimentary beds in Eastern Absheron. The Quaternary-Upper Absheron sedimentary layers were formed at a depth of 700-800 m in these areas. The studied thickness covers 200-250 m. The depth of the ceiling parts of the Absheron floor was found to be 66-88 m through wells. The sediments of this layer are distributed in the regions of the villages of Pirshaghi-Bilgah and Mashtaga-Buzovna. The base of the layers was discovered at a depth of 144-235 m. The piezometric level is located at a depth of 7.4-12.9 m. The flow rate of the wells during the water withdrawal is 0.6-2.6 l/s, and the specific flow rate is 0.21-0.5 l/s.m. The filtration coefficient of the water-retaining rocks varies between 0.3-1.9 m/day. In the Mashtaga-Shuvalan area, a complex of pressurized waters was discovered at 60-72 m. The base of the pressurized layers is located at a depth of 190-241 m. The flow rate of the wells during the water withdrawal is 1.90-2.40 l/s, and the specific flow rate is 0.15-0.30 l/s.m. The permeability of water-retaining rocks is 0.6-1.4 m/day.

Two pressurized water horizons were discovered through wells in the Bina-Govsan depression. Here, the ceiling of the Baku horizon lies at a depth of 30-46 m, and the bottom at a depth of 35-75 m. The piezometric level is located at a depth of 4-16 m. In the Govsan village district, the piezometric level is located at +0.5 m. During the water withdrawal period, the flow rate of the wells varies between 1.0-5.0 l/s, and the specific flow rate is 0.9-4.5 l/s.m. The permeability of water-retaining rocks reaches 10 m/day.

The second pressurized horizon in the Bina-Govsan depression belongs to Absheron sediments.

At the Gala height, this horizon lies at a depth of 19-69 m. During the water withdrawal period, the wells have a flow rate of 1.0 l/s, and a specific flow rate of 0.15 l/s.m. The percolation coefficient of the water-retaining rocks is 0.32 m/day.

The pressurized aquifer horizon at the Zira and Shahov capes belongs to the Baku and Absheron layers. The ceiling of the pressurized aquifer complex lies at a depth of 27-62 m, and the base at a depth of 40-68 m. The effective thickness of the aquifers is 4-6 m. The piezometric level is at a depth of 17-23 m. During the water withdrawal period, the wells have a flow rate of 0.7-1.0 l/s, and a specific flow rate of 0.02-0.04 l/s.m. The percolation coefficient of the water-retaining rocks is 1.0 m/day.

III. Results

The Absheron Peninsula, especially in the past 30-40 years, has been thoroughly studied through various hydrogeological exploration activities, and it exhibits a variety of hydrogeological characteristics. During this period, the data from drilled wells have been used to analyze the hydrodynamic conditions of the region in detail.

The tectonic structure of Eastern Absheron is characterized by the presence of structural formations such as the Kurdakhani-Mashtaga uplift, the Bina-Govsan and Dubəndi-Zira ridges. The geological and geomorphological features of these areas have created favorable conditions for the formation of groundwater reservoirs. The Absheron formation of sedimentary layers in Eastern Absheron is primarily represented by modern-day deposits. Due to the considerable thickness of these deposits, the productive groundwater layers are mainly found at deeper strata.

In the hydrogeological context of Absheron Peninsula, artificial factors, along with natural ones, also play a significant role. The dynamics of groundwater flow, especially in the central and eastern parts of the region, exhibit distinct patterns. The flow of groundwater in this area is primarily directed west, southeast, and east, which corresponds to the dynamic flow patterns defined by the region's geological structures.

Hydroisohypses maps and other hydrodynamic charts illustrate the absolute elevation of groundwater and its mineralization characteristics. Analyzing the density and hydrodynamic properties of the groundwater provides insights into how these waters spread across different areas, such as Khirdalan, Masazir, and others, and how these waters approach the surface. Notably, in the Baku formation area, the flow of pressurized waters and their relation to groundwater, as well as the discharge and filtration coefficients of pressurized horizons in the northwest and southwest parts, are essential for understanding the dynamics of groundwater.

The interaction between pressurized waters and groundwater in Baku city and other regions of the Absheron Peninsula represents significant indicators of the hydrogeological conditions formed by the groundwater flow. These relationships provide essential data for managing water reservoirs and properly assessing the region’s hydrogeological situation. The high mineralization of pressurized waters in the central parts of the city and their location in unusual hydrogeological conditions is also crucial.

Therefore, in-depth study of the hydrogeological characteristics of Absheron Peninsula, considering both natural and artificial factors, allows for efficient management of groundwater resources. This provides necessary information for evaluating the dynamics of underground water reservoirs.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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MELIORATIVE CONDITION OF IRRIGATED LANDS IN THE SHIRVAN PLAIN OF THE REPUBLIC OF AZERBAIJAN

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Abstract

It is well known that the meliorative condition of any region, including the Shirvan Plain, located in the central part of the Republic of Azerbaijan and one of the most important agricultural and livestock areas, is determined by a combination of geo-ecological, hydro-geological and anthropogenic factors. The study of the current state of this area is both timely and of great practical and scientific importance. This paper provides a brief history of research into the geological structure of the region, together with a description of the extensive meliorative efforts underway. It presents data on irrigated land and areas equipped with open, closed and vertical drainage systems within the study area. The hydrogeological and meliorative conditions of the irrigated areas of the Shirvan Plain were characterized on the basis of field studies carried out by the Hydrological-Meliorative Service in 2023-2024 under the scientific and methodological supervision of the authors. Changes in groundwater depth across the area have been identified and attributed to various factors, including ongoing climatic changes. Laboratory analyses of borehole samples have determined the degree of mineralization and chemical composition of the groundwater. A soil stratigraphy study was carried out in the Shirvan Plain to determine the distribution of groundwater and confined aquifers, their ionic and salinity composition and mineralization levels. The hydrogeological and hydrological condition of the study area was assessed by visual inspection and analysis of soil samples to evaluate its meliorative condition, salinity level and suitability for agricultural use. The potential for groundwater use for crop irrigation, livestock and settlement water supply was also determined. Analysis of the data shows that soil conditions can be improved through a variety of meliorative measures. Chemical melioration is recommended for the reclamation of highly or very saline irrigated lands in the Shirvan Plain. To increase filtration rates, methods such as leaching with sand mixing, phytomelioration and primary leaching with surface irrigation in conjunction with drainage are suggested. Maps have been prepared and recommendations made to improve the productivity of arable land through leaching.

Keywords: Shirvan Plain, mineralization and chemical composition of groundwater, water resources of Azerbaijan, irrigated lands, irrigation infrastructure

I. Introduction

Currently, environmental changes driven by technogenic factors have impacted all aspects of the geological environment, which in turn has significantly influenced the production of agro-industrial products. The construction of irrigation, hydraulic, and other agricultural structures, along with the expansion of irrigated land areas and the use of organic and chemical fertilizers, has considerably altered the geological environment of irrigated zones in the Lankaran, Kura-Araks, Ganykh-Agrichay, Priaraks, and Qusar-Shabran plains, among others (Table 1).

As of now, the total area of irrigated lands in the Republic of Azerbaijan covers 1,456,544 hectares, of which 616,025 hectares are undergoing comprehensive melioration work, 360,325 hectares are equipped

with open drainage systems, 244,500 hectares with closed drainage, and 11,200 hectares with vertical drainage.

For specific irrigated land masses, it is essential to study the hydrogeological and meliorative conditions in order to clarify the scale and improve the methods of work being carried out.

The Shirvan Plain is located in the central part of the Republic of Azerbaijan, bordered to the north and northeast by the foothills of the Ajinohur in the Greater Caucasus, stretching eastward to the tributary of the Hajiqabul River, with the Kura River forming its southern boundary. Covering an area of 6,740 km², the plain includes several administrative districts: Agdash, Goychay, Ujar, Zardab, and Kurdamir, as well as parts of Yevlakh, Aghsu, Shamakhi, Ismayilli, Hajigabul, and Gobustan [1, 2, 4, 10, 19, 21,22, 25, 28, 34, 36].

The population primarily engages in cereal farming, horticulture, and animal husbandry. Part of the Shirvan Plain lies within the low-altitude zone of the Greater Caucasus foothills, while the remainder occupies the Kura Depression. The highest elevation in the foothill area is +437.5 m, and absolute elevations in much of the plain range from 200 to 220 m. Along the Kura River, in sections near Lake Ajinohur and in the Kurdamir district, elevations reach about -20 m. The main orographic elements include the alluvial cones of the Turianchay, Goychay, Girdimanchay, and Aghsu rivers (Fig. 1).

Table 1: *Sources of Groundwater Recharge in the Shirvan Plain*

Sources of Recharge	m^3/s	%
Infiltration from irrigation structures	13.20	19.9
Infiltration from rivers (Kura tributaries)	21.85	32.93
Confined water sources	9.60	14.47
Condensed water	6.75	10.17
Infiltration from mechanically elevated water	3.45	5.20
Infiltration from atmospheric precipitation	4.05	6.10
Groundwater from mountain rock	3.00	4.52
Infiltration from rainfall on mountain slopes	4.20	6.33
Infiltration from irrigation with artesian water	0.20	0.30
Infiltration from kahriz water irrigation	0.05	0.10
TOTAL:	66.35	100

The population primarily engages in cereal farming, horticulture, and animal husbandry. Part of the Shirvan Plain lies within the low-altitude zone of the Greater Caucasus foothills, while the remainder occupies the Kura Depression. The highest elevation in the foothill area is +437.5 m, and absolute elevations in much of the plain range from 200 to 220 m. Along the Kura River, in sections near Lake Ajinohur and in the Kurdamir district, elevations reach about -20 m. The main orographic elements include the alluvial cones of the Turianchay, Goychay, Girdimanchay, and Aghsu rivers (see, Fig.1).

The hydrographic network of the Shirvan Plain primarily consists of the Kura River and its left tributaries- Alinjachay, Turianchay, Goychay, Girdimanchay, and Aghsu, as well as irrigation canals and collectors.

II. Objective of the study

The objective of this study is to determine the hydrogeological and hydrological state of the study area, evaluate the meliorative condition of the soil, assess its suitability for agricultural use, and explore

the potential use of groundwater for irrigation, livestock, and the water supply for settlements. The study also aims to improve soil conditions through various melioration activities.

Initial information on the geological structure of the mountainous areas to the northeast of the Shirvan Plain was provided by N.I. Andrusov. Subsequent research on the geological structure of the surrounding ridges was conducted and documented by V.V. Bogachev (1912), V.P. Rengarten, and F.F. Oswald.

Based on studies by A.N. Shardanov and V.E. Khain, the Kura-Araks lowland is considered a megasyncline between the meganticlines of the Greater and Lesser Caucasus, where geological surveying was conducted in specific areas.

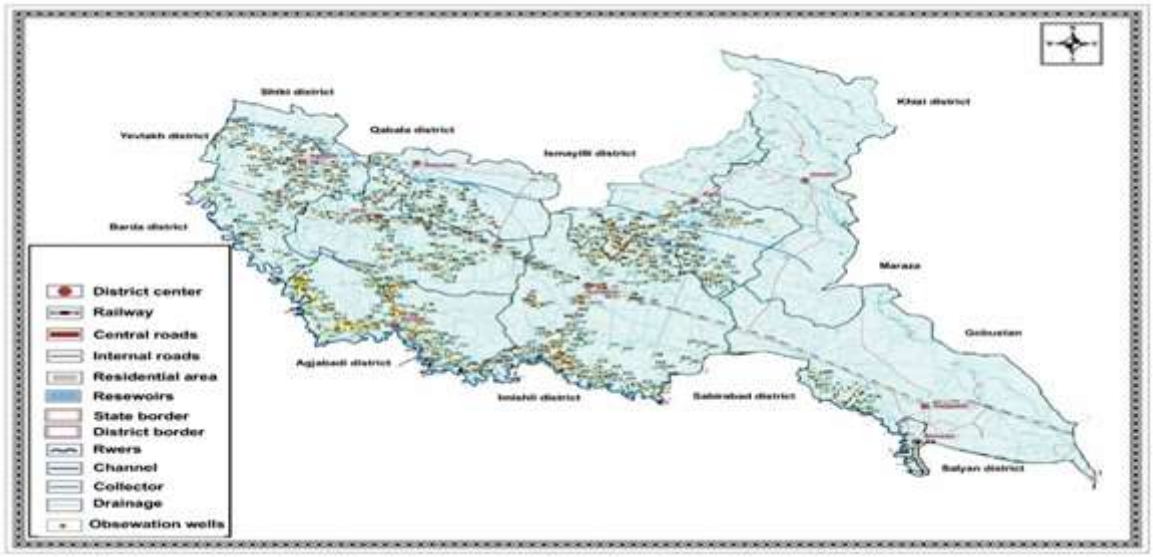


Figure 1. *Diagram of the irrigation and drainage network in the Shirvan irrigation area*

The upper layer of the Shirvan Plain's deposits (up to 1,400 m) consists of Quaternary sediments, with underlying Neogene, Paleogene, and Cretaceous formations identified through oil exploration drilling. These deposits, which cover the entire plain, consist primarily of alluvial sands, sandstones, clays, and alluvial-proluvial clays. In addition, proluvial-deluvial clays, sands, gravels, and pebbles are also present on the southern slopes of the Greater Caucasus, where the modern layer thickness reaches 40 m [6, 7, 8, 11, 15, 18, 27, 29, 30].

Since the 1920s, with the expansion of geological research, more intensive studies of the Shirvan Plain have been conducted. Following the establishment of the Water Management Authority of Azerbaijan in 1927, these studies took on a broader scope. The findings resulted in the creation of mineralization and hydroisogyps maps at a scale of 1:200,000.

In 1929, F.P. Savarensky published works on soil and groundwater salinization processes in the Kura-Araks lowland. During these years, studies on the groundwater regime began under V.A. Priklonsky's leadership, with exploratory wells drilled. Additionally, V.Sh. Sokhadze conducted new research into the causes of bog formation in the plains.

In our republic, 266,313 hectares of irrigated land are in the Shirvan Plain. Of these, 153,300 hectares are equipped with drainage systems: 40,400 hectares with open-horizontal drainage and 112,900 hectares with closed-horizontal drainage systems.

The groundwater table depth on irrigated lands spans various levels: under 1 m on 2,230 hectares (0.83%), 1.0-1.5 m on 15,581 hectares (5.85%), 1.5-2.0 m on 72,946 hectares (27.40%), 2.0-3.0 m on 116,510 hectares (43.75%), 3.0-5.0 m on 42,485 hectares (15.96%), and over 5.0 m on 16,561 hectares (6.21%) (Fig. 2).

On irrigated lands, groundwater salinity can be divided into categories distributed as follows: below 1 g/L on 59,665 hectares (22.40%), 1.0-3.0 g/L on 113,542 hectares (42.63%), and above 3 g/L on 112,498 hectares (34.97%) (Fig. 3).

Research findings reveal that drainage waters are fed not only by irrigation waters but also by groundwater and confined waters that are hydraulically connected to atmospheric precipitation, rivers, and irrigation water sources.

According to chemical analysis, 97% of the sampled water represents irrigation conditions (SO_4^{2-} - Na^+), 2% represents marine conditions (Cl^- - Mg^{2+}), and 1% represents deepwater and continental conditions (HCO_3^- - Na^+).

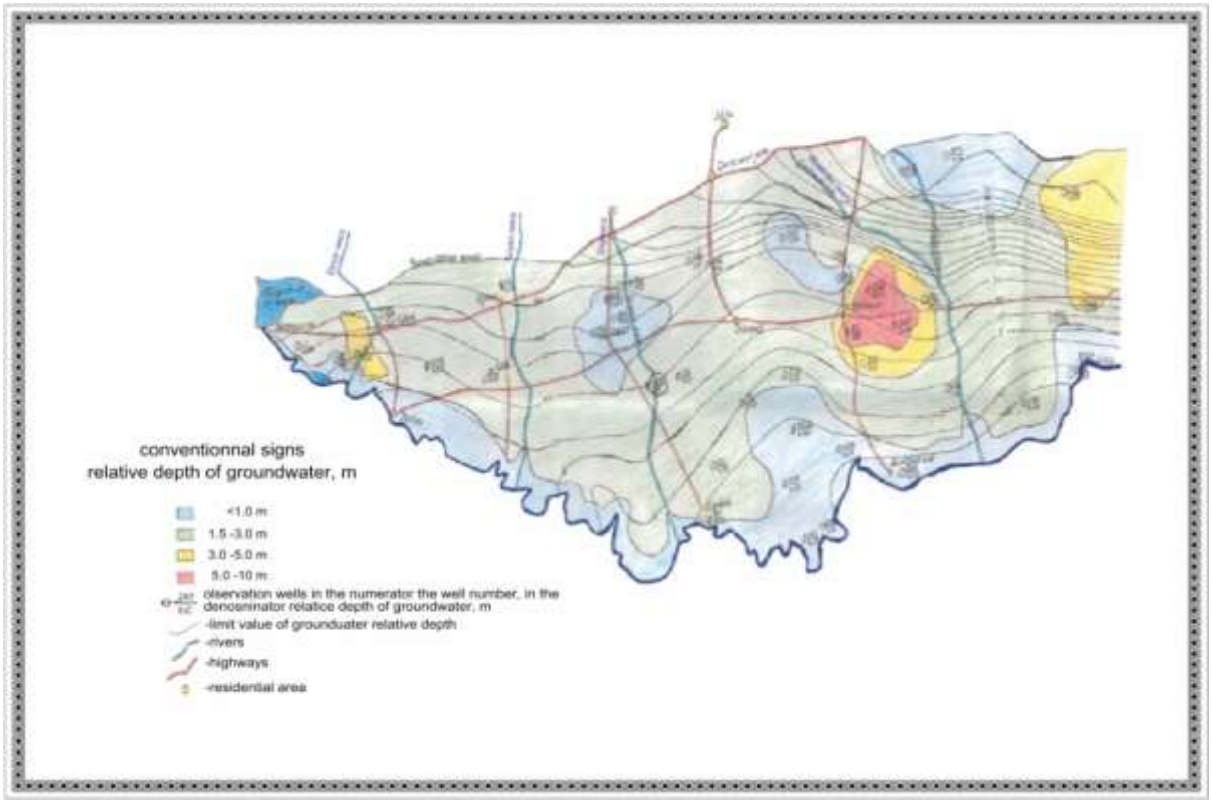


Figure 2: *Schematic map of hydroisogyps and groundwater depths in the Shirvan Plain*

III. Research Methods

Groundwater levels in drilled wells were measured, water samples were collected and then analyzed in laboratory conditions. Visual inspection and studies of soil cover samples were also conducted.

To remediate the salinity of irrigated lands in the Shirvan Plain, especially in areas with high and very high salinity, chemical reclamation should be used to increase the filtration coefficient. This can include leaching with sand mixing, phytomelioration, and surface irrigation techniques [12, 14,21, 31].

Chemical reclamation is applied as the main method for improving saline soils in the following cases: for improving alkali and neutral soils (where carbonate and gypsum layers lie at depths of 40-50 cm and contain more than 10% exchangeable sodium), for releasing carbon dioxide generated from carbonate reserves within the soil, and as an auxiliary method for intensifying self-purification processes to combat secondary salinization during irrigation.

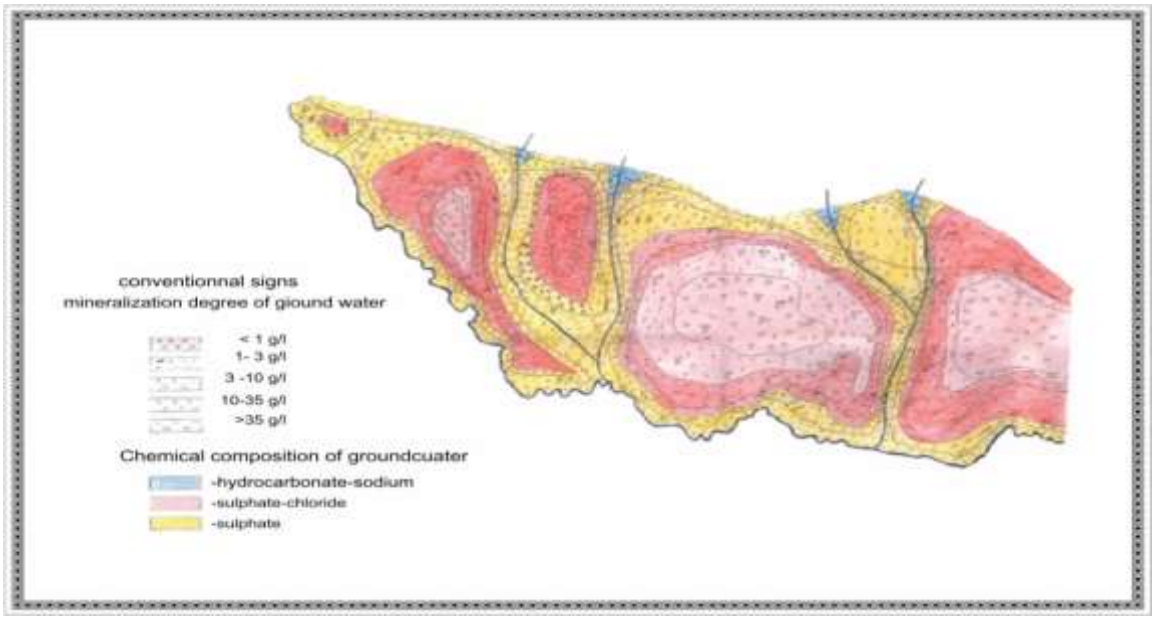


Figure 3: *Map of the chemical composition and mineralization of groundwater in the Shirvan Plain*

In applying this method to saline soils, compounds like calcium, acids, or acidic ameliorants are introduced into the stratified soil layer using specialized machinery (sprayers and spreaders for dry and liquid fertilizers), followed by plowing or cultivating with heavy disc harrows. Chemical reclamation is used both in irrigated areas and, in the absence of irrigation, in regions with an annual precipitation exceeding 300-350 mm. Ameliorants can be applied either across the entire area or to locally selected, saline spots. When distribution over localized spots are impractical, ameliorants are applied across the entire area. The ideal conditions for applying ameliorants are in the spring and summer, when the soil still retains enough moisture for effective incorporation and mixing with ameliorants.

During chemical reclamation in conjunction with irrigation, ameliorants dissolve and interact more effectively with soil, helping to remove exchange products from the ameliorated layer. Doses of chemical ameliorants are calculated based on the amount of exchangeable sodium in the saline soil layer. For alkali soils, it is also necessary to account for the amount of ameliorant required for full neutralization of soda. Dosage rates are divided into two types: ameliorative (calculated to replace exchangeable sodium and fully mitigate salinity's negative effects over 10-20 years) and agronomic (designed to provide similar ameliorative effects within one or two crop rotations) [26, 35].

Generally, the agronomic dose is half the ameliorative dose. The most common chemical ameliorants include gypsum, phosphogypsum (a by-product of phosphoric acid production), sulfuric acid (only with irrigation), and acidic ameliorants such as sulfur, iron, and aluminum sulfates. Other calcium compounds (e.g., calcium chloride, chalk) and industrial by-products are also used.

There are several empirical formulas for calculating the required amount of gypsum for saline areas. A typical gypsum dose calculation formula (D_g) is as follows (1).

$$D_g = 0{,}086 \bullet n \bullet d \bullet (Na_n - Na_k) \quad (1)$$

where n is the thickness of the amelioration layer (cm), d is soil density (g/cm³), Na_n is the initial exchangeable sodium, and Na_k is the sodium level after reclamation (mmol per 100 g soil). If a non-pure gypsum ameliorant is used, the dosage is adjusted based on its gypsum content. Gypsum application rates vary from 5 to 70 tons/ha, with typical field doses between 10-20 tons/ha.

For soil reclamation, 0.6-1.0% sulfuric acid is applied with irrigation water. The washing rate must be sufficient to displace and remove exchangeable sodium from the treated soil layer. Acid is stored and transported in acid-resistant containers, and it is introduced gradually over a period of up to 20 days, with washing potentially lasting up to 6 months. The sulfuric acid dose (D_g) is calculated as follows:

$$D_g = 0.049 \bullet n \bullet d \bullet K \bullet (OKO) \bullet (Na_n - Na_k) + S + CO_2 \quad (2)$$

where K is a factor accounting for the concentration of sulfuric acid, OKO is the cation exchange capacity (mmol per 100 g soil), S is the sum of CO_3 and HCO_3 ions, and CO_2 is the carbonate content.

The effectiveness of chemical reclamation in arid and semi-arid zones decreases significantly without irrigation due to low moisture, rendering the costs higher than the benefits. Therefore, deep ameliorative tillage, using natural soil gypsum and carbonates, is the primary method in such areas, as it mechanically breaks the saline layer and promotes calcium-sodium exchange.

The reclaimed carbonate layer depth (H_k) is calculated as (3):

$$H_k = 0{,}58 \bullet D_g \bullet 10 \; ; (CO_2 \bullet \gamma) \quad (3)$$

where: 0,58 – conversion coefficient from gypsum to calcium carbonate; D_g – the applied dose of gypsum; 10 – solubility correction coefficient for calcium carbonate; CO_2 – carbonate content in the carbonate layer (%); γ – density of the gypsum layer (g/cm³).

The depth of the plowed portion of the gypsum layer (H_k) is calculated using the formula H_k=Dg/($\alpha \cdot \gamma$), where α\ represents the amount of gypsum in the gypsum layer. During reclamation plowing of low-humus saline areas, it is recommended to add "organic fertilizer" to the reclamation layer to activate microbial activity and increase the concentration of carbon dioxide in the soil air. This results in the transformation of calcium carbonate into more soluble calcium bicarbonate, enhancing the effectiveness of reclamation. The following deep soil treatments are used: plantation plows, three-step plows, and in-soil rotary (milling) treatments. Plowing typically takes place after the top 15-20 cm soil layer is cut using heavy disk drills. Effective reclamation plowing is possible under the following conditions: soil moisture at 10-12%, hardness of 8 MPa, specific resistance of 0.13 MPa, and surface slope not exceeding 8°.

Analyses of the chemical composition of natural waters in the Shirvan Plain demonstrate that irrigation with different water sources alters the primary chemical composition of groundwater. Due to the current use of alternative water sources for irrigating the region, aggressive hydrochemical types of water are forming, which land users need to consider.

In peripheral sections of alluvial fans, groundwater recharge is complicated due to the abundance of clay in the soil, minimal precipitation, and a low hydraulic gradient. Intensive irrigation, meanwhile, contributes to the rising groundwater level. The spread of high-salinity groundwater is linked to an absence of river recharge and a drop in groundwater levels, resulting in systematic salt accumulation in the soil. Furthermore, prolonged evaporation under changing hydrological conditions also leads to salt accumulation. The presence of sulfate-sodium (SO_4^{2-} Na^+), sulfate-calcium (SO_4^{-2} Ca^{2+}), and chloride-sulfate-magnesium-sodium (Cl^- -SO_4^{-2}-Mg^{2+} -Na^+) salt types in the aeration zone indicates that capillary rise of groundwater in the soil contributes to salt accumulation [23, 32, 33, 37].

Notably, while all types of soil salinization are present in Azerbaijan, a comprehensive classification of the degree and type of soil salinity has not yet been developed. This gap poses certain challenges in addressing agricultural production issues, impacting scientific problem-solving (e.g., mapping, determining leaching rates, appropriate crop allocation according to soil salinity, etc.). Various scholars [19, 31] have proposed classifications for soil salinity, but their approaches differ.

In the past, results from tests conducted across the former USSR were synthesized by specialists and reissued with new instructions mandatory for implementation in local areas. These guidelines, though possibly effective in Russia, southern Ukraine, Central Asia, and other regions, are unsuitable for Azerbaijani conditions, a situation that persists today. Specialists often select unsuitable classification methods for Azerbaijan's saline soils, making further study on this issue essential.

To classify soil salinity in the Kura-Araks Lowland, including the Shirvan Plain, experiments were conducted in areas with varying soil hydro-physical characteristics. Test plots, each measuring 0.1-0.3 ha and differing in salinity type and degree, were selected. Soil cuts corresponded to the developmental

stages of cultivated crops, and samples were taken from saline patches with sparse or no vegetation, with each sample area tested three times. Comprehensive water extract analyses were performed on samples to clarify salinity degree and types, as well as determine pH and base saturation in cuts.

Irrigated soil on the Shirvan Plain, classified by salinity level, includes: 183,467 ha (68.89%) non-saline, 51,549 ha (19.35%) slightly saline, 16,853 ha (6.33%) moderately saline, and 14,444 ha (5.43%) highly and severely saline soils. Studies in Azerbaijan's cotton-growing regions have found that yields of 22-24 centners/ha of cotton or grain can be achieved in soils with 0.6-0.7% salinity of sulfate, chloride, and chloride-sulfate types.

Currently, many landowners (farmers) lack the means to flush saline soils to acceptable conditions due to limited resources and machinery. Farmers are thus encouraged to improve saline soil parts through agro-reclamation (crop rotation). Since leveling is essential for flushing, plots scheduled for flushing should be pre-leveled. Proper leveling ensures efficient use of irrigation water and uniform salt leaching. Adequate leveling, irrigation, and salt flushing are among the factors that improve the rationality of sowing operations. During irrigation, increased evaporation in higher areas and water pooling in lower areas cause a rise in groundwater levels. To mitigate this, plots should be leveled annually.

Between 1971 and 1975, 156,800 ha of irrigated land in the Azerbaijan Republic underwent reclamation, 88,000 ha were flushed, and 274,400 ha received deep salt flushing. Post-land privatization, capital investment in such activities has declined.

Given the high temperatures in the Shirvan Plain, it is essential to consider optimal sowing timing. Delayed autumn sowing promotes weed growth, which, without additional agrotechnical measures, reduces crop yields [16, 24, 29].

Analysis of water samples from drainage networks in advanced labs reveals that nitrate levels are below regulatory limits, indicating the need for appropriate fertilizers to improve soil productivity. Soil used for agriculture loses fertility over time, so timely application of organic and mineral fertilizers is necessary. Practice shows that 12 tons of organic fertilizers per hectare (e.g., manure, composts) help maintain soil fertility, meaning 12 tons/ha of organic and mineral fertilizers are required.

For increased soil fertility, crop rotation is vital, though challenging on small plots. Nonetheless, small farms should aim to rotate at least three crops, changing plant locations to preserve soil fertility. New plots should undergo deep plowing, leveling, cultivation, pest control, and timely fertilizer application at appropriate depths.

On irrigated lands, typically plowed to 20-25 cm, soil compacts over time due to two factors: water infiltration clogging pores with fine particles and the weight of agricultural machinery, which drives over the land 20-30 times, compacting lower soil layers. Agricultural crops cannot penetrate the compacted layer, limiting root depth to 20-25 cm and hampering nutrient uptake. Soil fertility on compacted plots decreases by 30-40%. Thus, periodic plowing to a depth of 100 cm (at least every five years) is recommended.

To maintain plowed soil fertility, organic and mineral fertilizers should be applied separately. Irrigation volumes must not exceed the required level for each crop, and the same crops should be cultivated within a single irrigation system to optimize water use.

IV. Conclusions

1. The Shirvan Plain is climatically characterized by high air temperatures and a lack of moisture. Under such conditions, agriculture is considered possible only with the application of artificial irrigation. The high mineralization and the close proximity of groundwater to the earth's surface, as well as the poor drainage of the studied area, indicate the necessity of artificial irrigation. Most of the groundwater evaporates and is used by plants for transpiration, leading to soil salinization. Therefore, it is important to periodically reassess the hydrogeological conditions of the region every few years.

2. The underground waters consist of groundwater, low-pressure, and high-pressure water horizons extending to a depth of 350 meters. Groundwater is mainly replenished by atmospheric precipitation, river and irrigation waters, as well as artesian waters lying below. The process of water discharge into them is associated with evaporation, transpiration by plants, underground runoff into the Kura River, and drainage systems. The depth of these waters varies from 20-25 meters in the north to 0.5-1.0 meters in the south.

3. The degree of mineralization of underground waters ranges from 0.4 g/L to 50 g/L (or more). Fresh groundwater (with a mineralization level up to 1.0 g/L) is observed in the upper parts of river cones and near irrigation canals. As the direction of the underground flow progresses, the salinity of groundwater increases, and its chemical composition changes to a bicarbonate-sodium-magnesium type.

4. Observations of the long-term regime show a constant rise in the groundwater level, which can only be explained by the influence of irrigation. On the one hand, the impact of fresh irrigation water contributes to the reduction of groundwater mineralization; on the other hand, the rise in groundwater level leads to increased evaporation and the accumulation of salts in the aeration zone. Therefore, the primary task of land reclamation should be the removal of high-mineralized waters from the area through artificial drainage (via collector drains) and the lowering of groundwater levels.

5. In most parts of the area, pressurized waters are characterized by high mineralization. Their mineralization increases from north to south. This pattern is disrupted in the western part of the Kurin strip, and the cause is the influx of fresh waters from the powerful Karabakh artesian basin located in the southeast, which has a mineralization of less than 0.5 g/L. Throughout the year, the groundwater of the plain, covering an area of 2400 km^2, receives additional replenishment amounting to 691.2 million m^3 from the pressurized waters located below.

6. Agricultural plants cannot penetrate through the compacted layer and spread in the upper 20-25 cm layer of soil, which is insufficient for their nourishment. In compacted soils, plant productivity decreases by 30-40%, so the soil layer should be periodically (at least every 5 years) plowed to a depth of 100 cm.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DETERMINATION OF REAGENT FLOW RATE DURING NATURAL GAS TRANSPORT

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Abstract

The complications arise due to the variation of thermodynamic parameters during the production, collection and transportation of gas under the marine environment. As a result, these complications prevent the normal operation of gas transportation equipment and create an emergency situation in the gas network. Investigations were carried out in gas condensate fields and the complex preparation of gas for transportation was studied in order to improve gas treatment. We determined the optimum methanol consumption rate to prevent hydrate bridging and made estimates to improve gas treatment. This paper presents the results of the calculation of the optimum methanol consumption for gas treatment to prevent hydrate bridging.

Keywords: gas condensate, methanol, hydrate, consumption rate, thermodynamics

I. Introduction

One of the operating costs incurred during the production, storage and transportation of oil and natural gas in offshore fields is the consumption of chemicals used to prevent hydrate formation and other technological difficulties. This increases the cost of produced gas in large volumes. Therefore, the regulation of qualitative and quantitative indicators of reagents used to ensure the unhindered transportation of gases is one of the urgent and important issues of oil and gas production.

Taking into account the above, research and mining work was carried out to improve the principle of operation of installations and the technological system for regulating the consumption rates of reagents used in the process of producing, drying and transporting gas from gas condensate fields, as well as the development of new scientific and technical proposals. Research was conducted on several fronts. When studying the operation of individual apparatuses of the gas treatment plant operating at the PA OGPD, it was found that methodological reports for regulating the flow of reagents used in the system were not carried out taking into account the actual indicators [1-5].

The results of studies conducted at offshore fields showed that since the production, collection and transportation of gas condensate is carried out under difficult conditions, it is advisable to improve the composition and technologies of reagents used to prevent hydrate formation in the process system.

II. Features of automation for the liquid fuel use supplied to the tube furnace

The general approach to thermodynamic modeling of phase equilibrium with aqueous and gas hydrates is relevant for the study of vapor-liquid equilibrium in the "natural gas-hydrocarbon condensate" system. However, modeling of the balance of the condensed water phase - water, chilled water, an aqueous solution of inhibitors, the application of a methodological approach to

the transformation of the ice phase into a hydrate and a separate thermodynamic state of each contact phase - was studied. This method has several advantages for thermodynamic gas treatment in the well, which ensures the accuracy of the phase balance report and the normalization of hydration inhibitors. Accurate accounting of phase imbalances in mining conditions requires accurate accounting of volatile or non-volatile components of the gas phase, including CO_2, H_2S, N_2, H_2O, and methanol. For this purpose, a modified thermodynamic model has been developed based on the Redlix-Kvong equation for the gas phase with a hydrocarbon or non-hydrocarbon component. According to the modification, the model used includes secondary viral coefficients and additional parameters characterized by the compression coefficient of gas mixtures at high pressure. The parameterization of the modification equation shows that the calculation of the volatile components of natural gas results in an error of 1-2%, which is more accurately calculated by the Peng-Robinson equation.

III. Selection and justification of process parameters used in the designed automation and control scheme

The advantage of modifying the equation of state is that when conducting new tests, additional changes caused by secondary coefficients are easily added, and the disadvantage is high parameters. This is characterized by an increase in the exact description of the Gibbs energy in the gas phase. Interval of effective use of equation -40°C ÷ +100-150°C, pressure is 0,1MPa÷12-14 MPa.

Recent chemical potential differences - $\Delta\mu^0$ and water-ice enthalpy of empty hydrate hydrate network - Δh^0, On the basis of more accurate data, the Langmuir coefficient of individual components of natural gas mixtures was recalibrated, since updating the parameterization of the hydrate phase model is considered important. Currently, the new prices are as follows:

For structure I: $\Delta\mu^0$ =1203 J/mol,; Δh^0 =1170 J/mol; T=273,15° K temprature;

For structure II: $\Delta\mu^0$ =1077 J/mol; Δh^0 =1294 J/mol; T=273,15° K temperaturda.

Ice enthalpy is equal to Δh^f 6008 J/mol.

Using the new data, the Langmuir coefficient was reconstructed, that is, the parameters of the gas hydrate phase were updated, which improved the description of the three-phase balance "gas hydrate" for the complex gas phase, but did not affect the description of the three-phase balance with pure gases. Based on the above models, a comprehensive program has been developed for taking into account the balance of natural gas with water, the specified pressure and temperature for individual hydrate compounds or gas mixtures in the gas industry.

Using a comprehensive reporting program, simple and appropriate analytical relationships were obtained in order to determine the rate of consumption of natural gas mixtures, hydration, hydrate inhibitors in the gas collection and processing system from various fields. To confirm the results of calculation of the gas-hydrate balance of gases of complex composition, it is advisable to use the thermodynamic method of comparative calculation, including the method of empirical correction of the thermodynamic model of the gas-hydrate phase using the hydration curve of the complex gas composition. At negative or positive temperature in a wide temperature range, the method of thermodynamic extrapolation of spatial data of equilibrium tests with a pressure of 100 MPa and higher is used.

Analysis of the thermodynamic model shows that test data obtained under the condition that the degree of filling of the gas hydrate cavity does not exceed 1 are calculated as follows [6-9].

$$\ln f - H(p,T) - \frac{\Delta V\ p}{(\nu_1+\nu_2)\,RT} \quad \div \quad \frac{1}{T}$$

f -component volatility; ΔV – difference in molar volumes of water and hydrate, sm^3; p – pressure, MPa ; $H(p,T)$ – Henri constant ;

ν_1, ν_2 –crystal-chemical constants (characterizing the type of hydrate structure).

Coordinate system approximation constraint:

$$Y = A + \frac{B}{T} + C \cdot \ln(T);$$

here: A, B, C – coefficients that also describe the data in more detail at the test points, allowing extrapolation of the relationship obtained at negative or positive temperatures over a wide range of cases. The equilibrium pressure at given temperature is determined by the following formula.

$$A + \frac{B}{T} + C \cdot \ln(T) = \ln(f) - \frac{p \cdot \Delta V}{(\nu_1 + \nu_2) \cdot RT} + \frac{\ln x_{H_2O}}{\nu_1 + \nu_2}$$

Determination of gas volatility at high pressure, water density and water solubility in gas is mandatory. The extrapolation method was carried out for two gases (methane, nitrogen), and the results obtained are sufficient in the range of the temperature balance of the hydrate compound for methane. For methan ~307° K (110 MPa) , for nitrogen ~301°K (230 MPa), percentage of errors in the report ~ 5-6% - dir (for pressure).

The thermodynamic properties of the metasabit phase are shown with respect to hexogonal ice, chilled water, and ice cube. Chilled water and ice cubes are formed by separating the gas hydrate as an intermediate phase. Hexogonal ice temperature as standard is T_o=273,15° K.

The thermodynamic account of the difference in chemical potentials between hexogonal ice and chilled water is based on the thermodynamic properties of the condensed water phase based on test data reported in the literature. Several phase equilibrium reports used to report the chemical potential difference between a cube of chilled water and ice % with error 240 – 273° K in the temperature range The slow hydrate separation model is presented and the main test data is concentrated. Detailed explanations of theoretical model typing and hydrate separation mechanism and gas hydrate surface separation properties are given.

In order to expand the possibility of gas hydrate preservation technology, V.A.Istomin must cover its upper surface with another solid-phase thermodynamic stable coating, unlike the hexonal ice layer, in order to slow down the release of gas hydrate [10-12]. The implementation of the kinetic mechanism of extraction depends on the composition of the gas in the hydrate, the morphology and structure of the hydrate, the thermobaric conditions of its formation and extraction. The leading power of the splitting process is determined in several ways: for example, ΔT - the temperature difference between the process of separation and separation of the hydrate into gas and aquoeous phase is calculated:

$$\Delta G = RT \ln f / f_0 \approx RT \ln p / p_0 ,$$

f, p - flight capability and gas pressure in the system,

f_0, p_0 - balancing value of flight capability and pressure.

When conducting tests at the initial stage, the driving power may change, the results of these tests show the properties of the mechanism of the process of separation of gas hydrates and kinetics at negative temperatures:

- staged (conservation effect leading to the first rapid stage and subsequent slow separation stage);
- clear image of the effect of self-preservation of hydrated methane and natural gas in a certain temperature range;
- formation of different metasabitic aqueous phases in the first separation step.
- formation of metasabit surface phase at different times depending on thermobaric conditions.

Depending on the test conditions, the mechanism of separation of gas hydrates at negative temperatures can be divided into options.

- To accurately separate the effect of preservation at the initial stage, release the hydrate into gas and chilled water, and then crystallize the chilled water coating under optimal conditions.

- Long-term storage of chilled water in a non-crystallized state, except for the complete release of a hydrate particle into chilled water and gas. In this case, it is impossible to stop the process. With the conservation effect, part of the hydrated particles is completely separated, and the other part is preserved independently.

If the first surface of the hydrate is separated by ice and gas, a layer of ice forms in the upper layer of the hydrate, and, despite the slowdown of the process, no abrupt flow occurs.

The process of surface separation of gas hydrates at negative temperatures is divided into three main stages: the first stage is the stage of separation into the metasabit phase, the stage of crystallization or recrystallization of the metasabit phase of water and the subsequent stage of slow separation with a diffusion mechanism. Sometimes the stages may not take place or the separation stage may end in the first stage. For wider implementation of the initial stage of the methane hydrate separation process is low (272,95°K) three-phase accounting of the water phase and the hydrated part of methane was carried out. Analysis of the results of the report allows us to determine the area of possible formation of very cold water and ice on the decomposing methane hydrate and, thus, analyze the reasons for the formation of the "self-preservation" effect in various conditions. The following are the temperature ranges for the presence of chilled water in the methane-methane-hydrate-chilled water system at various pressures.

Table 1: *Pressure reduction and methane hydrate splitting*
Thermobaric conditions for the existence of chilled water

Pressure, MPa	**Temprature diapason, °K**
0,1	~240 – 272,95
0,5	~256 – 272,95
1,0	~263 – 272,95
1,5	~266 – 272,95
2,0	~270 –272,95
2,5	not available

When the system is transferred from 1 region to 3 regions (Fig. 1.) And in the presence of ice in the hydrate as a result of the release of methane hydrate in the first stage, it goes into the chilled water stage, and the water directly crystallizes and turns into ice. If the water creates a dynamic layer between the hydrate and the ice, the separation rate decreases, the water layer softens and disappears, and thus a hydrate preservation step occurs.

It should be noted that the formation of chilled water looks visually (in the window of the hydrate pressure chamber, "darkening" of hydrate particles in transmitted light is observed). This visual representation of the decomposition process allows us to study the experimental line of the gas (methane, propane) - hydrate - chilled water band.

Similar studies were conducted for hydrates of other gases in order to determine the possible temperature range of the self-preservation effect. Propane, ethane, isopropane were also reported for another temperature range (Table 2). As can be seen from Table 2, the lower available cooling water frame for the obtained nitrogen hydrate is lower ~ 240 K from the theoretical point of view, in which case there is practically no cooling water. Therefore, the determination of the temperature range when depressurizing atmospheric pressure is an important element in the optimization and search for a method for preserving hydrate of various gases.

Thermodynamic analysis of the surface separation of the hydrate shows that its transition to the preservation method and process control are possible. The main parameter here is pressure. A decrease in pressure leads to the formation of cooling water in the upper hydrate layer. One of the leading parameters of the conservation effect is the temperature, the increase of which in the studies leads to the separation of the hydrate surface in the network of three-phase equilibrium lines "gas-hexogonal ice-hydrate" and "gas-cooled water-hydrate" in the appropriate sequence.

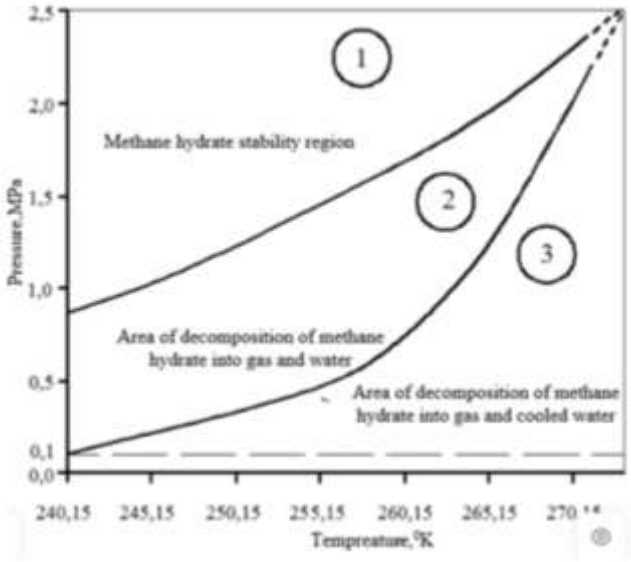


Figure 1: *As a result of methane hydrate pressure increase separation into gas-ice and gas-cooled water phases in different thermobaric.*

Table 2: *The presence of cooling water in the temperature range when the pressure drops to atmospheric pressure when separating various gas hydrates.*

Gas	Temprature, °K
Methane	~240 – 272,95*
Nitrogen	~223 – 271,85*
Ethane	~258 – 273,15*
CO2	~251 – 273,0*
C3H8	~270,5 – 273,15*
Iso-buthane	Not available

In the "Gas-chilled water-hydrate" network, the hydrate turns into chilled water. Under optimal conditions, it is important to crystallize this water. At low process power, water crystallization is accelerated, for example, recooling of the system or a combination of cooling with increasing pressure can be accelerated. The presence of ice in the hydrate allows it to control the separation process and enter the conservation stage, since ice leads to crystallization of chilled water.

Process paths can be selected for each gas hydrate. The hydrate sample is preheated in the pressure chamber of the hydrate oven. The temperature change of the chamber depends on pressure stabilization, which means that the hydrate separation process is completed. The process then continues at higher temperatures. At each temperature step, a separation process occurs whereby the pressure of the hydrated sample increases or becomes constant. When the pressure in the upper layer of the first hydrate sample increases, regeneration from the gas phase and water occurs. (composition of the new hydrate film is different). Thus, the separation process of the initial hydrate continues stably, and the pressure in the system is stabilized. From these tests it can be seen that a hydrate of one composition is converted to a hydrate of another composition by preservation. The process results in a hydrated hydrate preservation effect.

Depending on the conditions, the lower hydrate is released, a hydrate is formed from the gas dissolved in water, which prevents the partial release of the primary hydrate as a stable hydrate of a new composition. To control the effect of slowing hydrate separation, another method was discovered, which consists in coating one hydrate with another at positive temperatures under

thermobaric and stable thermodynamic conditions. It can be seen from the reports that one hydrate can be preserved with another hydrate and its pressure is below that of the other hydrate compound.

So, the composition of the gas mixture: 98% methane +2% propan; 95% methane +5% nitrogen; 70% isobutan + 30% nitrogen və 90% methane + 10% CO_2)

Analysis and thermodynamic reports show that the following conditions are possible for the effect of slow separation of gas hydrates:

- development of new methods of gas-hydrate balance study;
- hydrated gas storage and transportation technology;
- seasonality conditions of gas hydrates in metasabit conditions.
- Methodical approach to normalization of hydration inhibitors and their additional properties using volatile inhibitors.

All information on normalization of inhibitor consumption contains information on its process losses and other production needs. Production losses of inhibitor occurring during regeneration, storage, transportation are determined by the trial statistical method, other losses are determined by the reporting and analytical method.

To return the spent reagent to the process cycle, it is necessary to install a spent inhibitor regeneration unit, develop a recycling technology for the use of hydration inhibitors.

The methodical approach to normalizing the inhibitor is as follows.

The consumption of chemicals in the production of all gas production is determined in the form of group (H) as follows:

$$H = \frac{\sum H_i \cdot Q_i}{\sum Q_i},$$

here: H_i - individual consumption of chemicals per each device, kg/1000 m^3;

Q_i -any time (month, quarter, year) gas production for each facility,mln.m^3.

Chemical consumption H_i shows the specific flow rate for each device:

$$H_i = H_T - H_B + \sum g_i ,$$

here: H_T – inhibitor consumption rate in the process;

H_B – rate of specific consumption, chemical reagent returned by the cycle;

$\sum g_i$ – rate of final production losses.

The rate of inhibitor spent on the process for each device in the well is determined by the sum of inhibitor consumption in each individual process in accordance with the well plume.

The rate of inhibitor consumption in each individual area is determined by the following formula:

$$H_{T,i} = G \cdot K ,$$

here: G – specific consumption of the minimum important (theoretical) inhibitor;K – reserve ratio in the range of 1.05-1.25 for unaccounted factors;

K- coefficient of distribution by phase of components at non-isothermal and non-stationary flow of gas-liquid mixture is determined by tests.

Maximum initial field development cost is equal to 1,10÷1,25, When automating production processes, the inhibitor consumption is reduced to a factor of 1.05. The theoretical inhibitor flow rate for a single area of the process chain and the protected point aqueous phase flow rate are determined by the following formula: [13,14].

$$G = \frac{G_1 \cdot (X_2 - X_1) + G_1^{recycle} \cdot (X_2 - X_1^{recycle}) + (W_1 - W_2) \cdot X_2}{X - X_2} + \frac{100 - X_2}{X - X_2} \cdot [(Q_2 - Q_1) + (q_2 - q_1)]$$

$$G_2 = \frac{X}{X_2} + \frac{G_1 \cdot X_1 + G_1^{recycle} \cdot X_1^{recycle} + 100 \cdot [(Q_1 - Q_2) + (q_1 - q_2)]}{X_2}$$

G - specific consumption of the minimum important inhibitor, hardness *X*, kg/1000 m³;

G_1 - special quantity entering 1 point of liquid-water phase from previous inhibitor process area, kg/1000 m³;

$G_1^{recycle}$ - specific amount of inhibitor recycle aqueous solution to point 1, kg/1000 m³;

G_2 - specific amount of inhibitor recycle aqueous solution to point 2, kg/1000 m³;

X_1, X_2 – density of the inhibitor aqueous phase before point 1 and point 2, respectively,% mass;

X – inhibitor concentration per 1 point, % mass;

$X_1^{recycle}$ – concentration of treated inhibitor per 1 point, % mass;

W_1, W_2 – gas humidity at points 1 and 2 (balanced with liquid phase), kg/1000m³;

Q_1, Q_2 - amount of inhibitor in gas phase at points 1 and 2,kg/1000m³;

q_1, q_2 - amount of inhibitor in gas phase at points 1 and 2, kg/1000m³;

G_1, $G_1^{recycle}$, X_1, X_2, $X_1^{recycle}$, *X is assumed to be known values*,

G and G_2 and their values are found by calculation.

In practice, the theoretical inhibitor consumption is reported several times, that is, reports are kept at several technological points, and the prices obtained are summarized.

Here, the technique aims to facilitate the thermodynamic equation of the gas hydrate phase. Parameters were selected by formula based on test data. You can use the above-mentioned reporting methods to report hydration conditions.

In gas and gas condensate fields, the calculation of the concentration of hydration inhibitors at a given pressure and (K) at the protection point and the dependence between hydration temperatures on movement is determined as follows:

$$\Delta T = -A \cdot \ln \frac{(100 - X)/18}{(X/M + (100 - X)/18)},$$

A - empirical coefficient depending on gas pressure, its composition, structure of formed hydrates. This coefficient depends on the composition and pressure of the gas phase and is selected individually.

The humidity of complex natural gas can be calculated using the following formula:

$$W = a_1 \cdot W_0 = \gamma_1 \cdot x_1 \cdot W_0$$

here: γ_1 - water activity coefficient in water-methanol solution;

x_1 - molar part of water in water-methanol solution;

a_1 - water activity in water-methanol solution;

W_0 – humidity of natural gas in balance with clean water, kg/1000 m³.

An analysis of the methodological approach to the practical use of volatile and non-volatile inhibitors for the hydration inhibitors discussed above revealed a number of advantages. The advantages of a volatile inhibitor are its uneven distribution of methanol in phases depending on temperature and pressure. To protect against hydrates in gas treatment units used in low-temperature processes, methanol injection ensures hydrate-free operation of the unit. To calculate the rate of consumption of volatile hydration inhibitors, it is important to calculate the dependence of the inhibitor flow on the operation of the heating apparatus under thermobaric conditions and select the maximumfunction for calculating the inhibitor flow.

IV. Conclusıon

Thermodynamic models and software have been developed, the condensed water phase of hydrocarbon systems, including the metasabit phase, allows reporting of three- and two-phase equilibrium.

A method is proposed to correct the reported model of test data, thermodynamic extrapolation to improve the description of the three-phase gas-condensed water-hydrate balance.

Surface evolution of gas hydrates at negative temperatures of various gases thermodynamic analysis has been developed, methods for controlling the process of separating gas hydrates and preserving them have been proposed.

Developed on the basis of a trial analysis and a general base of methods for normalizing the flow rate of hydrate compound inhibitors and analyzing the main characteristics of its use for gas preparation technology.

Technological methods have been developed to reduce the specific consumption of methanol.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ADVANCED SEISMIC METHODS FOR RISK REDUCTION IN SUBSURFACE CHARACTERISATION OF COMPLEX GEOLOGICAL STRUCTURES

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Abstract

The Absheron archipelago, situated in the South Caspian Basin, is a geologically complex region with significant hydrocarbon potential. This study focuses on the geologically complex structures of the Absheron archipelago, employing 2D seismic exploration data to assess subsurface structures and reservoir distribution. The research involved stratigraphic correlation, tectonic fault mapping, and seismic attribute analysis. Structural interpretation identified multiple fault-controlled traps, influencing hydrocarbon migration and accumulation. Seismic attribute analysis, including Root Mean Square (RMS) amplitude, Chaos and Relative Acoustic Impedance, was conducted to identify potential reservoir zones. The integration of seismic attributes with well log data allowed for improved reservoir characterization, reducing exploration risks. High RMS values corresponded to sand-prone facies, while amplitude variations suggested lateral changes in fluid content and reservoir quality. These results enhance the understanding of hydrocarbon distribution in the Absheron Archipelago, providing valuable insights for future exploration efforts. The study demonstrates the effectiveness of advanced seismic methods in delineating potential hydrocarbon reservoirs in structurally complex geological settings.

Keywords: seismic attribute analysis, fault systems, seismic anomalies, geological assessment, reservoir characterization

I. Introduction

The Absheron Archipelago, located in the South Caspian Basin, is a structurally complex and hydrocarbon-rich region that plays a crucial role in Azerbaijan's petroleum system. Comprising a series of islands, submerged ridges, and faulted blocks, the archipelago has been a key target for seismic exploration and reservoir characterization. The geological complexity of the region is driven by active tectonics, sedimentary processes, and hydrocarbon migration, leading to the formation of various structural and stratigraphic traps [1,2].

Among the key structures in the region, the research area exhibit intricate fault systems and diverse lithological formations, influencing hydrocarbon accumulation. Traditional seismic imaging methods face challenges in accurately mapping these complex subsurface structures. To address these challenges, seismic attribute analysis provides valuable insights into reservoir characteristics by enhancing the interpretation of seismic reflections.

This study aims to assess the geological and seismic attributes of the complex structured areas of the Absheron archipelago using 2D seismic data. By integrating attribute analysis with well log data, the research seeks to improve reservoir characterization and reduce exploration risks. The

findings contribute to a better understanding of hydrocarbon distribution in the Absheron archipelago, offering a more refined approach to identifying prospective oil and gas reservoirs in structurally intricate settings.

II. Geological settings and methods

The Absheron Archipelago, located in the South Caspian Basin, is a structurally complex region with significant hydrocarbon potential. This archipelago consists of a chain of islands, submerged ridges, and faulted blocks that extend into the Caspian Sea, forming a critical part of Azerbaijan's petroleum system. Being target for seismic exploration and reservoir characterisation, the Absheron Archipelago is geologically evolving under the influence of tectonics, sedimentary processes, and hydrocarbon accumulation. The research area covers the Absheron Bank, Western Absheron, Darwin Bank oil and gas fields, as well as the Aghburun-Deniz, Mardakan-Deniz structures, and the Gala Bay shown in Fig. 1.

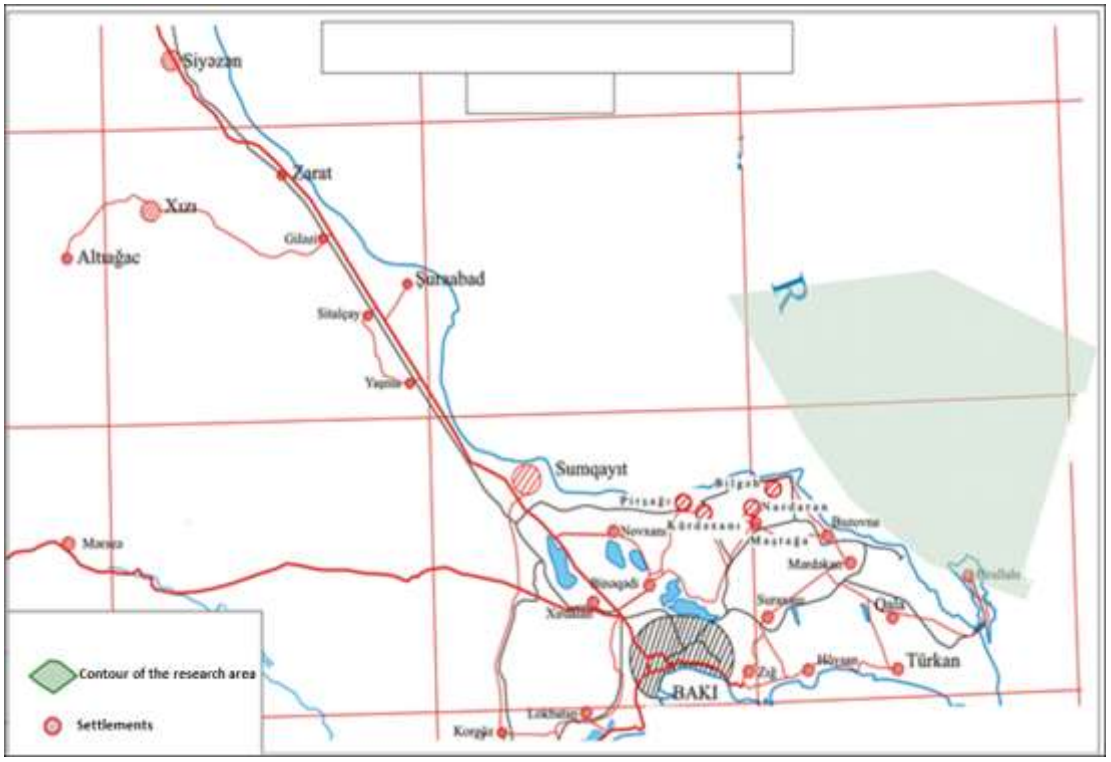


Figure 1. *Scale representation of the research area (1 cm = 5 km)*

The Mardakan-Deniz structure is an asymmetric anticline extending in a northwest-southeast direction and influenced by multiple fault systems. The structure's complexity arises from its steeply dipping limbs, numerous fault zones, and the presence of the Buzovna mud volcano, which plays a significant role in fluid migration. The anticline's southern limb has a dip angle ranging from 35° to 45°, while the northern limb is less steep, with an inclination between 12° and 22°.

Stratigraphically, the area consists of Middle Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary deposits. These formations include alternating layers of sandstones, siltstones, clays, and carbonates. The presence of discontinuous shale layers influences the migration and accumulation of hydrocarbons by acting as seals. The tectonic activity in the region has significantly impacted the structural configuration, forming multiple hydrocarbon traps and

affecting reservoir connectivity [3].

A critical aspect of the region's geological setting is the presence of faulted stratigraphic traps, particularly along the southern limb of the anticline [4,5]. These faults create compartmentalized reservoir zones, necessitating precise seismic imaging to map hydrocarbon-bearing formations accurately. Additionally, tectonic activity has resulted in tilted fault blocks that serve as potential hydrocarbon reservoirs [3].

The sedimentological characteristics of the region indicate a complex depositional history, with transgressive and regressive cycles affecting reservoir quality. The lower sections of the stratigraphic sequence contain poorly sorted sands, whereas the upper sections exhibit well-sorted, high-porosity sands that are ideal for hydrocarbon accumulation.

The region's tectonic evolution is characterized by a series of longitudinal and transverse fault systems that segment the anticline into smaller tectonic blocks. The main fault line trends northwest-southeast, forming a series of structural highs and lows that influence hydrocarbon entrapment.

Seismic interpretation of the research area reveals distinct seismic reflectors that indicate multiple depositional environments. The seismic reflections show sharp contrasts between high-density carbonate layers and low-density siliciclastic sediments. The presence of chaotic seismic signatures in some areas suggests zones of intense deformation, likely associated with fault activity. A significant feature observed in the study area is the angular unconformity between the Neogene and Paleogene formations, which serves as an important exploration target [6]. This unconformity marks a depositional hiatus and is associated with truncated reservoirs where hydrocarbons can accumulate.

The relief of the seabed is uneven throughout the area. As a result of underwater surveys, , and studies of seabed rocks, it has been found that the relief of the sea in the area is erosive in nature. Similarly, the coastline depends on the tectonics and lithofacies composition of the sediments that lie above and reach the seabed.

The complicated geology of the Absheron archipelago, including faults, folds, and varied rock types, has made it difficult for conventional seismic tools to image the subsurface clearly. This issue is resolved by seismic characteristics such as acoustic impedance, spectrum decomposition, coherence, and RMS amplitude. For instance, by identifying significant reflections, RMS amplitude identifies regions that may contain hydrocarbon deposits. Understanding the movement of fluids beneath requires the ability to detect faults and fractures. The detection of thin rock strata that might contain hydrocarbons is improved by spectral decomposition. Separating different types of rock and identifying potential oil and gas-containing zones are made easier by acoustic impedance.

By combining these seismic attributes with well data and geological models, one can get a clearer picture of the underground structures [7]. This reduces the risk of drilling dry wells and improves the chances of finding productive reservoirs. In the Absheron Archipelago, using seismic attributes makes oil and gas exploration more efficient and reliable.

III. Results

The geological assessment of 2D seismic exploration data from the Absheron archipelago was conducted using "IHS Kingdom Suite" and "Petrel" software packages. The study involved stratigraphic correlation of seismic horizons in time and depth sections, mapping tectonic faults, and performing attribute analysis. The area's tectonic features were considered, and seismic reflections were correlated using a disjunctive interpretation model, linking multiple closed-contour time and dynamic depth sections. Geological evaluation incorporated well log data from

nearby wells, previous seismic survey results, and dynamic wave characteristics. The structure's crest and flanks were found to be affected by complex tectonic faults, complicating correlation efforts. Numerous longitudinal, transverse, and radial tectonic fault planes of varying amplitudes were identified, with faults being more prominent in the crest and flank areas.

To predict the distribution of reservoirs, attribute analysis was performed on 2D seismic data. The physical basis of attribute analysis is related to seismic wave dynamic parameters, including amplitude, frequency, and phase, as well as the lithological characteristics of rocks [7]. The reservoir properties of rocks depend on sediment genesis and subsequent geodynamic conditions. As the acoustic impedance contrast between layers increases, the amplitude of reflected waves rises, while wave frequency is influenced by layer thickness and lithology. Various seismic attributes such as amplitude and frequency were calculated and compared with well and core data to characterize the overall geological environment. To identify high-quality reservoir zones, attributes like RMS, Chaos and Relative Acoustic Impedance were analyzed alongside well test data and geophysical logging. The seismic data covered a time interval of 0–4500 ms, and the RMS attribute variations across the study area were presented. High RMS values correspond to sand-rich facies, while low values indicate clay-rich facies, revealing sand/clay ratio variations in the attribute cross-section. The research area is systematically divided into two distinct seismic profiles, designated as Profile 1 and Profile 2. The time section of the Profile 1, extending from Qala Bay to the Absheron structure, reveals significant amplitude variations that correlate with lithological changes in the subsurface and shows local objects within the Qirmaky (QD) and Lower Qirmaky (QA) deposits. The RMS attribute analysis highlights high-amplitude anomalies in the lower sections of the QD horizon and QA sediments, particularly near the Qala Bay shown in Fig.2.

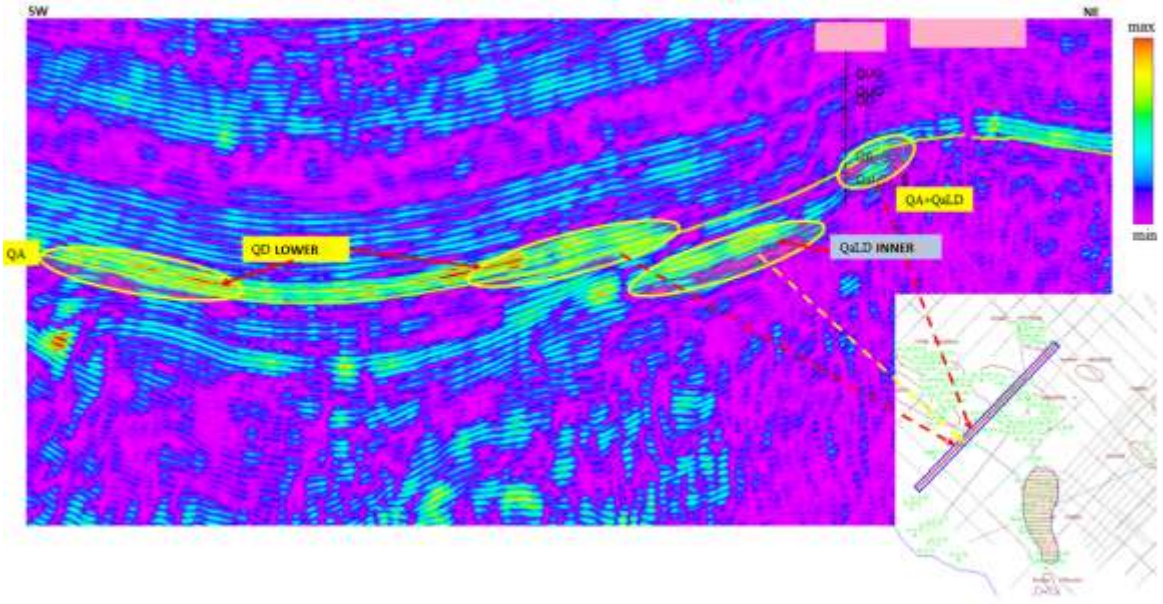


Figure 2: *RMS Amplitude Map of Profile 1*

These high amplitudes are indicative of sand-prone facies, which are potential hydrocarbon reservoirs. The analysis also suggests the presence of localized depositional features, such as channelized sand bodies or stratigraphic traps, that may contribute to hydrocarbon accumulation. Additionally, seismic attribute mapping along this profile shows lateral changes in amplitude strength, potentially indicating variations in reservoir quality and fluid content.

Running parallel to Profile 1 but slightly offset, Profile 2 provides additional confirmation of

the seismic anomalies observed in the previous section. This profile further delineates local high-amplitude objects in the lower sections of the QD horizon and Miocene sediments. The amplitude distribution suggests possible hydrocarbon-bearing zones with a distinct separation between sandy and clay-rich facies. Moreover, the profile highlights potential reservoir compartmentalization, where variations in seismic response may correspond to structural or stratigraphic barriers. The attribute analysis along this section provides critical insights into the lateral extent of reservoir-quality sediments, reinforcing the interpretation of hydrocarbon potential in the area shown in Fig. 3.

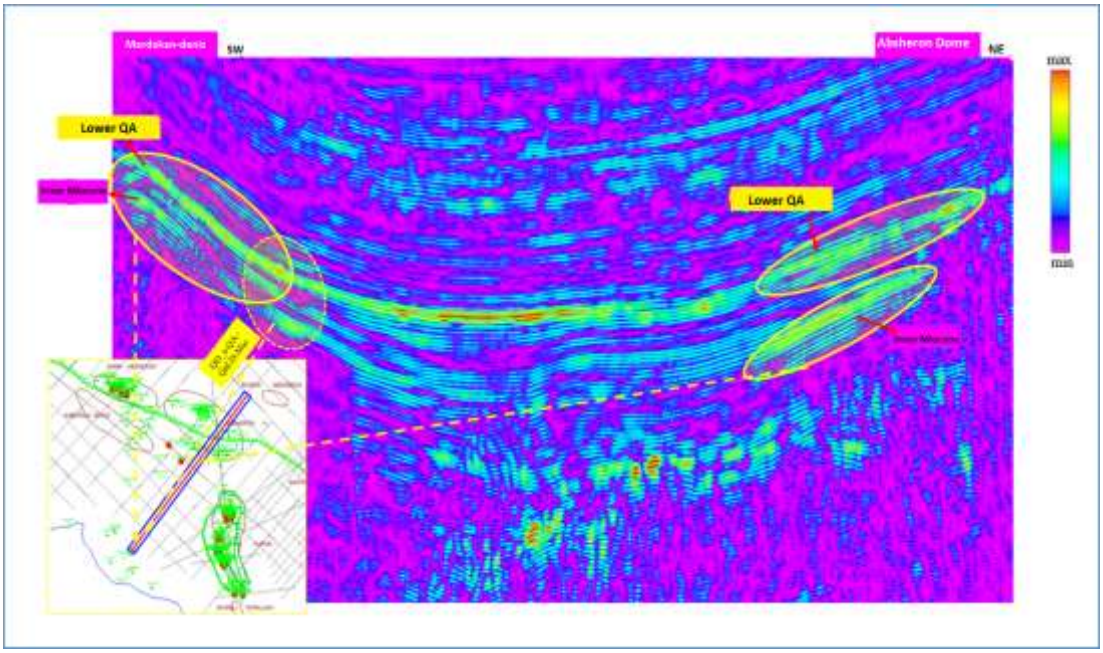


Figure 3: *RMS Amplitude Map of Profile 2*

Using the Relative Acoustic Impedance (RAI) attribute, it is possible to observe the acoustic contrast reflected at layer boundaries in time sections, the sequence of layer deposition, unconformity surfaces, and fault structures shown in Fig.4.

Based on the Relative Acoustic Impedance attribute calculated for the time section of the research area, which intersects the Darwin Bank structure in a southwest-northeast direction, the erosion surface within the Miocene sediments can be identified.

The Chaos attribute is applied as a stratigraphic attribute and provides precise information about wave pattern characteristics, including fracturing, disjunctive dislocations, channels, anomalies, gas migration pathways and so on. As observed in the Chaos attribute calculated for the time section of Profile 1, a complex seismic data zone associated with faults is clearly traceable in the crest area of the studied area, shown in Fig. 5.

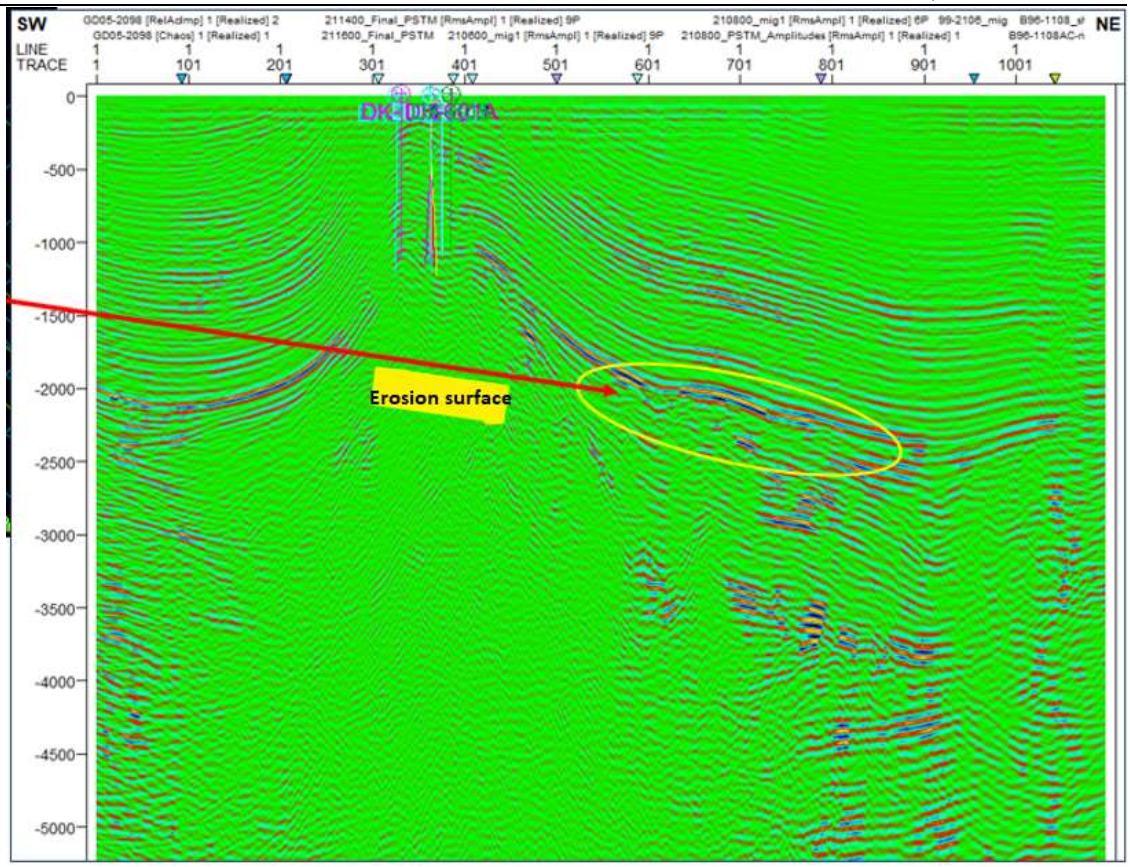


Figure 4: *Relative Acoustic Impedance Map of the Research Area*

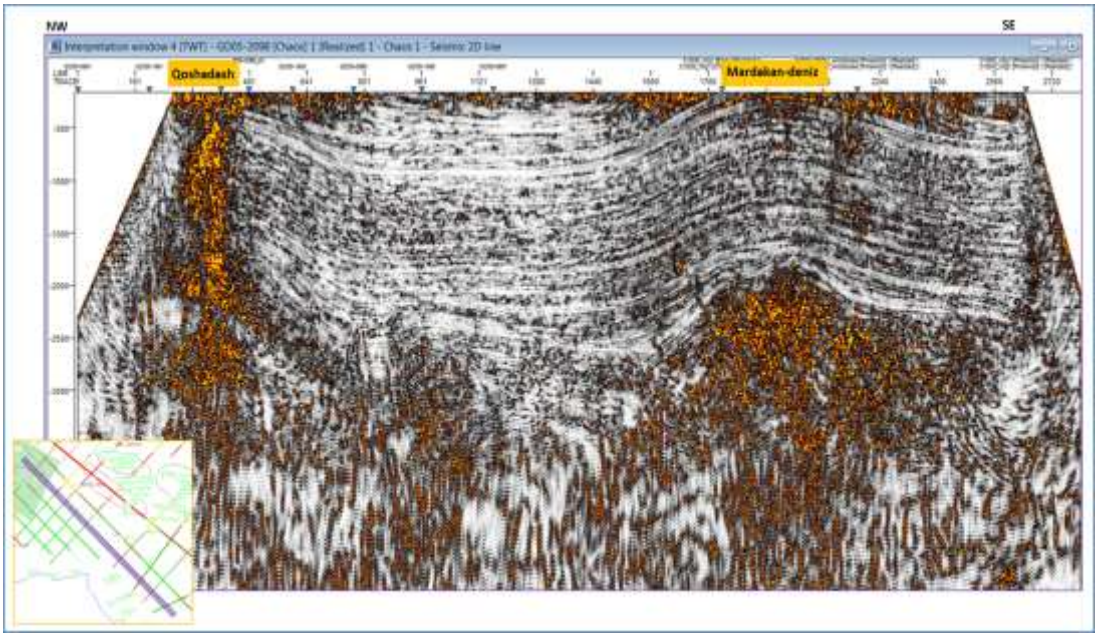


Figure 5: *Chaos attribute Map of the Profile 1.*

IV. Conclusion

- The integration of seismic attributes, such as Relative Acoustic Impedance, Chaos and RMS Amplitude has enhanced subsurface imaging. RMS amplitude variations indicate sand-rich facies suitable for hydrocarbon accumulation, while Chaos attributes effectively delineate faulted zones and potential fluid migration pathways.

- Structural maps created from 2D seismic data have provided detailed insights into depth variations and tectonic faults. High-amplitude anomalies in the QD and QA horizons indicate potential hydrocarbon-bearing zones, highlighting reservoir compartmentalization.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ASSESSMENT OF KUTAISI CITY ATMOSPHERIC AIR POLLUTION WITH THE HIGH RISK-FACTOR PM2.5 PARTICLE BY MEANS OF NUMERICAL MODELING

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Abstract

The spatial distribution and temporal variation of highly dangerous PM2.5 particles in the atmosphere of Kutaisi, one of Georgia's most important tourist and recreational centres, has been studied using numerical modelling. This modelling was achieved through the combined integration of 3D non-steady nonlinear equations of mesoscale atmospheric processes and equations of air contaminant transfer and diffusion. The distribution of PM2.5 emitted by motor vehicles into the air in Kutaisi in winter during a gentle background breeze has been modelled and analyzed numerically. Graphs showing the time-dependent changes in PM2.5 concentration at different points in the city were plotted based on the calculated results. It was shown that, at a height of 2 m above the ground, the time change in the concentration of pollutants in the morning, evening and night hours is mainly determined by motor traffic intensity, while during the day it is mainly determined by local thermal and dynamic processes. The characteristics of the spatial distribution of PM2.5 particles in the surface and boundary layers of the atmosphere have been obtained. The expected times and areas of high pollution have been identified. It has been demonstrated that pollution primarily occurs in the central part of the city and around highways passing through adjacent territories. Aerosol propagation in the upper part of the surface layer and in the boundary layer of the atmosphere mainly occurs in the direction of the background wind, with less dependence on local relief and the location of emission zones.

Keywords: PM2.5, atmospheric pollution, numerical modeling, concentration, gentle breeze

I. Introduction

Aerosol pollution of the atmospheric air is a phenomenon of high risk-factor for human health [1-6]. It is dangerous not only for population of heavily polluted industrial centers, but also for relatively clean separate regions and cities of Europe and Asia [4-6]. Microparticles PM2.5 and PM10 have especially negative effect on human health. They are absorbed through aspiration ways and frequently cause oncological, cardiovascular and other diseases. Investigations showed that in 2021 the global life shortening caused by air pollution comprised 1 year, while in some countries of Africa and Asia reached 1.2-1.9 years [4-5]. The problem of PM pollution of the atmosphere has been thoroughly examined in the fundamental work [8].

Air-protection measures carried-out in the XXI century by developed countries of the world have led to reduction of microparticle emission into atmosphere and improvement of air purity degree. Nevertheless, air pollution level in a wide range of cities still exceeds international standards [9-12]. In the cities with developed environmental pollution monitoring services, the

atmospheric air purity degree is assessed through analysis of operating supervision data [4, 6, 7]. In such places, where observation data are incomplete or insufficient, namely computer modeling of polluting agents propagation is one of the ways of environmental pollution level assessment [12-16].

Kutaisi is the second largest city of Georgia. It has very important administrative, international, medical and health-promoting, and touristic destination, due to which hundreds of thousand humans visit it every year. Based on the city function, study and assessment of environmental state, diagnostic forecast of pollution level and maintenance of high level of air purity are of special importance. PM2.5 and PM10 monitoring in the city has been started since 2018 and is implemented in 2 fixed surveillance points. According to obtained data, Kutaisi is not ranked among heavily polluted cities [11], though in some cases PM2.5 concentration in the air exceeds maximum permissible concentrations [10, 17]. At the same time, it should be noted that a monitoring carried out in two observation points is not enough to completely reflect the complete picture with urban air purity in terms of PM2.5. That is why, in order to overcome the above-mentioned problems, the propagation pattern and time behavior of PM2.5 generated by motor transport and emitted into atmosphere of Kutaisi and adjacent territories has been simulated and analyzed in the presented article using computer modeling of atmospheric propagation of admixtures.

II. Research method

An equation describing atmospheric transfer and diffusion processes of admixtures in the area of complex orography may be written as follows [18]

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+(\tilde{w}-\frac{w_0}{h})\frac{\partial C}{\partial \zeta}=\frac{\partial}{\partial x}\mu\frac{\partial C}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial C}{\partial y}+\frac{1}{h^2}\frac{\partial}{\partial \zeta}\nu\frac{\partial C}{\partial \zeta}+F \quad (1)$$

here t is time, x, y and z – coordinates along parallel, meridian and directed upward vertically, $\zeta = (z-\delta)/h$ – dimensionless vertical coordinate, $\delta(x,y)$ – terrain height over sea level; $h = H - \delta$ – tropopause thickness, $H(t,x,y)$ – tropopause height; C – ingredients' concentration; u, v, w and $\tilde{w}$ – wind velocity components along x, y, z ღა ζ axes; w_o – precipitation rate of polluting ingredients; $F(t,x,y,\zeta)$ – rate of ingredients atmospheric emission by the source; μ and ν – coefficients of horizontal and vertical turbulence. Wind velocity components, coefficients of turbulence in free atmosphere, surface and boundary layers of the atmosphere are calculated by means of equations and formulas given in [8, 9].

PM2.5 aerosol propagation has been numerically modeled at the 13.4×13.4×9 km^3 space domain (Fig. 1), with Kutaisi in its center. Orography height in the modeling area varies from 80 to 400 m. Numerical integration of equations of the mathematical model given in [19, 20, 21] has been made using relevant initial and boundary conditions. Numerical grid steps in horizontal direction equal to 200 m, and in vertical direction in free atmosphere – 300 m. Vertical steps in 100 m thick surface layer of the atmosphere vary from 0.3 m to 15m. Time step is 1 sec. Calculation have been made for 3-day period.

III. Numerical modeling results

PM pollution of Kutaisi atmosphere in December has been modeled. There is a gentle breeze at 100 m height of surface layer of the atmosphere – wind velocity is 6 m/s. Above surface layer of the atmosphere there is a western wind, which velocity linearly increases with height and reaches 20 m/s at 9 km altitude. Relative atmospheric humidity is 50%. It is assumed that PM2.5 pollution of the atmosphere is caused by motor transport traffic in the city and its adjacent territories. Aerosol is emitted from the earth surface to 0.3 m height in 5 types of areas: at the territories of

highways, central city streets, residential, industrial zones, adjacent villages and unpopulated territories. Emission rate is different depending on areas, periodical with 24-hour periodicity and proportional to motor transport traffic intensity. It is minimal in the interval of 0-4 h, afterwards linearly increases from 4 to 10 h, and is constant in time interval from 10 to 18 h. Within time period from 18 to 24 h emission rate linearly decreases and by 0 h becomes equal to existing emission rate. Maximum emission rate is 12.5 μg/s.

In Fig. 1 there are shown the graphs of time change of PM2.5 concentration obtained via calculations for points with 5 basic types of pollution. It is seen from Fig. 1 that time change of concentration is qualitatively similar for points with all type of pollution and is characterized by 2 intervals of large values and 2 ones of small values. Large concentration values are obtained at 10 h and within time interval from 16 to 19 h, while small ones – in the intervals from 2 to 4 h and from 12 to 15 h.

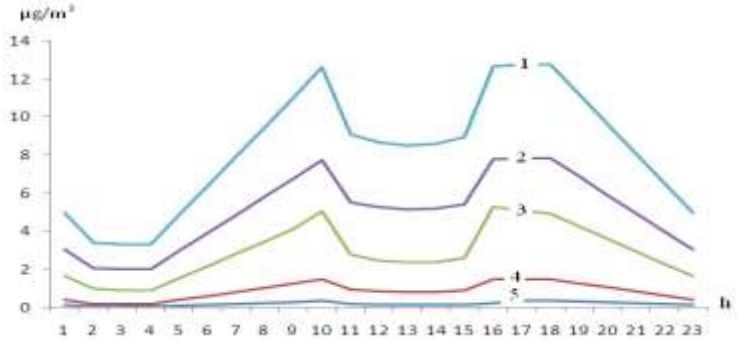


Figure 1: *Time change of PM2.5 concentration obtained via calculations at the territories of highway (1), city central streets (2), industrial (3), rural (4) zones and unpopulated points (5) at the 2m height from earth surface*

It should be noted that time change of concentrations in case of identical meteorological and pollution conditions, partially differ in quantity and quality terms from each other in winter and summer seasons [20,21]. While in summer season, the second concentration maximum is obtained around 20 h and further starts to reduce, in winter season the second concentration maximum is obtained by 16 h and is preserved for 3 hours. From 11 to 17 h an aerosol emission rate is constant. Despite this fact, a paraboloidal reduction of concentration in time takes place in points of all types, during which a minimal concentration value is obtained within 12-15 h interval of time. Physically, the mentioned change is associated with thermal interaction of underlying surface and air masses located nearby, during which a change of atmosphere stratification and air turbulization pattern occurs [21].

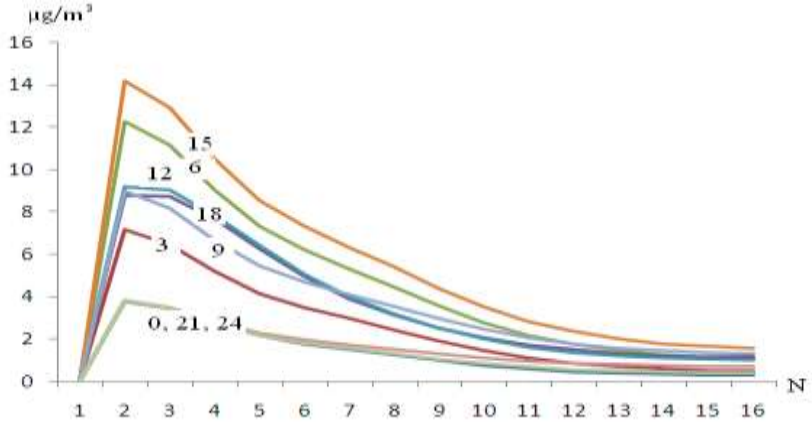


Figure 2: *Vertical distribution of PM2.5 concentration in the point located at highway in surface layer of the atmosphere, when t = 3, 6, …, 24 h (N is vertical numerical grid number*)

In Fig. 2-4 there are shown PM2.5 concentration values obtained via calculation in surface layer of the atmosphere in vertical grid points located at highway, industrial and rural territories. It is seen from Fig. 2-4 that vertical distribution of concentration in the mentioned points substantially differs from each other. There is both qualitative and quantitative difference. At different points of time, maximum concentration values in points located at highway are within limits of 4-14 μg/m^3 and they are obtained in N = 2 point (0,3 m) of the vertical grid located in the close proximity to underlying surface. With a distance from earth surface the concentration decreases. This reduction is intense in the lower 10 m thick layer (N = 5). Above 10 m, concentration reduces more smoothly, at slow rate and at 100 m height (N = 16) its values don't exceed 2 μg/m^3.

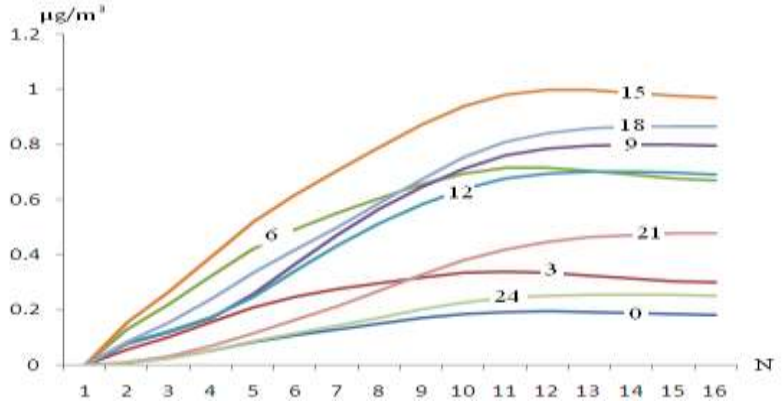


Figure 3: *Vertical distribution of PM2.5 concentration in the point located at the territory of agricultural purpose in surface layer of the atmosphere, when t = 3, 6, …, 24 h (N is vertical numerical grid number)*

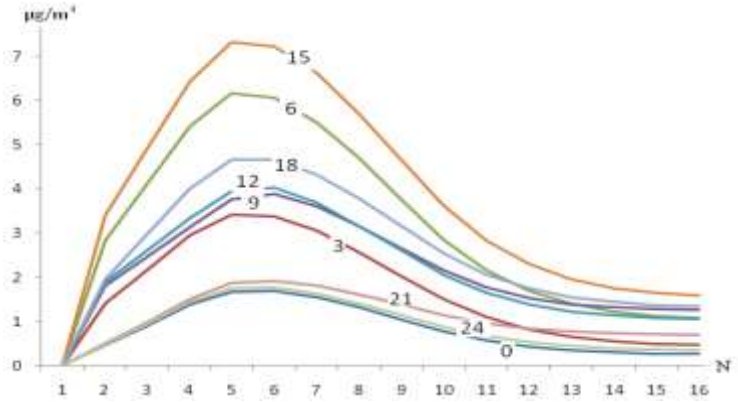


Figure 4: *Vertical distribution of PM2.5 concentration in the point located at the territory of industrial purpose in surface layer of the atmosphere, when t = 3, 6, …, 24 h (N is vertical numerical grid number)*

There is an opposite vertical distribution of concentration in the points of agricultural purpose (Fig. 3). It is minimal in a close proximity to underlying surface (0-0,1 μg/m^3), increases with height and at 12, 18 and 21 h varies within limits of 0,2-1 μg/m^3 at 60 m height (N = 12). The mentioned growth of concentration is caused by ensuing horizontal diffusion of aerosol transferred upward vertically from severe pollution source.

The graph of vertical distribution of concentration in different points of time over the point located in industrial area is highly interesting (Fig. 4). It is similar to graph of Gaussian Distribution formula and is characterized by rapid growth of concentration in the lower part of surface layer

up to 15 m height (N = 6). At this level its value reaches 7,5 μg/m³. Above 15 m concentration is reduced at relatively slow pace and at 100 m height concentration values drop to 0,3-1,5 μg/m³.

Fig. 5-7 show the fields of wind velocity and PM2.5 particles during a day with 3-hour intervals at 2, 100 and 600 m heights from earth surface. As is seen from these Figures, the effect of Kutaisi terrain on background flow doesn't cause noticeable change of local wind. There is a western wind in boundary layer of the atmosphere and its value in the surface layers varies within limits of 2-13 m/s. As for spatial distribution of concentration, it is qualitatively similar when h = 0 and 3 h at 2 m height from earth surface, and the quantitative difference between them is negligible (Fig. 5). Concentration values at highways and urbanized territories of the city don't exceed 5 μg/m³, while PM2.5 concentration at rural areas and unpopulated territories is less than 1 μg/m³. Pollution level increases with rise of motor transport traffic intensity. By t = 6 h, PM2.5 concentration at separate territories of Gamarjveba, Ukimerioni, City-Museum and Kakhianouri administrative units reaches 10 μg/m³. Concentration growth up to 5 μg/m³ is obtained in the surrounding of highways and central avenues. When t = 0 and 6 h (at night) concentration values at 100 m height reach 0,7 and 1 μg/m³, respectively, while at 3 h – 0,5 μg/m³ (Fig. 5). As for higher levels (600 m), concentration values are within several hundredth of μg/m³. Pattern of surface distribution of concentration shows that there is an intense carry-over of ingredients to the east, in direction of background wind.

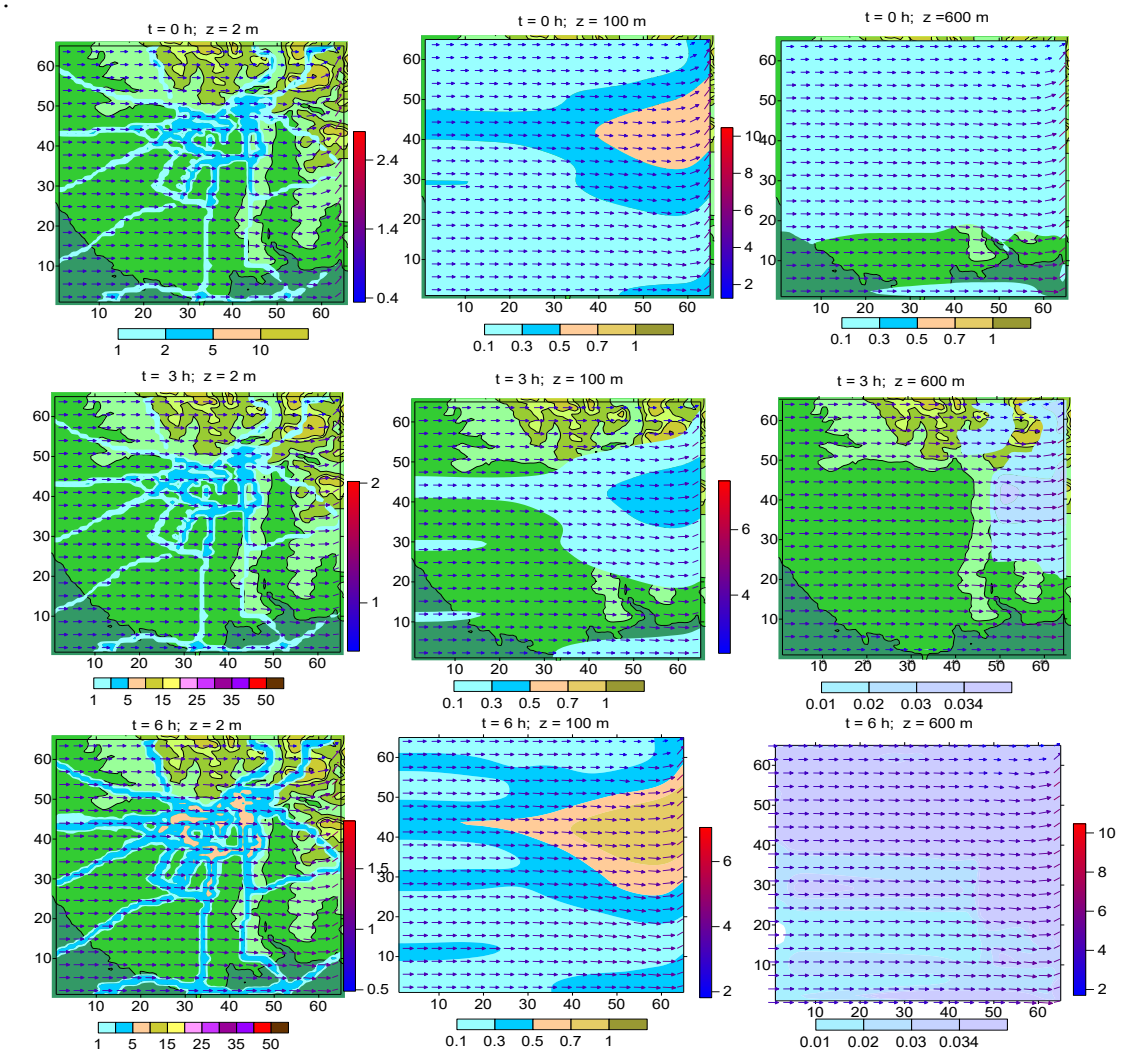


Figure 5: *Distribution of PM2.5 concentration ($\mu g/m^3$) and wind velocity (m/s) fields at 2, 100 and 600 m heights from earth surface, when t = 0, 3 and 6 h*

It is seen from Fig. 6 and 7 that in time interval from 9 to 18 h, concentration values at 2 m height from earth surface at urbanized territories of the city and in the vicinity of highways are mainly within 5-15 μ g/m³. When t = 9 and 18 h, concentration is high at some places of heavy motor traffic of Gamarjveba, City-Museum, Kakhianouri and Ukimetrioni administrative units. Maximal values at these territories reach 10-15 μg/m³.

From 9 to 15 h and then, within interval from 15 to 18 h, microaerosol content in the ground air reduces first, and afterwards increases and reach maximum – 15 μg/m³. After 19h, concentration starts to reduce. By t = 24 h, the pattern of its spatial distribution at 2 m height from earth surface is similar to that obtained for t = 0-3 h (Fig. 7). At higher levels, there is a definite qualitative and quantitative difference. At 100 m height, concentration increases after 18 h and by 21 h reaches maximal value – 1,3 μg/m³. After t = 21h, concentration reduces little by little. As for 600 m height, concentration values at this level are within 0,1-0,3 μg/m³, and decrease at slow pace with the passage of time

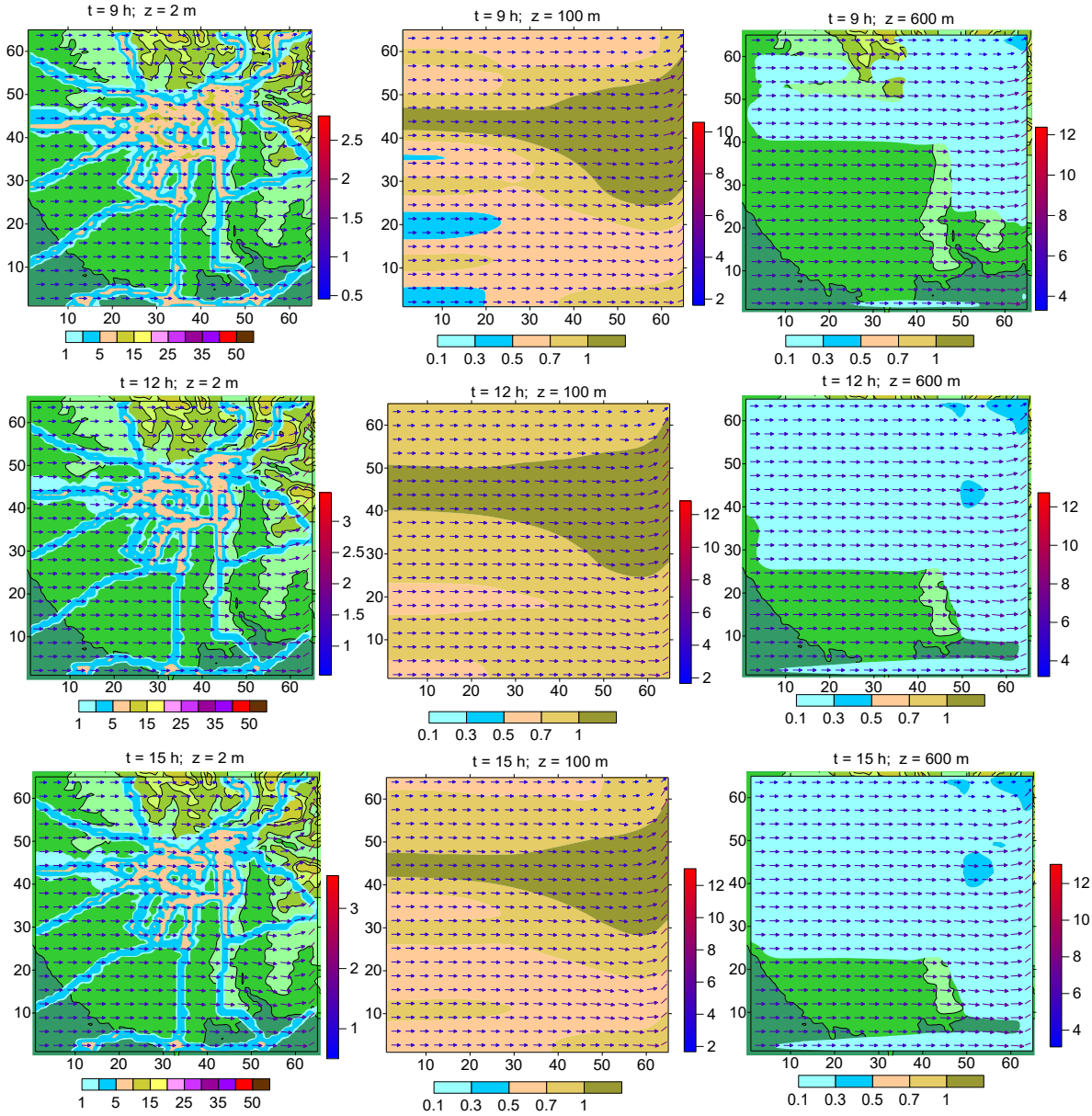


Figure 6: *Distribution of PM2.5 concentration ($\mu g/m^3$) and wind velocity (m/s) fields at 2, 100 and 600 m heights from earth surface, when t = 9, 12 and 15 h*

In Fig. 8 there is shown vertical distribution of PM2.5 concentration in surface layer of the atmosphere obtained via modeling in zonal section passing through the central part of the city. It is seen from Fig. 8 that PM2.5 propagation in atmospheric air occurs as a result of both turbulent diffusion and advection and convection processes. These processes form thermals in 10-20 thick

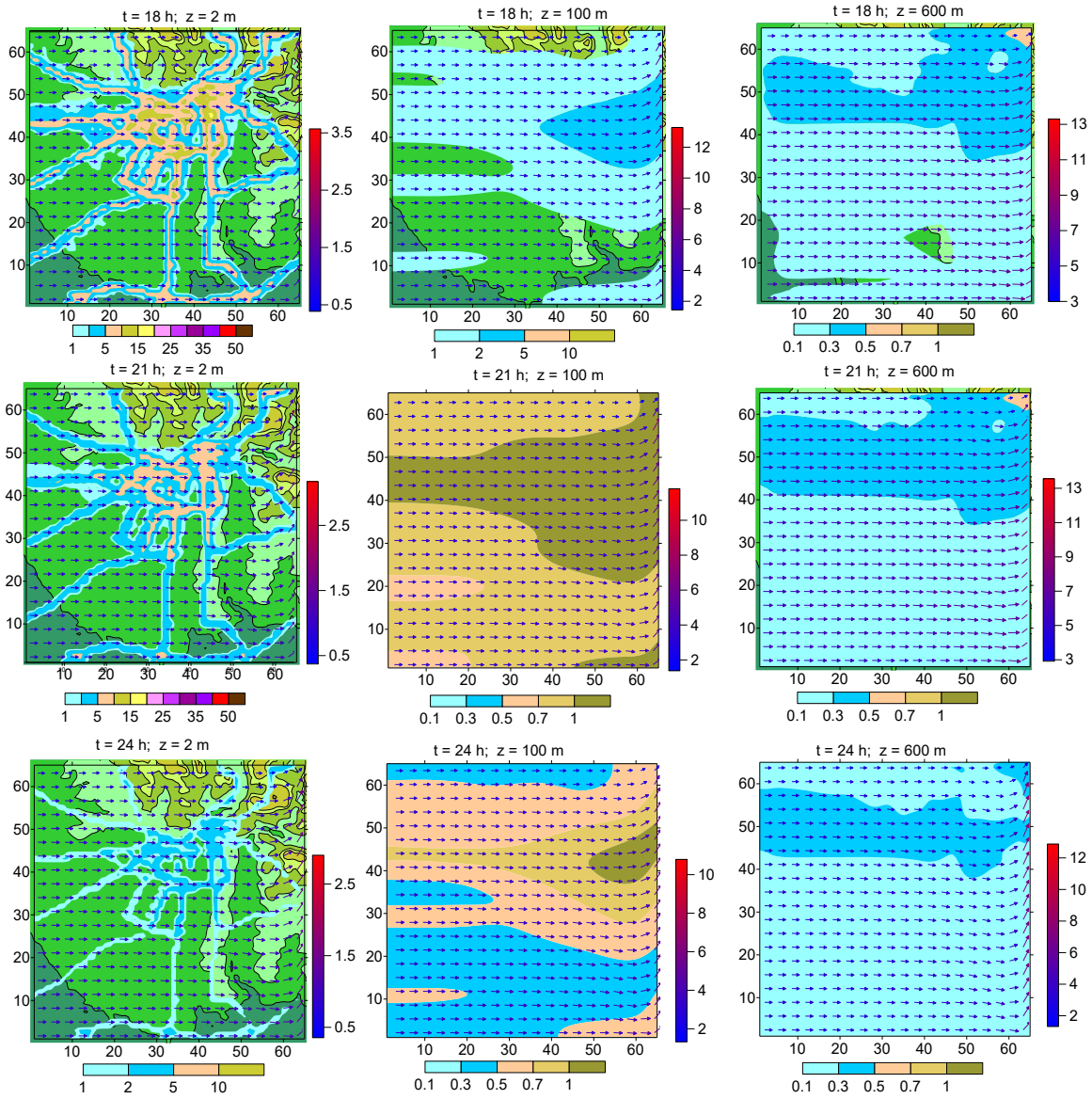


Figure 7: *Distribution of PM2.5 concentration ($\mu g/m^3$) and wind velocity (m/s) fields at 2, 100 and 600 m heights from earth surface, when t = 18, 21 and 24 h*

surface layer of the atmosphere, which are caught taken up to the upper part of surface layer of the atmosphere by background flows of eastern direction.

IV. Discussion

Kutaisi atmosphere pollution with PM2.5 – one of the most dangerous substances with high risk-factor has been studied in the work. Microparticles emitted into atmosphere by the motor transport represent pollution source when conducting numerical modeling. As far as there are no large industrial enterprises in the city, the mentioned assumption is quite acceptable in a first approximation. In future studies it would be reasonable to take into account background values of PM2.5 concentration in the city and its adjacent territories, emission of small-size enterprises operating in the city and pollution caused by household activity. Improvement of modeling by means of reduction of the horizontal grid steps is scheduled also.

V. Conclusions

Peculiarities of spatial distribution and time change of PM2.5 generated by motor transport at the territory of Kutaisi in winter season during western medium-powered background wind have been investigated via numerical modeling. It has been shown that the relief of Kutaisi and adjacent territories causes no changes in wind direction. Patterns of spatial distribution of PM2.5 concentration have been obtained as a result of modeling. Nature of time change of concentrations

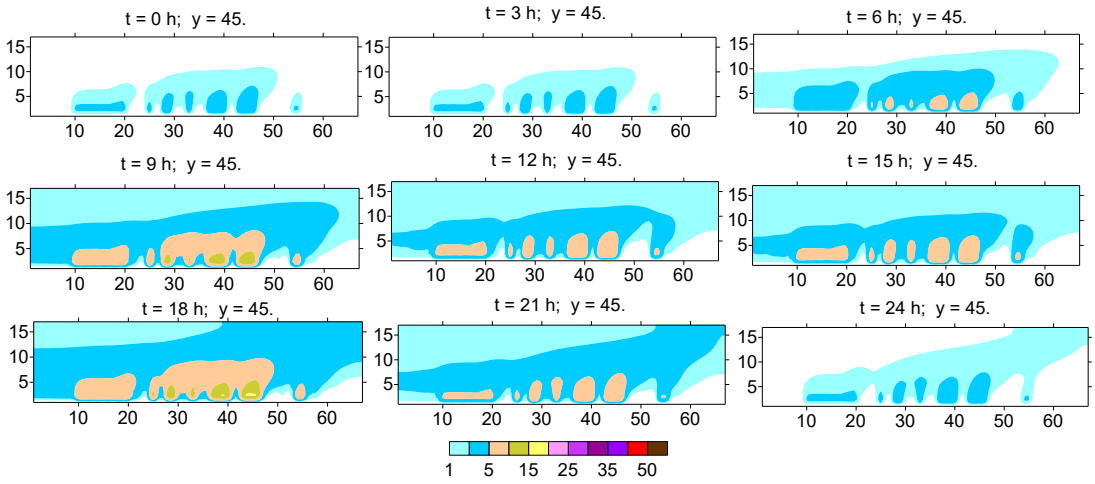


Figure 8: *PM2.5 ($\mu g/m^3$) distribution in surface layer of the atmosphere in vertical cross-section along the parallel passing through the city center*

both in surface and boundary layers of the atmosphere has been established. It has been shown that during medium-powered background wind, the processes of diffuse and advective transfer promote admixtures' displacement from modeling area and atmosphere self-purification process. As a result, there is no formation of especially heavily polluted areas. City atmosphere is mainly polluted in the central urbanized parts of the city, where maximal concentration values don't exceed 15 $\mu g/m^3$. Peculiarities of diurnal variation of vertical distribution and concentration of PM2.5 emitted into atmosphere at the territories of city highways, industrial and agricultural areas have been investigated.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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IMPACT OF ENERGY PRICES ON ABSOLUTE POVERTY IN MOLDOVA

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Abstract

Moldova is a country that imports energy. The energy crisis and repeated increases in end-user tariffs have impacted the population's well-being. This topic is relevant because it examines the vital role of energy security in ensuring citizens' economic well-being. This study aims to evaluate the impact of rising energy prices on absolute poverty in Moldova. Energy prices are one of the main factors affecting household expenditure, particularly for vulnerable groups who spend most of their income on meeting basic needs. The study focuses particularly on the relationship between energy prices and poverty, demonstrating how price fluctuations can exacerbate socio-economic inequality. To achieve this, econometric methods such as ordinary least squares (OLS) and two-stage least squares (2SLS) were employed while addressing issues such as multicollinearity and endogeneity. The results show that rising energy prices reduce disposable income by increasing expenditure on essential goods and services, thereby increasing the financial burden on households. Logically, an increase in absolute poverty will not only decrease the well-being of the population, but also undermine economic stability. Understanding these patterns is crucial for policymakers developing strategies to reduce poverty and ensure inclusive growth. This study proves that, in order to achieve energy security and social equality in Moldova, strategies must be promoted to ensure the availability of energy resources and increase households' resilience to economic shocks.

Keywords: energy prices, poverty, energy security, socio-economic analysis, economic well-being

I. Introduction

The relationship between energy prices and economic well-being is an increasingly popular topic in global and regional research, especially in fragile economies such as Moldova. Energy prices affect household budgets, the cost of the consumer basket, and the standard of living. In Moldova, where a significant portion of the population lives below the poverty line, fluctuations in energy prices have a substantial effect on the poverty level, and citizens who previously had a decent life now find themselves below the poverty line. In Moldova, there is even a phenomenon known as in-work poverty.

Absolute poverty is defined as the inability to meet basic needs such as food, housing, and clothing. This indicator, along with the relative poverty indicator, is used to assess the well-being of the population. Over the past ten years, fluctuations in the poverty rate have been due to economic shocks (energy crisis, COVID-19, climate cataclysms) and policy measures. Geopolitical crises have also had a negative impact on the economy and the well-being of the population, increasing the number of poor people [1]. The rise in energy prices during this period has aggravated the financial burden of households, reduced disposable income, and increased the cost of basic goods and services. As a result, the poverty rate has increased significantly: in 2015, every fourth citizen was poor, and in 2024, every third citizen became poor [2].

Energy security is, on the one hand, an integral part of economic security, and on the other hand, it ensures economic stability. At the same time, Moldova is a candidate country for joining

the European Union. The economy of Moldova is integrating into the EU economy, and the volatility of energy prices in Europe is very high. The high dependence of the Moldovan economy on energy imports makes it particularly sensitive to global price shocks. Unlike its neighboring countries, Moldova has limited domestic energy production and a low level of diversification of energy sources. This circumstance aggravates the impact of energy price volatility on the economy of Moldova [3]. Global experience in combating energy poverty shows that one of the solutions is the development of green energy [4], and this requires subsidies and investments in renewable energy sources [5].

There are few studies on the relationship between changes in energy prices and poverty, and most of these few studies examine the impact of energy poverty, not absolute poverty. The countries for which such studies have been conducted are the European Union [6], the United States [7], and Asian countries [8]. There are no such studies for Moldova. The only work on a related topic studies the relationship between green energy and human development [9]. This proves the novelty of the study in this article. The purpose of the study is to examine the impact of rising energy prices on absolute poverty in Moldova.

II. Materials and methods

This study examines the relationship between the Producer Price Index for electricity, gas, steam, and air conditioning supply (PPIES) and the absolute poverty rate in Moldova. In order to profoundly investigate the socio-economic factors affecting poverty, in addition to the price index, the study covers additional variables such as foreign direct investment (FDI), unemployment rate (UR), and personal remittances (PR). To obtain reliable conclusions about the dynamics of the relationship between PPIES and poverty, econometric methods were used, including ordinary least squares (OLS) and two-stage ordinary least squares (2SLS). To examine the impact of energy prices on the absolute poverty rate in the Republic of Moldova, we first use standard OLS regressing *PPIES* on Absolute Poverty Rate (APR), as shown in the main equation below:

$$y = \delta \times PPIES + \sum_{i=1}^{n} \beta_i \times x_i + \xi \quad (1)$$

where,

y – absolute poverty rate, %,

PPIES – production price index for electricity, gas, steam, and air conditioning supply, %,

x – the value of other control variables, such as *FDI*, *UR*, *PR*, etc. (n variables),

δ – the regressor; it shows the effect of *PPIES* on the *APR*,

β – parameters,

ξ – stochastic term.

We consider the absolute poverty rate as a critical measure for assessing welfare in the Republic of Moldova. The National Bureau of Statistics (NBS) presents the results of the Household Budget Survey (HBS). This research identifies disadvantaged households and individuals while assessing the impact of policies and programs on the socio-economic conditions of the population. Additionally, the HBS provides data for calculating the Consumer Price Index (CPI), estimating household final consumption, and measuring poverty and social exclusion. Conducted on a random sample of urban and rural households across Moldova (excluding areas on the left bank of the Nistru River and Bender municipality), the survey encompasses all members of selected households, including temporarily or long-term absent individuals who maintain household ties and contribute to the household budget.

From 2014 to 2022, the NBS changed the methodology for calculating many indicators reflecting the socio-economic development of the country. Statistical studies of households are related to the method for calculating the country's population. Until 2019, the NBS calculated the stable population. In 2017-2018, it tested a new methodology, which was finally adopted in 2022. The recalculation of indicators was carried out for data starting from 2014. That's why the data

covers the period between 2014 and 2024 inclusive. A brief description of the variables is provided in Table 1. Lack of data prevented an extension of this analysis beyond the current period. The Absolute Poverty Rate and the PPI for energy supply are taken from the NBS.

Table 1: *Variable description*

Variable	Mean	Sample standard deviation	Min	Max
Absolute Poverty Rate, %	27.71	3.33	23.0	33.6
Producer Price Index for electricity, gas, steam, and air conditioning supply, %, previous year=100%	113.10	35.53	92.7	212.0
Foreign Direct Investment, % of Gross Domestic Product (GDP)	2.60	1.10	1.1	4.4
Unemployment Rate, %	3.99	0.70	3.0	5.1
Personal Remittances, % of GDP	16.22	3.30	10.5	22.1

Source: The authors' computation

According to the NBS, the average absolute poverty level is 27.71%. The dynamics of the poverty level provide an idea of the country's economic sustainability and the effectiveness of social support systems. For our primary independent variable, we selected the PPIES. It measures the overall evolution of the prices of industrial products and services manufactured and delivered at the first trading stage by domestic producers during a specified period, compared to a reference period. The sample standard deviation (Bessel's correction) of the PPI for energy supply is too much (35.53), which is evidence of the volatility of prices.

The first control variable we used in our analysis is Foreign Direct Investments, net inflows (% of GDP of Moldova). These represent the net inflows of investment aimed at acquiring a lasting management interest (defined as ownership of 10 percent or more of voting stock) in an enterprise operating outside the investor's home economy. FDI includes the sum of equity capital, reinvested earnings, other long-term capital, and short-term capital as reported in the balance of payments. This metric reflects the net inflows (new investments minus disinvestments) made by foreign investors into the reporting economy. It serves as an indicator of investor confidence and the effectiveness of policies aimed at improving the business environment.

The second control variable used is unemployment rate, i.e, the share of the total labor force that is without work but available for and seeking employment. We believe this affects the absolute poverty rate, as higher unemployment leads to reduced household income, making it more challenging for individuals and families to meet basic needs, thereby increasing the likelihood of experiencing poverty. The last and not least control variable used is personal remittances, as part of GDP. Personal transfers refer to all current transfers, either in cash or in kind, made or received by resident households from nonresident households. This category encompasses all current transfers between resident and nonresident individuals. Compensation of employees covers the income earned by border, seasonal, and other short-term workers employed in a country where they are not residents, as well as income from residents working for nonresident employers. The data on personal remittances represent the sum of these two components, as defined in the sixth edition of the IMF's Balance of Payments Manual. It is a well-known fact that the Republic of Moldova's GDP is massively dependent on personal remittances; hence, we decided to include it as a relevant control.

III. Evolution of absolute poverty and potential predictors

A comparative analysis of the dynamics of the absolute poverty rate and PPI for energy supply suggests that there is a relationship between these indicators. Still, the extent of this relationship will be understood by further analysis in the next section. In 2022, a two-fold increase in PPI for energy supply and an increase in the absolute poverty rate by 6.6 percentage points

were recorded (see Fig.1). The energy crisis died down in the second half of 2023, so the price index in 2024 is below 100%. Still, the prices for energy resources themselves remain higher than before the energy crisis.

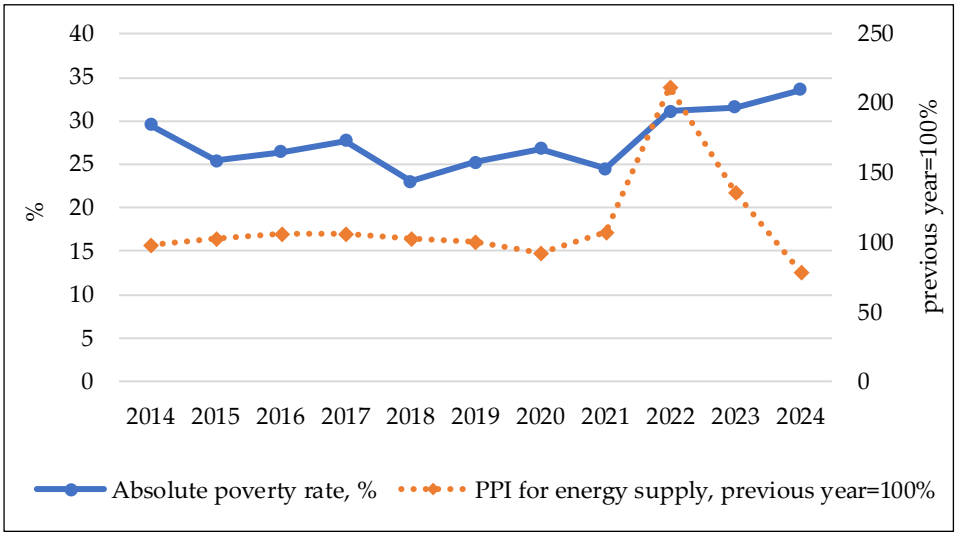


Fig. 1: *Evolution of absolute poverty rate and PPI for energy supply, 2014-2024*

Over the 11 years analyzed, significant declines in foreign direct investment (% of GDP) were recorded in 2016 (by 1.8 percentage points), 2020 (by 3.0 percentage points), and 2023 (by 1.9 percentage points). During these same years, the absolute poverty rate increased by 1.0, 1.6, and 0.5 percentage points, respectively (see Fig.2). This pattern suggests that there is an inverse relationship between these two indicators. We will test this assumption in the next section.

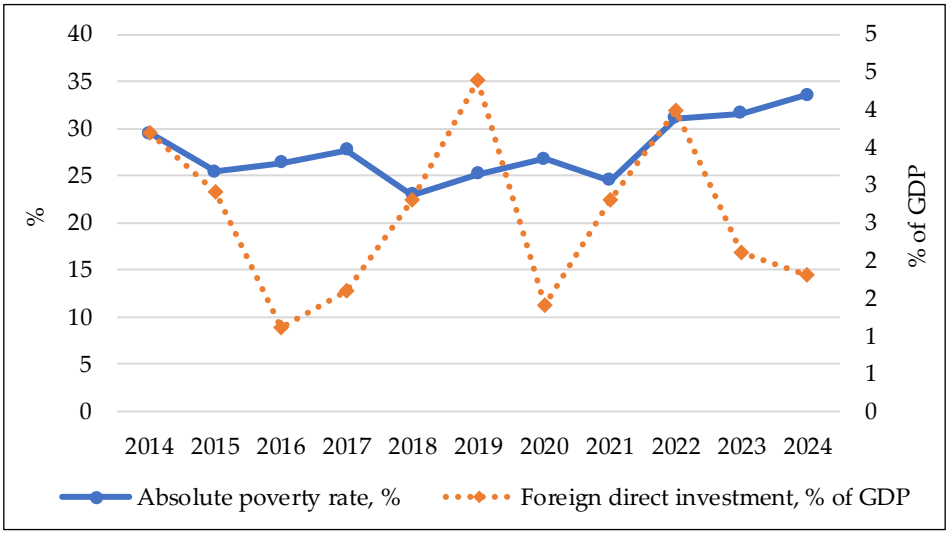


Fig. 2: *Evolution of absolute poverty rate and foreign direct investment, 2014-2024*

The trends in the evolution of the absolute poverty rate and personal remittances look identical for 2014-2021. Still, over the past three years, there has been a clear inverse relationship between them (see Fig.3). We will answer the question of whether there is a relationship between these indicators and whether it is significant in the next section using the methods listed in the previous section (OLS and 2SLS).

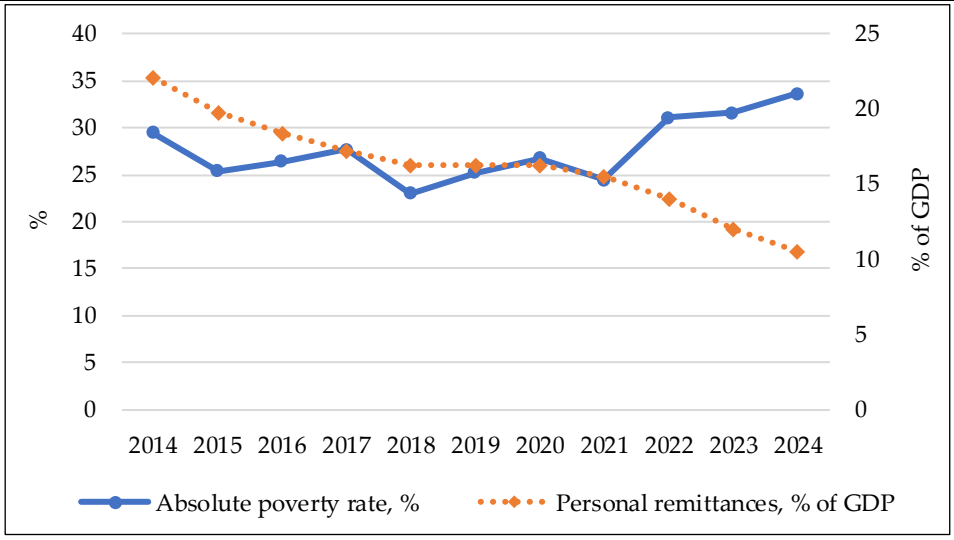


Fig. 3: *Evolution of absolute poverty rate and personal remittances, 2014-2024*

Further analysis of the drivers behind the (non-) stationarity of these trends and the tools the governments can employ to counteract the negative repercussions of the subsequent effects is a subject matter that can be explored in the next section.

IV. Results and discussions

The method of ordinary least squares (OLS) was used to examine the impact of energy prices and other predictors on the absolute poverty rate in Moldova. The results are presented in Table 2, and these show that while energy prices have a positive association with the absolute poverty rate in Model 1, this relationship becomes more nuanced as additional variables are introduced in subsequent models. In model 1, the relationship between the energy price index and the poverty level is positive and statistically significant, indicating that higher energy prices are associated with higher poverty levels in Moldova. However, when the second predictor, "Foreign Direct Investment," is included in model 2, this relationship weakens, and the significance of the coefficient considering energy prices decreases. We could suggest that FDI may play a role in moderating the impact of energy prices on poverty. In Model 3, when we include the predictor "Unemployment Rate," energy prices continue to show a positive relationship with poverty. Still, the effect is somewhat reduced, suggesting that unemployment may also affect poverty.

Table 2: *Results of applying the OLS method for elaborating Models 1-4*

Variable / Model	Model 1	Model 2	Model 3	Model 4
Production Price Index for energy supply, %	0.0505*	0.0553*	0.0660**	0.0688*
Foreign Direct Investment, % of GDP		-0.4277	-0.3058	-0.3510
Unemployment Rate, %			3.2614	3.1338
Personal Remittances, % of GDP				0.0656
R-squared	0.396	0.422	0.537	0.539
Adjusted R-squared	0.320	0.257	0.305	0.171
F-statistic	5.242	2.554	2.317	1.463
Prob (F-statistic)	0.0513	0.147	0.175	0.338

Note: **: 5% sig. *: 10% sig. P-values based on regression analysis
Source: The authors' computation

Finally, in Model 4, adding a fourth predictor, "personal remittances," further reduces the significance of the estimated coefficient, suggesting that remittances may help cushion the impact

of energy price increases on the absolute poverty line. Other variables, such as FDI, unemployment, and personal remittances, do not show consistent or statistically significant relationships with the absolute poverty rate across the different models, and their effects appear economically insignificant in most cases.

Moreover, the model exhibits high multicollinearity, which can affect the robustness of the results. Figure 4 illustrates plots of the covariance matrix and variance inflation factors of each independent variable, including the geopolitical risk index [1], which we will use further in our analysis. The Variance Inflation Factor (VIF) is a statistical measure used to assess the level of multicollinearity in a set of explanatory variables in a regression model. Specifically, the VIF quantifies how much the variance of a regression coefficient is inflated due to multicollinearity with other predictor variables. A higher VIF indicates greater multicollinearity, which means that the variable is highly correlated with other variables in the model.

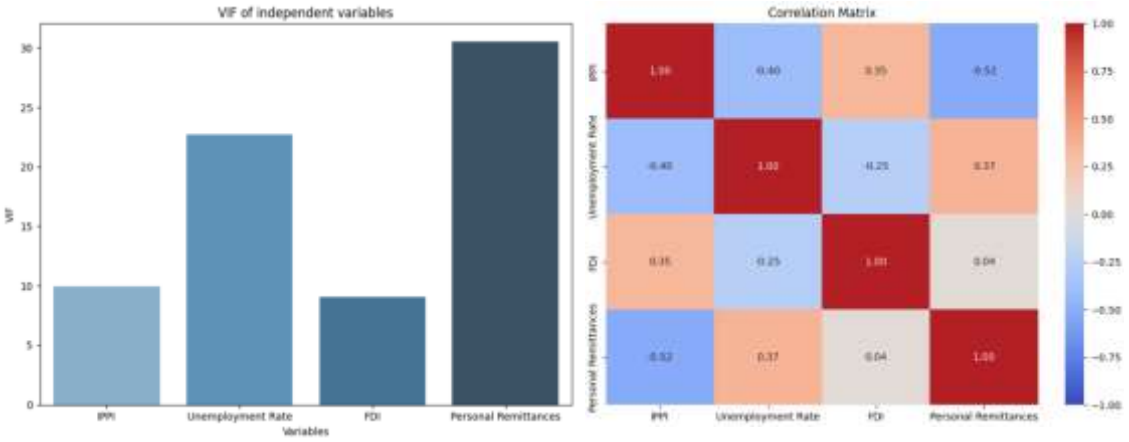


Fig. 4: *VIF and Correlation Matrix of independent variables (including personal remittances)*

High multicollinearity was found for the unemployment rate and personal remittances variables, with VIF values of 22 and 31, respectively. To ensure the stability of the 2SLS results, we excluded the personal remittances variable. As a result, Figure 5 illustrates that the VIF values are now below 10, and the correlation between each variable falls within the range of -0.8 to 0.8.

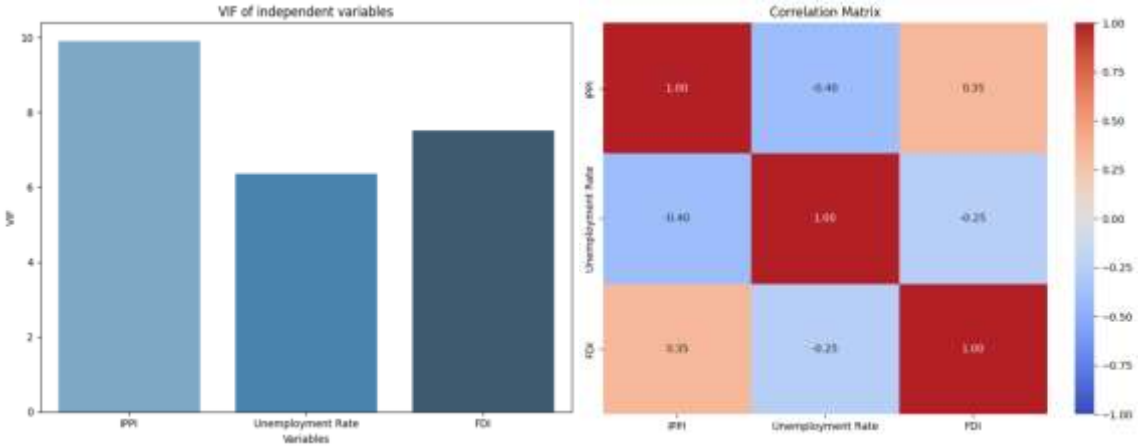


Fig. 5: *VIF and Correlation Matrix of independent variables (excluding personal remittances)*

To ensure a robust estimate of the relationship between potential predictors and poverty, we employ 2SLS regression. This method addresses potential endogeneity issues. Endogeneity occurs

when independent variables are correlated with the error term of the regression model, leading to erroneous estimates of the coefficients. In our case, endogeneity can arise either from omitted variables or reverse causality.

Results of the 2SLS regression are shown in Table 3. The 2SLS method uses instrumental variables to account for endogenous predictors, thereby reducing endogeneity. In our case, the instrumental variable for PPIES is the geopolitical risk index (GRI). We assume that the Geopolitical Risk Index is relevant as an instrument, meaning it is correlated with the *PPIES* variable, but is not directly affecting the poverty rate (the dependent variable) except through its effect on *PPIES*.

Table 3: *Results of applying the 2SLS method for elaborating Models 1-3*

Variable / Model	Model 1	Model 2	Model 3
Production Price Index for energy supply, %	0.2203***	0.1133***	0.1066***
Foreign Direct Investment, % of GDP	0.1528	-	0.3816
Unemployment Rate, %	-	9.9260***	9.7598***
R-squared	0.9475	0.9896	0.9897
Adjusted R-squared	0.9344	0.9870	0.9853
F-statistic	107.58	1160.5	1418.1
Prob (F-statistic)	0.0000	0.0000	0.0000

Note: ***: 1% sig. **: 5% sig. *: 10% sig. P-values based on regression analysis
Source: The authors' computation

According to the data in Table 3, in all three models, PPIES is positively correlated with the poverty level with coefficients of 0.2203, 0.1133, and 0.1066. All these coefficients are statistically significant at the 1% level. This suggests that higher energy prices contribute to an increase in poverty. Specifically, *a 1-point increase in the PPIES is associated with an approximate 15% rise in the absolute poverty rate* – a notably high figure.

On the other hand, Foreign Direct Investment (FDI) shows coefficients of 0.1528 and 0.3816 in Models 1 and 3, respectively. Still, these are not statistically significant, indicating that FDI does not have a substantial impact on poverty. The unemployment rate is included in Models 2 and 3, where it has a strong positive effect on poverty, with coefficients of 9.9260 and 9.7598, both statistically significant at the 1% level. The models exhibit strong explanatory power, with R-squared values ranging from 0.9475 to 0.9897 and F-statistics indicating high overall significance (p-value = 0.0000 for all). The results provide evidence that energy security plays a vital role in reducing poverty in Moldova.

V. Conclusion

This study proves that there is a direct relationship between the energy price index and the absolute poverty rate in Moldova. According to the results, the coefficient in regression model 1 is statistically significant, thus higher energy prices will lead to an increase in the poverty rate. However, including additional predictors (FDI) in the model allows us to understand the relationship better. The predictor "unemployment rate" amplifies the impact of rising energy prices on the decline in household welfare.

To mitigate the negative impact of rising energy prices on poverty in Moldova, the government should promote policies aimed at increasing energy availability and sustainability. To increase the availability of energy resources, it is necessary to provide direct financial assistance to low-income households and vulnerable groups. The government should attract investment in the development of "green" energy, and develop and implement strategies for the diversification of energy sources. These measures have a dual purpose: on the one hand, they will reduce dependence on unstable energy markets, and on the other, they will stabilize prices in the long term.

The following measures should be implemented to improve energy efficiency: introduce energy-saving technologies, and use insulation for home renovation. These measures help reduce overall household energy consumption. Model 3 shows that there is a strong positive correlation between unemployment and poverty. Thus, increasing employment, creating new jobs, especially in green energy, will reduce poverty. Vulnerable groups should be offered vocational training programs to help them find employment. Finally, attracting domestic and foreign investment in sectors that create new jobs, including in green energy, will improve living standards and inclusiveness in Moldova.

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Authors declare that they do not have any conflict of interest.

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GRASSLAND ECOSYSTEMS OF THE MOUNTAIN PART OF THE CHECHEN REPUBLIC AND THEIR ROLE IN CARBON SEQUESTRATION

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Abstract

The Chechen Republic is characterized by a complex and contrasting landscape structure, owing to its heterogeneous geological and geomorphological structure—the presence of ridges of varying elevations and lithological compositions, separated by intermontane basins in the southern part of the republic, and flat plains of varying levels in the north. A distinctive feature of the territory is the large area of undulating foothill plains located south of the Terek-Sunzhenskaya Upland, with the low Terek and Sunzhensky ranges separated by the Alkhanchurt Valley and the smaller Grozny, Bragunsky, and other ranges. These plains have experienced intense anthropogenic impact over a long period, leading to significant landscape transformations. In recent decades, shifts in land use patterns have been observed here, resulting in active landscape dynamics. Based on field research, new quantitative data were obtained on spatial differences in the biogeocycle and phytomass stocks, making it possible to assess the dynamics of greenhouse gas emissions in mountain forest landscapes of the Chechen Republic. At the local level (at the level of key monitoring sites), new data were obtained on phytomass stocks and their spatial variability. Representativeness of ecosystem sites in the mountainous territories of the Chechen Republic was ensured by creating maps of various components, including climate, biota, and soil cover, which demonstrate differences in natural conditions for carbon accumulation

Keywords: mountain landscapes, forest-steppe ecosystems, carbon accumulation, natural conditions.

I. Introduction

Global climate change has affected every region of the world. In mountainous regions, the consequences of climate change include the degradation of glaciers and snow cover, shifts in the rhythms of natural climate and slope processes, and changes in the boundaries of altitudinal zones. Attempts to understand the cause-and-effect relationships in the complex "climate-biosphere-human" system have led to the study of carbon balance. It is believed that reducing carbon emissions or its long-term sequestration in soils and vegetation can slow the rate of global warming. Without delving into the nature (and ambiguity) of this problem, it is worth considering approaches and methods for assessing carbon balance in different landscapes.

This is especially relevant for mountainous areas, which, according to various estimates, occupy up to 25% of the planet's territory, and in Russia, almost half the country [1,2]. The complex differentiation and diversity of the natural landscapes of the Chechen Republic, coupled with anthropogenic pressure and land use change in recent decades, have highlighted the importance of studying the relationship between carbon accumulation and the specific landscapes involved in a

given land use. Only by understanding this relationship can we develop effective measures to optimize land use patterns to enhance sustainability and long-term carbon accumulation.

Currently, in connection with research into the biosphere's role of various landscape components, their productivity, and resilience against the backdrop of global climate change, interest in studying the carbon cycle has revived. Accounting for the cycling of substances in individual blocks is still very rough. A systems approach and the construction of conceptual balance models are widely used as a methodological basis for studying the cycling of substances in biogeocenoses [3,5]. This system of describing a community is used to objectively predict the fate of a community, evaluate various interventions within the community, and select those that will be beneficial for both the development of the community and its practical activities. Research in ecology demonstrates that a systems approach is the most appropriate method for studying the structure and functioning of ecosystems.

In terrestrial ecosystems, carbon sequestration is the removal of carbon dioxide from the atmosphere by increasing the natural uptake, processing, and long-term storage of carbon in vegetation and soils. Carbon sequestration can be achieved by fixing more carbon in plants through photosynthesis, increasing plant biomass per unit area, reducing soil organic matter decomposition, and increasing the area of carbon-storing ecosystems.

Several issues related to time and space scales must be addressed. The desired time scale should be large enough to encompass the entire vegetation and management cycle for a given agroecosystem (e.g., the succession of fallow crops), and these cycles should be considered over several decades.

II. Methods

Landscape structure studies of this vast territory were conducted along several typical elevation profiles. The profiles intersected the most characteristic combinations of landscapes of different types and subtypes (steppe, forest, and meadow), formed on dissimilar rock types and slopes of varying aspect. Particular attention was paid to determining the upper boundary of forests and mountain meadows, the steppe distribution of meadow landscapes, the characteristics of different forest types (small-leaved and broad-leaved), and the influence of rock types on the differentiation of biogenic components. Large-scale topographic maps at scales of 1:50,000 and 1:100,000, available online, as well as Google Maps and satellite imagery of various scales, were used to extrapolate field point data and profiling data. The most informative picture was provided by the results of vegetation interpretation and classification, for which Sentenel-2 imagery was used.

III. Results

The biogeochemical carbon cycle and its study in landscapes, especially mountainous ones, is quite complex, as it involves not only the functioning of all life forms on Earth but also the transfer of inorganic substances both between and within various carbon reservoirs. Its study deserves special attention, as this process plays a crucial role in the sustainable functioning of ecosystems. The main carbon reservoirs are the atmosphere, terrestrial biomass, including soils, the hydrosphere, and the lithosphere.

Studies of the soil-plant cycle in forestry began in the late 19th century, leading to the conclusion that tree species have little need for additional nitrogen. This conclusion was based on data on the low nitrogen content of annual tree growth and the return of significant amounts of nitrogen compounds to the soil with litterfall. Only after the adoption of the International Biological Program in the 1950s and 1960s did extensive research on the cycling of organic matter and mineral nutrients in various ecosystems begin in many countries. A summary of studies on nutrient cycling in forest ecosystems was completed in 1965. Most studies provide data on total phytomass, annual

phytomass production, and its carbon and nitrogen content. When assessing carbon and nitrogen cycling in forests, the total phytomass and its content of these elements are widely used as indicators of the productivity of the biogeocenosis. This indicator fluctuates depending on the age of the stand, the composition of the stand, and the growing conditions.

The phenomenon of introzonality in the republic is represented by soil types such as solonetz, bog, and alluvial soils, which intersect in patches or strips within zonal soils. This gives the soil cover a complex character. It reaches its greatest diversity on the Terek-Sunzhenskaya Upland, the adjacent Nadterechnaya Plain, and the Gudermes Flatland, where solonchaks and solonetz soils are found. On the Chechen Sloping Plain, the diversity is created by alluvial soils, and in the zone of mountain-forest brown soils, by bog soils.

In addition to the noted geographical and geomorphological phenomena, landslides and subsidence processes occur in the republic's soil cover, complicating its nature [4,7]. Mountain-meadow and mountain-forest brown soils, formed on clays of the Maikop Formation and clay shales of the Middle Jurassic, are most susceptible to landslides.

Soil subsidence due to a decrease in soil mass caused by the leaching of soluble salts is observed on the Nadterechnaya Plain and in the Alkhanchurt Valley, where irrigated agriculture is developed.

The vegetation cover of the meadow-steppe in the Chechen Republic extends from 1,330–1,400 to 2,000–2,500 meters, depending on the elevation of the mountain ranges. Its lower and upper boundaries rise somewhat higher on the southern slopes. Meadow formations predominate here, but shrub and tree communities are also found.

Along with the predominant forb-grass communities, there are grassy, predominantly forb and sedge meadows. The dominant species of subalpine meadows are variegated fescue (*Festuca varia*) and variegated brome grass (*Zerna variegata*), which determine the overall appearance of the subalpine meadows. About half (50%) of the meadow communities are Festuca tumvaria and variegated fescue, with variegated brome grass accounting for 25–30%. The remaining 20–25% are meadows with bent grass (*Agrostis*), Caucasian reed grass (*Calamagrostis saucasica*), reed grass (*C. arundinacea*), and ground reed grass (*C. epigeios*), as well as marshy meadows.

The predominance of variegated fescue communities is explained by its poor palatability by livestock due to its very tough leaves. They are confined primarily to wetter, northern-facing slopes. They are also found on southern slopes, but in areas with a better water regime. On shallower, rockier, and less moist soils, the valuable forage plant, variegated brome grass (*Bromopsis variegata*), dominates. Many species found in the subalpine zone also contribute to the formation of the herbage of alpine meadows, but the dominant ones are Festuca supina and Nardus stricta (*N. glabriculmis*). Variegated fescue and variegated brome grass are also found, often accompanied by Colpodium versicolor, and species of foxtail grass – Alopecurus arundinaceus, and vaginal (*A. vaginatus*) and others, ovate paniculate trisetum (*Trisetum ovatipaniculatum*), Bush's slender-legged grass (*Koeleria albovii*), Caucasian bluegrass (*K. caucasica*), various species of bluegrass (Poa) - alpine bluegrass (*Poa alpina*), Caucasian bluegrass (*P. caucasica*), blue bluegrass (*P. glauca*), Prima's bluegrass (*P. primae*) and purple barley (*Hordeum violaceum*).

Carbon sequestration in grassland-steppe ecosystems is either the pure removal of CO_2 from the atmosphere or the prevention of net CO_2 emissions from terrestrial ecosystems into the atmosphere. Atmospheric carbon dioxide concentrations can be reduced either by reducing emissions or by removing carbon dioxide from the atmosphere and preserving terrestrial, oceanic, or freshwater ecosystems.

Anthropogenic impacts have led to imbalances in the biogeochemical carbon cycle in terrestrial ecosystems. These include deforestation, forest fires, and cultivation. Human needs have been and continue to be met through intensive land use, which significantly influences climate change and carbon cycles [8,10]. A consequence of this type of activity is a decrease in soil carbon content, which also disrupts the ecological stability of terrestrial ecosystems (Fig. 1, Table 1).

The amount of carbon and nitrogen removed annually by plants to build their growth varies widely and depends on age, composition and growing location.



A. B.

Figure 1. Selection of phytomass in the Makazhoy depression

Table 1 Reserves of above-ground phytomass in the observed areas of mountainous and lowland landscapes

Landscape zonal type and subtype	Observed areas in landscapes	Ground phytomass reserves (t/ha)
Mountain-meadow, meadow-steppe	Makazhoy Basin	0,8-1,3
Forest and forest-steppe landscapes	Old Sunzha Massif	0.2-142
Low-mountain-forest, forest-steppe landscapes	Ulus-Kert Tract	10-92

When assessing nitrogen cycling, the amount of nitrogen required to form a unit mass of dry matter is used. The contribution of different plant parts to the total nitrogen removal from the soil varies. There is extensive literature on this topic. The highest nitrogen content is observed in tree leaves and grasses, with lower nitrogen content in pine and spruce needles and even lower levels in wood. Birch leaves contain 2-2.5% nitrogen, pine needles 1.0-1.5%, and wood 0.1-0.2%. The herbaceous and dwarf shrub layer also participates in the nitrogen cycle in the forest, with nitrogen content in the aboveground phytomass ranging from 2 to 4 kg/ha [11,12].

Living plant parts typically contain no more than 10% of the total fixed nitrogen in biogeocenoses. A significant portion of the nitrogen accumulated by plants in their phytomass during the growing season returns to the soil with litterfall. The mass of litterfall depends more on the stand and growing conditions than on age. For example, in 30- and 80-year-old birch forests, the mass of litterfall is approximately the same. Litterfall returns approximately one-third of the total nitrogen consumed by plants during the growing season. According to some authors, in taiga forests, litterfall returns 20 to 50 kg of nitrogen per year.

As grass stands age, carbon sequestration tends to increase, and the conversion rate may be higher. Equilibrium carbon dioxide levels in forage reservoirs (accumulation equals losses) are reached after 30-70 years of moderate natural resource management. However, meadow soils with low organic matter content can sequester more carbon over a longer period.

The nature of carbon sequestration in pastures is less predictable. In natural pastures, biomass is partially returned with livestock organic matter, resulting in sequestration, on average, not exceeding 4% of net primary production. It is only known for certain that the type of livestock grazed and the intensity of grazing are factors that significantly influence the level of biomass

sequestration. Moderate grazing under rotational grazing does not impede the absorption of CO_2 from the atmosphere by pastures, since rotational grazing in different areas potentially stimulates biomass growth. The meadow-steppe ecosystems of the Chechen Republic, like other natural areas, are subject to intensive and unsystematic grazing, even on mature pastures. This leads to the destruction of the stability and strength of the root system, preventing it from acting as active carbon sinks, which is often the dominant source. Consequently, degradation of the root system, which accounts for 80-90% of the total phytomass, leads to the release of additional CO_2 from the primary carbon storage reservoir.

When harvesting hay, almost all aboveground biomass is removed without excretion, meaning no organic residue remains on the site. If mowing is particularly intensive and occurs intermittently, the amount of plant biomass (carbon) will inevitably decrease. Thus, the amount of accumulated CO_2 varies proportionally to the intensity of biomass removal from the site, depending on the species composition and density of the grass stand. Pastures that are annually overstocked are characterized by a steady accumulation of organic matter, accompanied by increased methane and nitrous oxide emissions from forage lands. Furthermore, intensive trampling of grassland significantly reduces the biodiversity of the grassland, which threatens to reduce biomass (carbon accumulation) and the forage value of pastures. The carbon content of natural forages can be somewhat increased by switching to a rotational grazing system. However, this will lead to a certain increase in the labor intensity of pasture livestock farming and the cost of its production. Therefore, with targeted management, natural grassland ecosystems can make a significant contribution to carbon dioxide accumulation. The largest contribution to carbon sequestration, taking into account the area of forage land, comes from croplands abandoned in recent decades. The average CO_2 content in the organic matter of litter and plant associations of overgrown cropland is 46.1%. Within 4-5 years of being withdrawn from cultivation, soil profiles become more capacious reservoirs for the steady removal of atmospheric CO_2. The rate of carbon dioxide accumulation depends primarily on the soil thickness, the length of time the arable land takes to become established, and the type of fertile horizon.

Along with the supply of nitrogen to forest ecosystems, there are also constant losses from the soil: as a result of leaching by water and in gaseous form due to the activity of certain groups of microorganisms. Some authors have found that losses via soil runoff are generally small (no more than 4-5 kg of nitrogen per year). Nitrate nitrogen is lost in greater quantities than ammonium nitrogen. There is evidence of gaseous nitrogen losses from forest soils as a result of denitrification. Denitrification can occur in poorly aerated soils, as well as in plant rhizospheres. The extent of gaseous ammonium nitrogen losses from forest soils remains controversial.

IV. Conclusion

The main factor shaping landscape diversity in the study area is altitudinal zonation, associated with changes in the ratio of heat and moisture. The following belts are distinguished in the region: nival-glacial (above 3000–3500 m); mountain meadow (2000–3500 m); mountain forest (up to 2000–2600 m) and various variations of mountain steppe and forest-steppe landscapes (up to 1800–2400 m). The identification of the mountain forest-meadow landscape type is primarily associated with the anthropogenic transformation of a significant portion of the mountain forest zone (2000–2600 m). The mountain forest-meadow-steppe landscape type is an ecotone between mountain steppes and forests (up to 1800–2400 m). The boundaries of landscape types and subtypes were clarified through the analysis of Sentinel-2 satellite images. Heterogeneous carbon balance conditions are observed in mountain forest-meadow-steppe and mountain-steppe landscapes [6,8]. These landscapes, especially the steppe ones, located predominantly in intermontane basins, experience precipitation deficits. On southern-facing slopes, high insolation levels result in significant evaporation. Unstable natural moisture conditions are compounded by economic activities such as grazing, haymaking, terraced farming, and artificial irrigation in some areas near

settlements. Few untouched steppe areas remain.Steep slopes often experience deceration, soil creep, and the formation of pathlike terrain and landslides. In these cases, the soil and vegetation cover is usually fragmented, and large quantities of organic matter are removed and accumulate at the foot of the slopes or washed into rivers. The use of meadows for grazing significantly contributes to the biogeocycle, from which a significant portion of organic matter is removed through grazing by livestock or haymaking, which affects the carbon balance [13,14]. To identify the conditions of carbon dynamics in the Chechen Republic, field data and analysis of all three types of landscape structure were used. To study the morphological structure of the landscapes, field expedition methods were employed, including constructing complex profiles in various altitudinal zones and belts, interpreting high-resolution satellite images, and geoinformation methods for identifying landscape habitats based on a digital elevation model and creating derivative layers (aspects, slope angles). As a result, landscape maps of various scales were compiled. An analysis of the vertical-temporal structure of key natural complexes on the landscape profiles was conducted. Characterization of the vertical structure included a description of geomasses and geohorizons with simultaneous measurements of temperature and humidity, which were correlated with data series from nearby meteorological stations. To determine phytomass reserves, an important indicator of landscape functioning, haystacks and mortmass were collected from sample plots. A forest inventory was conducted at these sample plots, followed by processing according to the methodology adopted for field research. Data from carbon research sites, most detailed in the low-mountain forest landscape type and the mid-mountain-high-mountain region of the Makazhoy Basin with its heterogeneous landscape structure, were also used to assess, primarily, seasonal carbon dynamics in key natural complexes [10]. Peat soils that form beneath marshy meadows, which are found on gentle, concave slopes composed of clay shales and argillites, serve as carbon reservoirs.

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Authors declare that they do not have any conflict of interest.

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PROTECTIVE SCREENS AND THEIR INNOVATIVE DEVELOPMENT CONTRIBUTING TO THE PERCEPTION AND PREVENTION OF EMERGENCIES IN GEOTECHNICS

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Abstract

In the fields of geotechnics, hydraulic engineering and engineering geoecology, one of the most effective engineering measures for protecting various civil and industrial structures from external dynamic and filtration impacts is the use of screen structures. The authors have developed innovative protective screens designed to mitigate the effects of shock waves during mine and tunnel construction. These screens are made from recycled metal cans and used vehicle tyres, offering simplicity and cost-effectiveness. The authors have also developed a method for creating a borehole-based dynamic screen to protect structures from catastrophic seismic waves. This approach involves detecting approaching seismic waves from major earthquakes using specialised electronic sensors installed in zones of anticipated seismic activity. These sensors then initiate short-delay explosions of borehole charges to form the dynamic protective screen. During detonation, an explosion-induced pseudo-fluidised zone is created in the rock or soil, absorbing the destructive energy component of the seismic wave. Methods have also been developed for engineering loess collapsible loams using rigid protective-reflective screens. This is achieved by reinforcing the perimeter of the compacted area through the base of contour trenches down to the bottom of the collapsible layer using binder injection, thermal treatment or freezing. Studies of the borehole explosion-protective screen were conducted in Zaporizhzhia, Ukraine. A reduction in vertical ground vibration intensity behind the seismic protective screen was recorded during explosions of nearby charges in the range of 1.2–2.2 times the intensity (attenuation factor). Additionally, the authors have developed a new anti-filtration screen design where brine waste is used as the anti-filtration medium and where the drainage pipes are made from recycled vehicle tyres bonded together.

Keywords: protective screen, seismic waves, borehole, innovative designs, waste materials, explosion, protected structure, drainage pipes

I. Introduction

In geotechnics, hydraulic engineering, and engineering geoecology, one of the most effective engineering measures for protecting various civil and industrial structures from external adverse dynamic and filtration effects is the use of different types of protective screens.

It is well known that during the excavation of underground tunnels and mines, various protective screen designs are used to mitigate the negative impact of underground explosions.

An analysis of engineering methods for seismic protection of structures against the effects of

seismic waves generated by catastrophic earthquakes shows that underground screens represent one of the most promising yet understudied solutions.

The theoretical foundation for the creation of underground barriers (screens) to impede the propagation of wave disturbances in soil—whether of seismic, explosive, impact, or vibrational origin—was established in the mid-20th century through the efforts of researchers such as G.I. Pokrovsky [1], G.M. Lyakhov [2], A.A. Vovk [3], N.U. Turuta, I.A. Luchko, and V.A. Poplavsky [4], L.M. Geiman [5], I.I. Glass [6], A.I. Ivolgin [7], A.A. Gurin, P.S. Maly, and S.K. Savenko [8], V.S. Polyakov, L.Sh. Kilimnik, and A.V. Cherkashin [9], U.T. Begaliyev [10] and others.

Research into the construction of anti-filtration screens made from various materials has been extensively covered in the monographs by S.N. Popchenko, Yu.N. Kasatkin, and G.V. Borisov [11], V.V. Sokolskaya [12], V.N. Zhilenkov [13], V.M. Goldberg and N.P. Skvortsov [14], V.S. Altunin, V.A. Borodin, V.G. Ganchikov, and Yu.M. Kosichenko [15], L.I. Kulchitsky and F.G. Gabibov [16] and others.

The attenuation of shock air waves is achieved by constructing massive screens (barriers) near the explosion site from various materials, such as concrete, rock, metal, water, and others.

Seismic protection screens function by reflecting and damping the destructive component of seismic energy, allowing only a residual portion of the seismic energy - safe for the protected structures - to reach them.

Anti-filtration screens are intended to prevent the ingress of water or contaminating (toxic) fluids into protected areas.

The development of cost-effective and efficient protective screen designs, along with the corresponding construction technologies, is a pressing issue in the fields of geotechnics, hydraulic engineering, and engineering geoecology.

II. Development of innovative screens for attenuating shock air waves using recycled waste

Conventional and widely used designs for mitigating shock air waves typically involve the construction of thick concrete structures, which require significant material and labor resources [17]. Moreover, the dismantling of such screens is often technically complex and costly.

The authors developed two original designs of protective screens utilizing recycled household waste materials.

The first screen design (see Fig. 1) includes a supporting shield (1) made of wooden planks or metal sheets, anchored to the walls of the excavation using anchor bolts (4). On the surface of the shield facing the direction of the shock air wave, preassembled honeycomb blocks (2) are attached. These blocks are constructed from recycled, uniformly shaped metal cans. To absorb the impact of the shock wave, the honeycomb blocks are covered with a membrane (3) made from either a wooden or plastic sheet.

The honeycomb blocks represent a spatial structure composed of identical recycled metal cans, which are tin cylindrical hollow elements. These elements are connected either by adhesive bonding or by simple stacking.

To enable the honeycomb structure to absorb the pressure of the shock wave, its surface on the side facing the wave is covered by a membrane (3) made of a lightweight sheet material (e.g., fiberglass, plywood, etc.). The membrane (3) is attached to the honeycomb blocks, for example, using adhesive bonding. The membrane is not connected to the excavation walls and can move relative to the support shield along the axis of the excavation, functioning like a piston. The support shield (1) is fixed to the excavation walls using anchor bolts (4).

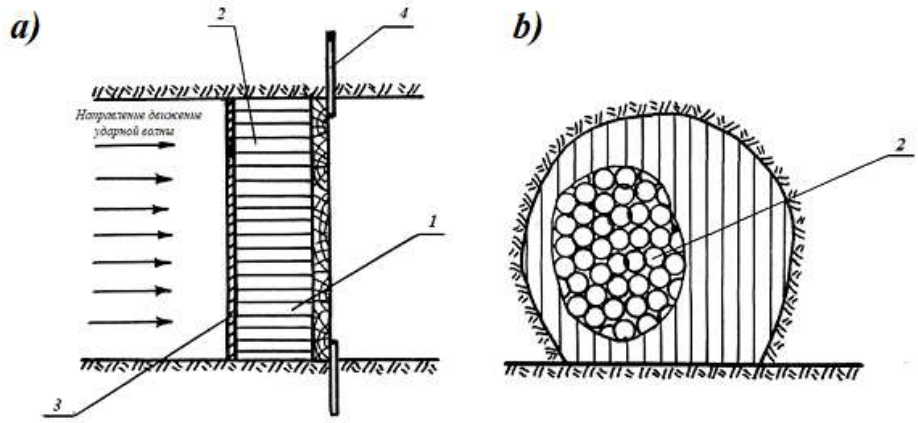


Figure 1: *Screen for attenuating shock air waves: a) longitudinal section; b) front view*

The system operates as follows.

When the shock wave strikes the membrane (3), it causes the membrane to move like a piston along the axis of the excavation. This movement relative to the support shield results in deformation of the honeycomb structure, which is composed of cylindrical metal cans. As the honeycomb blocks (2) deform, they absorb the energy of the shock wave.

The energy absorbed by the honeycomb structure is determined by the following expression:

$$A = F \cdot L, \tag{1}$$

where F is the resistance force of the honeycomb blocks to deformation, and L is the length of the honeycomb blocks.

The deformation force of the honeycomb blocks is determined by the following expression:

$$F = \sigma \cdot S, \tag{2}$$

where σ - the failure stress and S is the cross-sectional area of the honeycomb structures. The failure stress of honeycomb structures made from recycled tin cans is determined by the following formula:

$$\sigma = 28.63\sigma_T \frac{t^2}{d^2} + 1{,}16\sigma_{\text{shear}} \frac{t}{d}, \tag{3}$$

where σ_t is the tensile yield strength of the material of the recycled tin cans, σ_{shear} is the shear yield strength of the can material, t is the wall thickness of the recycled can, and d is the diameter of the can.

In the proposed design, the damping effect is determined by the geometric parameters of the honeycomb structure formed from recycled cylindrical metal cans and the length of the honeycomb blocks. If necessary, the honeycomb blocks can be assembled from multiple rows. When selecting the above-mentioned honeycomb parameters, it is important to ensure that the failure stress of the honeycomb structure is lower than the failure stress of the support shield (1) and membrane (3).

The efficiency of the proposed design lies in its significantly reduced cost, as the honeycomb blocks are made from recycled materials with a specific geometric shape that allows for the formation of a honeycomb structure by simply laying the cylindrical elements horizontally against each other. This considerably simplifies the assembly of the screen structure without compromising its functionality. Additionally, the use of perfectly cylindrical elements improves

the accuracy of structural calculations. The dismantling process of the screen is also extremely simple.

The second protective screen design (see Fig. 2) consists of a support shield (1) fixed to the excavation walls using anchor brackets (2). Toroidal elements (3) are mounted on the surface of the shield using hooks (4) attached to the shield (1). To absorb shock waves, the toroidal elements are covered with a membrane (5), which is connected to the toroidal elements (3) using rotating latches (6) that pivot around their axes.

The protective screen is assembled as follows: The support shield (1) is made from wooden planks or metal sheets, which are secured to the excavation walls using anchor bolts or anchor brackets (2).

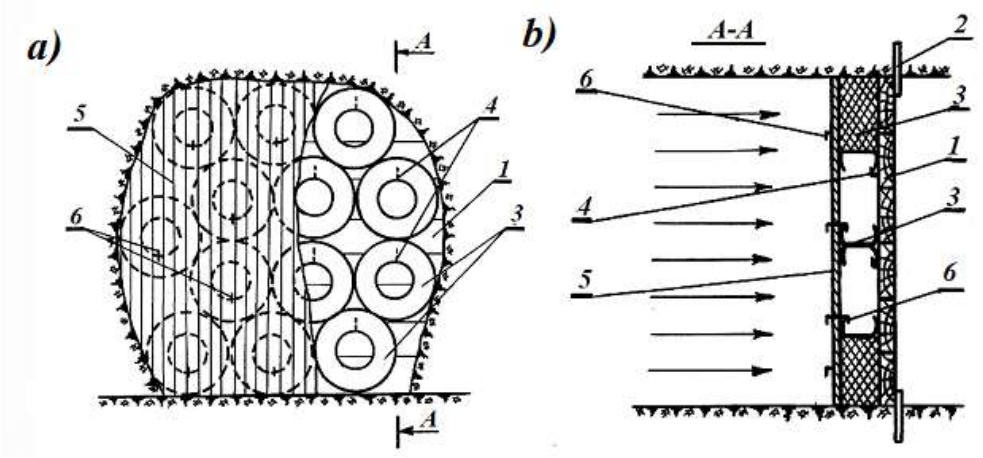


Figure 2: *Screen for attenuating shock air waves using recycled tires: a) front view; b) longitudinal section A–A*

Uniform toroidal elements (3) are selected, which are made from recycled steel-belted vehicle tires. The tires (3) are sequentially positioned against the support shield (1) for marking, and at the point where the central vertical axis of each tire intersects the circumference of its inner hole, hooks (4) are installed and fixed to the shield (1), with the hooked ends oriented upward.

After installing the hooks (4), which contact the shield using one of the tire's side flanges, the membrane (5) - a lightweight sheet material such as fiberglass - is marked to match the geometry of the tires (3) mounted on the shield (1). At the intersection points of each tire's vertical axis with the circumference of its inner hole (in the lower part), U-shaped rotating latches (6) are installed. These latches (6) are initially oriented with their bends facing upward. During the attachment of the membrane (5) to the tires, the latches (6) are rotated 180° around their axes so that the inner hook of each latch enters the hollow toroidal space of the tire and locks onto the opposite side flange of the tire.

This protective screen operates as follows.

When a shock wave impacts the membrane (5), it causes the membrane to move like a piston along the axis of the excavation. This movement relative to the support shield results in elastic, damping compression of the spatial structure formed by the rubber-reinforced toroidal tires. Due to the unique mechanical properties of recycled steel-belted tires, the energy of the shock air wave is effectively dissipated.

When selecting the tires, it is essential to ensure that the compressive yield stress of the recycled tires is lower than the failure stress of the support shield and membrane.

The effectiveness of this second protective screen design lies in its high damping capacity, structural simplicity, and ease of assembly and disassembly.

III. Development of a borehole-based dynamic screen for protection against seismic waves

The analysis of known borehole screens for protection against hazardous seismic waves, presented in [18], has shown that such systems generally involve the creation of cylindrical cavities (either vertical or inclined), which are most often filled with materials capable of absorbing the destructive component of seismic vibrations. These types of screens typically function as passive systems, waiting in place to respond to seismic impact.

The authors have developed a method for creating a borehole-based dynamic screen intended to protect structures from the effects of catastrophic seismic waves.

Figure 3 shows a schematic arrangement of boreholes (1) placed on the side facing the protected structure (2), designed to reduce seismic impact. Special explosive charges (3) are placed within the boreholes (1). In plan view, the boreholes (1) with charges (3) are positioned along an arc, with the convex side facing the predicted epicenter (4) of the earthquake. If the epicenter is difficult to predict accurately, the boreholes (1) with explosive charges (3) are arranged in a circle around the protected structure (2) at equal intervals.

With such an arrangement, the detonation of each borehole charge (3) produces a stress wave, according to Huygens' principle, which propagates toward the incoming seismic waves. This interaction is intended to occur in the zone in front of the dynamic protective screen.

The goal is to ensure that interference or amplification between the explosive and seismic waves does not occur. This is feasible because the seismic wave generated by the earthquake and the dynamic wave produced by the borehole charges (3) differ significantly in shape and timing of their compression phases. Furthermore, as the distance from the earthquake epicenter increases, the seismic shock wave stretches in duration.

The most reliable reduction in seismic intensity is achieved when the seismic wave from the catastrophic earthquake reaches the location of the explosive charges (3) at the moment of gas bubble pulsation and formation of the compression zone. The delay interval between the onset of the earthquake and the detonation of the charges (3) in the dynamic screen, taking this phenomenon into account, can be calculated using the following formula:

$$\tau = \frac{r}{C_y^m} - \frac{r_s}{v_y}, \tag{4}$$

where ρ is the distance from the earthquake epicenter to the explosive charges of the screen; C_y^m is the propagation velocity of longitudinal stress waves in the rock mass, m/s; r is the radius of the compression zone formed by the detonation of the screen explosive charges, which can be determined using the formula provided in [19]; v_y - the velocity of rock mass displacement during the detonation of the dynamic screen BB explosive charges, approximately equal to 100 m/s.

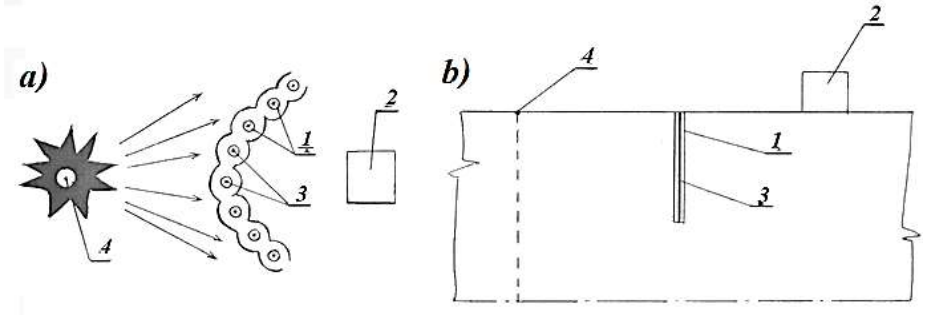


Figure 3: *Schematic of object protection using a dynamic screen: a) plan view; b) longitudinal section*

The radius of the compression zone generated by the detonation of the screen explosive charges is determined by the formula given in [19].

$$r_s = k_x R_0 = 10 R_0 \left(\frac{25 \cdot 10^4 g}{\sigma_s C_y{}^m \rho} \right)^{1/8} \times \sqrt[3]{\frac{\rho_x G_x}{\rho_A G_A}} \quad , \tag{5}$$

P_0 – radius of the explosive charge in the dynamic screen; g – acceleration due to gravity; σ_{s-} – compressive strength of the rock; ρ– density of the rock (soil); ρ_A – density of ammonite; ρ_x – density of the explosive charges; E_A– explosion heat (energy) of ammonite; E_x – explosion heat (energy) of the explosive used.

$$k_x = k \sqrt[3]{\frac{\rho_x G_x}{\rho_A G_A}} \; ; \tag{6}$$

$$k = 6 \div 7.$$

By substituting equation (5) into equation (4) and performing mathematical transformations, we obtain the final formula for determining the delay interval between the onset of the earthquake and the detonation of the explosive charges in the protective screen.

$$\tau = \frac{r}{C_y{}^m} - 0.1 R_0 \left(\frac{25 \cdot 10^4 g}{\sigma_s C_y{}^m \rho} \right)^{1/8} . \tag{7}$$

In practice, the reduction of seismic wave intensity during a catastrophic earthquake using the proposed method can be achieved through short-delay blasting, by selecting the charge mass at each stage such that the amount of explosive material decreases toward the protected object. In this case, the seismic waves generated by the larger explosive charges at the initial delay stage are mitigated by the successive delayed detonations of the following stages.

The approach of a seismic wave from a catastrophic earthquake is detected by special electronic sensors installed in regions of predicted seismic activity. These sensors initiate the short-delay detonations of borehole explosive charges in the dynamic protective screen.

During the detonation of the borehole charges (3) in the dynamic protective screen, a blast-induced pseudo-liquefied zone of rock or soil is formed. This zone absorbs the destructive component of the energy carried by the catastrophic seismic wave.

Following the activation of the short-delay borehole charges, the dynamic screen transitions into a static screen phase, as the mechanical properties of the rock or soil within the screen zone differ significantly from those of the surrounding medium - particularly when the surrounding material is solid (rocky) ground. When camouflet cavities are formed in soft soils after borehole detonations, and compacted zones are formed along borehole walls, additional seismic wave attenuation also occurs.

The seismic waves that reach the protected object after passing through the protective screen will have lost their destructive energy component, and the remaining seismic energy is absorbed by the structure without causing visible damage.

The distance between the dynamic protective screen and the protected structure must be selected such that the seismic waves generated by the short-delay explosions produce a permissible and safe background level with respect to the protected object, as well as for humans, animals, and the surrounding environment.

IV. Development and study of protective screens in deep compaction of collapsible soils using hydro-blasting

F.G. Gabibov developed engineering methods for the compaction of loess-like collapsible clay loams using rigid protective-reflective screens [20]. The formation of screens along the perimeter of the compacted area significantly reduces the intensity of seismic vibrations beyond the treated zone. This occurs due to both the reflection of waves from the inner surface of the screen and the attenuation of wave energy within the screen material itself. The wave reflected from the screen stretches the seismically active period caused by internal blasting within the compacted zone, thereby improving the quality of compaction of the collapsible clay mass.

One of the simplest problems concerning the interaction of a plane wave in a linearly elastic medium with a flat barrier was examined by G.M. Lyakhov [21]. According to [22], the system of equations governing the adiabatic motion of an ideal fluid, in cases of planar, cylindrical, and spherical symmetry, can be expressed in the following form:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial x}=0;\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial x}+\rho\frac{\partial u}{\partial x}+\nu\frac{\partial u}{x}=0;$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}=0;p=p(\rho S), \quad (8)$$

where u – particle velocity; ρ – density; p – pressure; S – entropy; t – time; ν – equal to 0, 1, or 2, respectively.

The motion of a continuous medium can be described using two approaches: the Eulerian and the Lagrangian methods.

In the developed methods for compacting collapsible clay loam masses in built-up areas, protective screens are formed prior to the wetting of the soil mass. This is achieved by reinforcing the perimeter of the compacted area - through the base of the perimeter trenches down to the bottom of the collapsible layer - using grouting with binding solutions, thermal treatment (firing), or freezing.

The creation of screens around the perimeter of the compacted mass or zone not only allows for more efficient use of the energy from deep explosions and prevents damage to nearby structures, but also reduces water loss away from the compacted zone.

Field investigations of a borehole blast-protection screen were conducted in the 17th microdistrict of the Khortytsia residential area in Zaporizhzhia (Ukraine). The construction site is composed—down to a depth of 32.0 meters - of a stratum of loess-type collapsible soils, underlain by Neogene deposits up to 10 meters thick. The collapsible soil layer is characterized by frequent interbedding and pinching out of layers with varying properties. The upper layers, down to a depth of 18 meters, exhibit a relative collapsibility ranging from 0.04 to 0.73; the lower layers, from 18 to 32 meters deep, show a relative collapsibility of 0.01 to 0.03. The total potential deformation magnitude is 2.56 meters.

The preparation of the foundation for a residential building using the hydro-blasting method was carried out in a partially developed microdistrict. The minimum distance from the blast boreholes to the foundation of an existing residential building was 10.5 meters. A nine-story residential building was constructed on the hydro-blasted foundation.

Due to the fact that the distance between the compacted sites and the existing ten-story residential building was only 11 meters, it was necessary to implement a seismic protection screen along the path of propagation of blast waves from the deep charges toward the structure being protected. Experimental and theoretical studies of such screens (artificial barriers) demonstrated that their use can reduce ground vibration intensity by a factor of 1.2 to 2.

Prior to the blasting operations, as part of the engineering design of the building's foundation

preparation, the effectiveness of vibration attenuation by the seismic protection screen was determined through numerical analysis. The screen consisted of two rows of fully drilled boreholes, each with a diameter of 350 mm, depth of 15 meters, and spacing of 1 meter.

For the purpose of verifying the calculated data and to determine the permissible explosive charge mass, experimental studies of ground and structural vibrations under blast loading were carried out. Ground and building vibrations were measured using standard seismometric equipment, and the oscillograms were recorded on roll photographic paper.

Vertical vibration displacement sensors were installed on the ground to determine the screening coefficient of the seismic protection barrier. Measurements of horizontal vibration displacements of the residential building were taken on the first floor and on the roof.

Since horizontal vibrations dominate during deep blasting impacts, vertical vibrations of the building were not recorded.

The obtained maximum vibration parameters correspond to the impacts of individual deep explosions (with an explosive charge mass of 5 kg) in the rows closest to the existing residential building. Analysis of the experimental data on ground and building vibrations allows for the following key conclusions:

The amplitudes of horizontal vibration displacements of the residential building at the first and tenth floors were 0.26–0.68 mm and 0.37–1.78 mm, respectively. The vibration intensity at the building foundation was estimated at 3–3.5 points on the seismic intensity scale, which does not exceed the permissible limit of 4 points. The horizontal displacement amplitudes at the tenth floor generally did not exceed 1.1 mm, which is considered acceptable.

A reduction in the intensity of vertical ground vibrations behind the seismic protection screen was observed during explosions of the nearest explosive charges to the protected building, with a reduction factor ranging from 1.2 to 2.2.

The periods of forced ground oscillations (under deep explosion loads) were determined to be: in the horizontal direction T_H= 0.2–0.5 s and in the vertical direction T_V =0.19-0.4 s.

V. Development of an anti-filtration barrier for groundwater remediation from petroleum products

Fig.4 shows a drainage system with an anti-filtration barrier used for the remediation of groundwater contaminated with petroleum products.

Perpendicular to the flow of groundwater (1) and petroleum products (2) floating on its surface, an anti-filtration curtain (3) is constructed from compacted gumbrin, without extending it down to the aquiclude. A perforated drainage pipe (5) is installed in the trench, placed above the base of the petroleum product layer (4), with openings (6) located in the upper third of its circumference. A filter layer (7) - for example, made from gravel-crushed stone - is placed above the drainage pipe (5). The upper boundary of the filter (8) is positioned above the maximum petroleum product level (9).

The drainage system with the anti-filtration curtain used for groundwater purification from petroleum products operates as follows:

The petroleum products (2), migrating with the groundwater, reach the anti-filtration curtain (3) and are retained by it. The curtain is constructed in the following manner: a trench is excavated (not reaching the aquiclude), and gumbrin is filled into the trench. Gumbrin is a waste product from the purification of industrial oils, specifically a bentonite clay used to filter technical oil. The resulting gumbrin retains hydrophobic and anti-filtration properties typical of clays. However, unlike traditional clays, gumbrin has low cohesion.

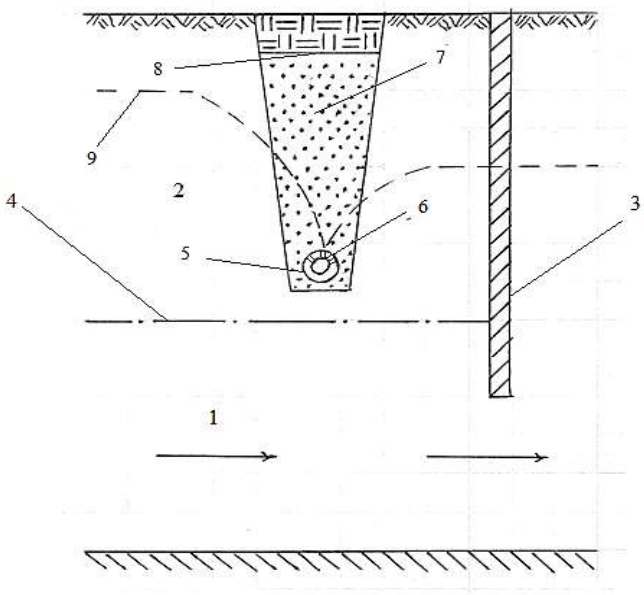


Figure 4: *Anti-filtration barrier used for groundwater remediation from petroleum products*

When compacted layer by layer, gumbrin forms a stable and effective anti-filtration barrier (3) within the trench.

As groundwater continues to flow beneath the anti-filtration curtain (3), it proceeds toward natural discharge zones, while petroleum products (2) are directed into the drainage pipe (5) through the filter material (7) and the perforations (6).

The technical and economic efficiency of this newly proposed design lies in its cost-effectiveness, achieved by utilizing waste products from the oil refining and transportation industries to construct the anti-filtration barrier.

IV. Conclusion

1. The authors developed innovative protective screens for attenuating blast air waves during the construction of mines and tunnels, utilizing recycled metal cans and automobile tires. These designs are characterized by simplicity and cost-effectiveness.

2. A method was developed for creating a borehole-based dynamic protective screen to safeguard structures from the impact of catastrophic seismic waves. In such a dynamic protective screen, short-delay detonations of borehole charges form a blast-induced pseudo-fluidized zone in the rock (or soil), which absorbs the damaging portion of the seismic wave energy.

3. Engineering methods were developed for the densification of collapsible loess-like silty clays using rigid protective-reflective screens. This is achieved by reinforcing the perimeter of the treated area through the bottom of contour trenches and to the base of the collapsible layer using grout injection, thermal firing, or freezing.

4. Field investigations of borehole-type seismic protective screens were conducted in the city of Zaporizhzhia, Ukraine. A reduction in the intensity of vertical ground vibrations behind the seismic screen was recorded during detonations of nearby explosive charges in the range of 1.2 to 2.2 times.

5. The authors developed a novel anti-filtration barrier design, in which gumbrin, a byproduct of industrial oil filtration, is used as the anti-filtration medium. The drainage pipes in the system are constructed from recycled automobile tires fastened together.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INNOVATIVE METHODS FOR USING NATURAL AND TECHNOLOGICAL CONSEQUENCES FROM DEBRIS FLOWS

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Abstract

There are numerous engineering and management methods to protect various settlements, industrial facilities and economic infrastructure, as well as people and animals, from large-scale debris flows. Debris flow protection structures are mainly constructed from reinforced concrete, metal, and local soil (protective dams). Structures containing components made from recycled waste materials, such as used metal drilling pipes, car tyres and reinforced concrete railway sleepers, have also proven to be effective. Natural formations, such as depressions and ravines, are often incorporated into the design of engineering measures for debris flow protection. Large boulders, which are products of glacial activity or rockfalls, are a common feature of mountainous regions and are often incorporated into the design of such structures. Towards the end of the last century, a group of Russian authors proposed using large boulders in the construction of debris flow protection structures. These boulders were anchored to the riverbed and to each other using a complex cable-and-anchor system. However, the effectiveness of this engineering concept was undermined by the weak anchoring system used. In the present study, the authors proposed an improved method for securing and fixing boulders in debris flow protection systems: metal piles made from pipes or standard metal profiles should be used. These piles are passed through vertical through-holes drilled along axes passing through the centre of gravity of each boulder, and are embedded into the riverbed to the required depth. Risk analysis of the potential consequences of debris flows has shown that using large natural boulders as the main elements in debris flow protection structures, in combination with a reliable anchoring system, significantly increases the reliability of these structures at relatively minimal cost. At the same time, the sustainable protective structures preserve the geoecological landscape attractiveness of mountainous areas.

Keywords: debris flow, construction, petrostructure, risk, riverbed, pile, building, catastrophe

I. Introduction

Debris flows are widespread in mountainous regions and, in some cases, in elevated plains. In inhabited areas, debris flow events often result in human casualties and considerable material damage. Cities and settlements, railways and highways, power and communication lines, oil pipelines, canals, agricultural lands, and recreational areas are frequently affected by debris flows. Various methods of protection against debris flows have been explored in the works of S.M. Fleishman [1], M.S. Gagoshidze [2], I.I. Kherkheulidze [3], A.N. Oliferov [4], Zh.B.Bainatov [5], S.G. Rustamov et al. [6], F.K. Kochergin [7], A.F. Barinov [8], V.F. Petrov [9], B.S. Stepanov and R.K. Yafiazova [10], F.G. Gabibov et al. [11].

When selecting protective measures against debris flows, it's important to note that a standardized approach is not appropriate. Each specific case requires an individual and tailored solution.

According to N.A. Alekseev [12], a comprehensive system of debris flow protection measures includes organizational and economic, agrotechnical, forest reclamation and hydraulic engineering measures. The first three are aimed at preventing the occurrence of debris flows at their source, while hydraulic engineering measures are intended to combat already-formed Debris flows. It

should be emphasized that each of these measures is equally important, and their implementation should begin either simultaneously or with minimal delay, and continue until fully completed.

Common debris flow protection structures are typically constructed from reinforced concrete, metal, or local soil (such as protective dikes). Structures incorporating recycled materials (e.g., used metal drilling pipes, tires, and reinforced concrete railroad ties) have also proven to be quite effective.

Natural formations such as depressions and ravines are often utilized in the design of debris flow control engineering measures. Local soil materials are employed in the construction of anti-debris flow dikes.

II. Use of local petrostructures for the design of debris flow protection structures

An analysis of numerous debris flow protection structures has demonstrated the potential for developing new designs based on the use of local natural georesources in the form of widespread petrostructures. In a debris control system functioning as a permeable barrier with an extensive planform layout along a debris-prone channel - developed by specialists from Aeroproject (Russia) - locally available boulders are actively utilized. These are large, rounded rock fragments ranging in size from 0.5 to 9.0 meters.

In this permeable barrier [13], individual boulders (1) (Fig. 1), located on the bed (2) of the debris flow channel, are randomly interconnected by flexible cables (3), and connected to anchors (4) fixed along the banks and the channel bed (2). The cables (3) are further connected to the anchors (4) via additional vertical cables (5).

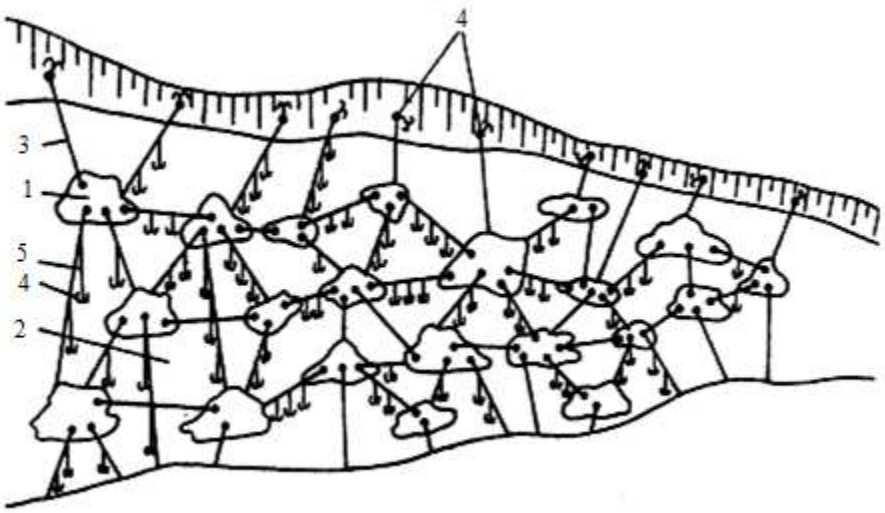


Figure 1: *Debris flow protective through-type dam*

This through-type debris flow protection dam functions as follows. When a debris flow encounters the barrier - a spatial lattice formed by interconnected boulders (1) and randomly secured cables (3 and 5) with anchors (4) - it is delayed and loses momentum.

No evidence has been found regarding the practical implementation of this structure. Despite the conceptual appeal of this engineering solution, it presents significant drawbacks. Securely attaching cables directly to the boulders is technically challenging and poses a risk of connection failure. Moreover, the construction of such a structure in practice would require numerous anchoring elements, substantially increasing construction costs.

III. Development of innovative debris flow protection structures using local petrostructures to significantly reduce stability loss risk

The authors have developed new designs for through-type debris flow protective dams utilizing large, locally sourced boulders.

In the first variant of the proposed design [14], boreholes are drilled to a calculated depth at randomly selected locations within the debris flow channel (1) (Fig. 2). Into these boreholes, pile-posts (2) are installed. As pile-posts (2), repurposed drilling pipes that have reached the end of their service life (typically around 5.5 meters when cut in half), decommissioned railway rails, or standard steel profiles such as I-beams and pipes may be used.

Once the pile-posts (2) are in place along the debris flow channel (1), through-holes are drilled along the central axis of selected large boulders (3). The diameter of these holes is slightly larger than the diameter (or maximum cross-sectional width) of the pile-posts (2). Using a crane, each boulder (3) is lifted and placed onto a pile-post (2) through the pre-drilled hole. The boulders (3) are then fixed in place on the pile-posts (2) using bolts (for pipes) or other fasteners (4).

This through-type debris flow protection dam functions as follows. When a debris flow occurs, it encounters a barrier consisting of randomly positioned, securely fixed large boulders (3), anchored to designated locations in the channel bed using pile-posts (2) and fasteners (4). The flow is partially obstructed and loses momentum. A portion of the solid material within the debris flow is deposited within the dam's structure, while the remaining, weakened flow continues downstream either to the next protective structure or deposits its solid load within the alluvial fan zone.

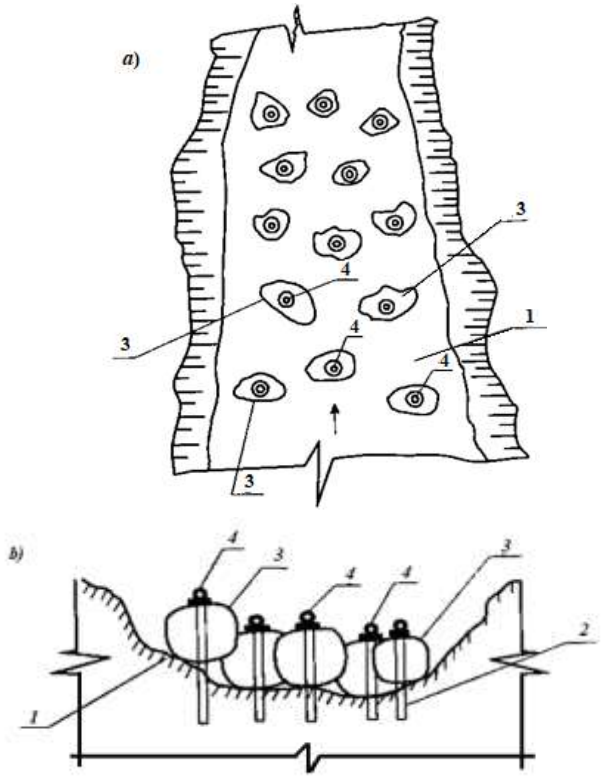


Figure 2: *Debris flow protection dam constructed from individual boulders mounted on pile-posts: a) plan view; b) front view*

In the second variant [15] of the proposed debris flow protection structure (Fig. 3), boreholes are drilled in a staggered (checkerboard) pattern at designated locations along the debris flow channel (1) to a specified calculated depth. Pile-posts (2) are then installed into these boreholes -

typically made from repurposed drilling pipes that have been cut in half after reaching the end of their service life. The depth of the boreholes for the pile-posts (2) is calculated to exceed the expected scouring depth.

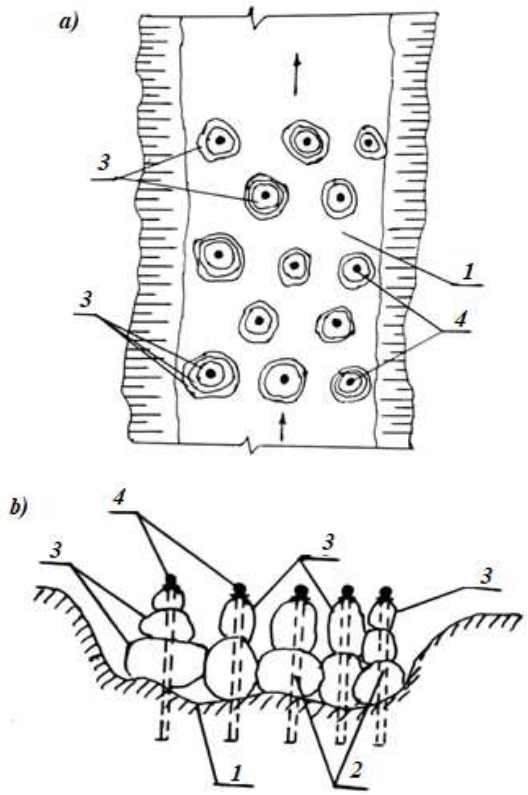


Figure 3: *Debris flow protection dam constructed from multiple boulders mounted on pile-posts: a) plan view; b) front view*

After the pile-posts (2) are installed into the boreholes, liquid concrete is poured into the holes. Once the concrete has cured and gained sufficient strength, the pile-posts (2) are ready for further assembly of the debris flow protection structure.

Next, through-holes are drilled (or bored) in selected large boulders (3) of various sizes, along axes passing through the center of gravity of each boulder. The diameter of each hole slightly exceeds the diameter of the pile-posts (2). Using a crane, each boulder (3) is lifted and mounted onto the pile-post (2) via the pre-drilled hole.

The boulders (3) are mounted on the pile-posts (2) in the following sequence: first, the largest boulder (3) selected for a given pile-post (2) is mounted; then, a smaller boulder (3) is placed above the larger one on the same post. In cases where three boulders (3) of different sizes are mounted on a single pile-post (2), the sequence is as follows: first the largest, then the medium-sized, and finally the smallest boulder (3).

The boulders (3) are secured at the top of the pile-posts (2) using fasteners (4), such as washers and spherical nuts threaded onto the tops of the pile-posts (2).

The debris flow protection structure operates as follows: when a debris flow occurs, the flow moving along the channel encounters a barrier formed by stacks of large boulders (3) mounted on pile-posts (2). This barrier slows the flow and causes it to lose a significant portion of its energy. A portion of the solid material carried by the debris flow is deposited within the structure, while the remainder of the weakened flow continues downstream - either toward the next protective structure or to deposit its solid content within the alluvial fan zone.

The technical and economic efficiency of the proposed new designs lies in the increased reliability and stability of the debris flow protection structure, as well as in the reduced construction

costs. This cost-effectiveness is achieved through the use of a simpler method for securing large boulders to the debris flow channel.

IV. Conclusions

1. Natural landforms such as depressions and ravines are utilized in the design of engineering measures for debris flow protection. Local soil and geomaterials are used in the construction of anti-debris flow dams.

2. Analysis of numerous existing debris flow protection structures has demonstrated the potential for developing new designs based on the use of local natural geo-resources, particularly widely distributed petrostructures in the form of large boulders (rounded rock fragments ranging from 0.5 to 9.0 meters in size).

3. A through-type debris flow dam design was previously developed in Russia. Despite its conceptual appeal, the design presents significant drawbacks, as securely attaching cables directly to boulders is technically challenging and introduces a risk of connection failure. Additionally, the practical implementation of this design requires numerous anchoring elements, substantially increasing construction costs.

4. The authors have developed new debris flow protection structures using natural petrostructures (large boulders). In these designs, the boulders are reinforced within the debris flow channel using pile-posts embedded into the riverbed. The boulders are mounted from above onto the pile-posts through axial through-holes drilled along the center of gravity of each boulder. This approach ensures the structural stability and reliability of the protective system under the impact of debris flows.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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SOME ECONOMIC, TECHNICAL AND ENVIRONMENTAL CHALLENGES OF WIND ENERGY

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Abstract

This article examines recent global developments in the economic, technical, and environmental aspects of wind energy. It highlights the crucial role of emerging climate policies in ensuring a sustainable, eco-friendly energy future. In recent years, wind power capacity has grown significantly, while the cost of energy generated by wind turbines has fallen to the same level as nuclear energy. The effective planning and operation of wind farms requires accurate wind mapping at around 100 metres above ground level, which necessitates the development of advanced satellites and meteorological stations. The article also highlights the ecological benefits of wind energy, including the substantial reduction in toxic emissions resulting from replacing conventional power plants with renewable sources.

Keywords: wind energy, wind turbines, renewable energy, wind mapping, environmental impact, energy payback, sustainability

I. Introduction

Wind energy plays a crucial role in the transition to sustainable energy sources. By harnessing the kinetic energy of the wind to generate electricity, it has become a key component of the renewable energy sector, offering numerous advantages. However, like all energy sources, wind energy has its challenges and limitations. Understanding both its benefits and drawbacks is essential for ensuring a greener and more sustainable future.

New climate policies have begun to reduce the reliance on non-renewable fuels and promote the development of technologies that lower the cost of wind turbines. Between 2010 and 2020, global wind power capacity grew by nearly 10%. In 2020 alone, wind power capacity increased by 24%, reaching a record 75 GW. Wind power stations in China and the United States accounted for approximately 60% of this capacity [1]-3].

Critics of alternative energy argue that wind power is not financially viable, claiming that the cost per kilowatt of electricity produced by wind farms is higher than other energy sources and that wind turbines produce less energy over their lifetime than was required to manufacture them. In reality, these claims are inaccurate. In recent years, the reliability and efficiency of wind technologies have significantly improved, while costs have nearly halved. [4],[5],[6].

Today, the cost of energy produced by wind turbines is already competitive with that of nuclear power plants. In contrast, solar power stations have not yet achieved this, with the cost per kilowatt being 1.5 to 2 times higher. Naturally, gas and hydroelectric power plants are still more financially attractive (coal-fired plants, however, are no longer considered cost-effective). Over the next decade, the cost of solar and wind energy is expected to decline further, while the cost of nuclear and gas energy is likely to increase [7]-10]. As a result, wind energy will gain prominence—even without considering its environmental advantages.

III. Results

According to Vygon Consulting, in 2020, the average cost of electricity from new solar power plants in Russia was 9.5 rubles per kWh, from wind farms – 6.3 rubles per kWh, from nuclear power plants – 5.1 rubles per kWh, and from combined-cycle gas plants – 3.6 rubles per kWh [12]

A mid-2020 report by the International Renewable Energy Agency (IRENA) shows that the cost of renewable energy continues to decline compared to energy generated from fossil fuels. More than half of the renewable energy projects commissioned in 2019 delivered electricity at a lower cost than the most efficient new coal-fired power plants.

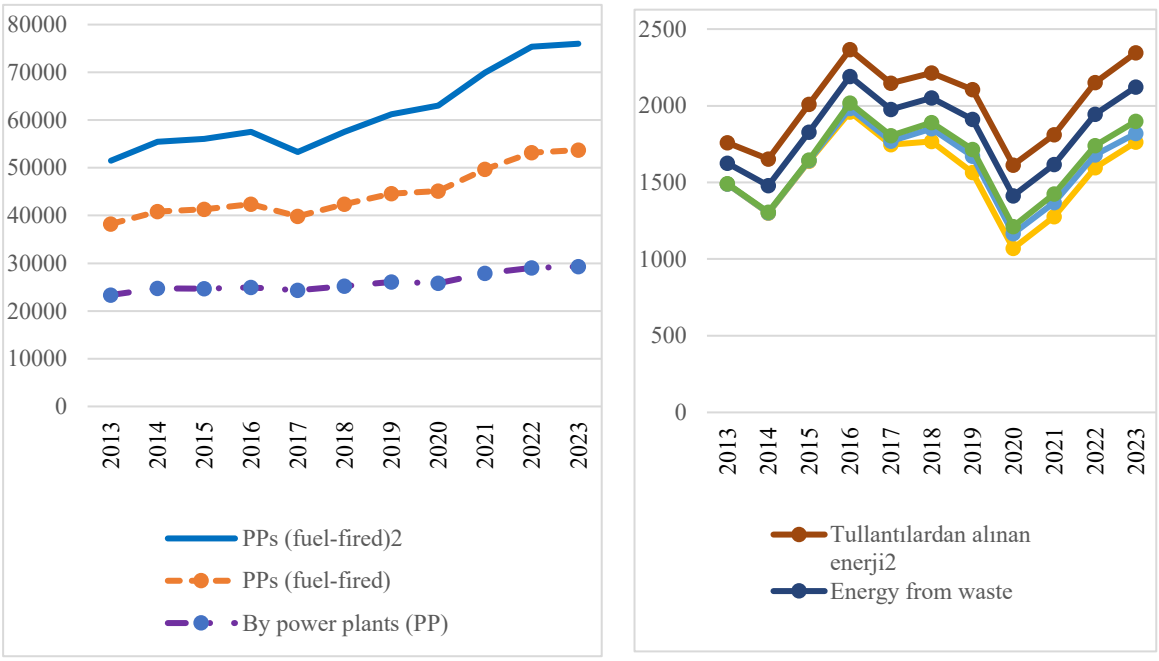
In general, the operational costs of new onshore wind installations are lower than those of many existing coal-fired power plants. Analysis suggests this trend will continue until coal is phased out entirely. Replacing coal-fired plants with a total capacity of 500 GW with solar and wind power could save the energy system up to $23 billion per year and reduce annual CO_2 emissions by about 1.8 gigatons—equivalent to 5% of global CO_2 emissions in 2019. According to the International Energy Agency (IEA), electricity production is the largest source of carbon dioxide emissions across all industries [11], [12].

Over the past decade, the cost of generating renewable electricity has dropped sharply thanks to technological advancements, economies of scale, cheaper equipment, increasingly competitive supply chains, and accumulated experience among developers. Since 2010, the operating costs of industrial wind power stations have decreased significantly—by 39% for onshore and 29% for offshore facilities. Globally, the cost of wind energy declined by approximately 9% compared to the previous year, falling to $0.053 per kWh for onshore and $0.115 per kWh for offshore wind power.

Table 1: *Installed Capacity of Wind Power Plants by Country (MW), 2018–2020*

Country	2020	2019	2018
China	290000	237029	209529
USA	122328	105433	96363
Germany	62784	61357	59313
India	38625	37529	35129
Spain	27446	25808	23494
Great Britain	24167	23515	20743
France	17949	16646	15313
Brazil	18010	15452	14707
Canada	13588	13413	12816
Italy	19850	10512	9958
Turkey	9305	8056	7369
Other countries	110000	96035	84814
Total	**744000**	**650085**	**589547**

According to the Global Wind Energy Council (GWEC) 2020 report, the number of wind farms worldwide is expected to rise significantly. However, a potential shortage of necessary materials and price increases for wind turbine components may arise. If the current growth rate of wind energy is maintained, wind power alone could be sufficient to meet the planned green energy transition targets by 2035–2040 [13].



Graph 1: Dynamics of electricity production in Azerbaijan for 2013-2023
Source: Compiled by the author based on data from the ARSK

It is planned to increase the share of renewable energy sources in the country's total electricity production to 20–30%. By the end of 2027, approximately 1,870 MW of "green energy" is expected to be integrated into the national energy system. To achieve these goals, reforms are being implemented in the energy sector. It is anticipated that the installed capacity of the Unified Energy System (UES) will reach 8,000 MW, and energy transmission and load flows to neighboring countries—Georgia, Turkey, and Iran—will increase by about 3,000 MW. Additionally, due to the construction of new high-voltage substations and the development of distributed generation, the total transfer capacity of the UES of Azerbaijan will increase, ultimately reducing technological losses to 5% in the future.

The growth in the number of wind power plants depends on a multitude of factors, making it nearly impossible to describe with a simple function. It is necessary to consider variables such as the cost of raw materials, production dynamics of components, changes in logistics costs, and levels of financial investment. Currently, due to global economic fluctuations—especially those linked to the COVID-19 pandemic—these factors remain unstable.

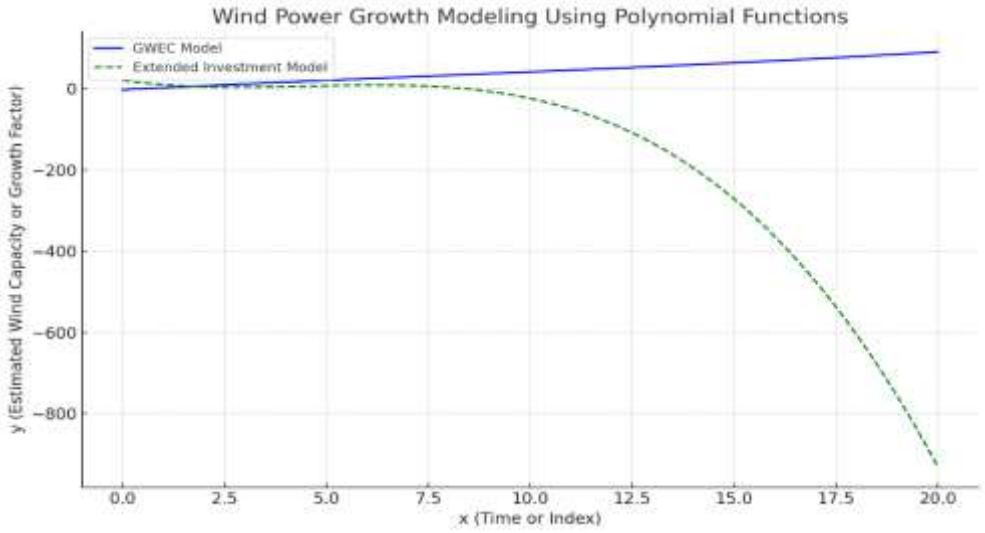
To model potential growth, a polynomial function is used. This approach separates the positive and negative effects of various factors and selects a power function for each group. The final model is the sum of these power functions, with a higher polynomial degree indicating that a greater number of factors have been taken into account. One such polynomial function, proposed by the Global Wind Energy Council (GWEC), is:

$$y = 0.0043x^3 - 0.1022x^2 + 4.978x - 2.4623$$

This model incorporates potential shortages of raw materials and the decommissioning and disposal of wind turbines. A second model is:

$$y = 0.0064x^2 - 0.2625x^3 + 3.5617x^2 - 13.909x + 20.683$$

This function additionally accounts for increased investments in wind power plants. The growth is partly driven by the rising prices of fossil fuels in Europe (particularly natural gas), which significantly increases production and operational costs that are no longer compensated by previous economic functions.



Graph 2: Polynomial Models of Wind Energy Growth

The graph presents a comparative visualization of two polynomial models forecasting the growth of wind energy capacity. The blue line represents the GWEC model, which estimates growth based on a set of baseline industry factors, including potential resource limitations and turbine decommissioning. In contrast, the green dashed line shows an extended model that also incorporates the impact of increasing investments in wind energy infrastructure [15].

The difference between the two curves highlights how capital inflows—driven by rising fossil fuel prices and a global push for energy diversification—can significantly accelerate development. The higher polynomial degree of the extended model reflects the influence of additional factors such as logistics costs, technological advancements, and financial incentives [13],[14].

Table 2: *Classification of Wind Energy Resources at 10 and 50 Meters Above Ground Level*

Class	Height, 10 m		Height, 50 m	
	Wind speed, m/sec	Specific power, W/m2	Wind speed, m/sec	Specific power, W/m2
1	0 – 4.4	0 - 100	0 – 5.6	0 - 200
2	4.4 – 5.1	100 - 150	5.6 – 6.4	200 - 300
3	5.1 – 5.6	150 - 200	6.4 – 7.0	300 - 400
4	5.6 – 6.0	200 - 250	7.0 – 7.5	400 - 500
5	6.0 – 6.4	250 - 300	7.5 – 8.0	500 - 600
6	6.4 -7.0	300 - 400	8.0 – 8.8	600 - 800
7	7.0 – 9.0	400 - 1000	8.8 – 11.9	800 - 1200

At present, the development of wind maps at approximately 100 meters above ground level is considered a crucial task. This requires new satellites, meteorological stations, and ideally, the establishment of specialized units within energy companies capable of calculating optimal placements for wind turbines. These units should factor in not only wind speed but also terrain features, distances to nearby structures that could distort wind flow (including neighboring turbines), and other relevant geographical and environmental conditions.

In the United States and European countries, wind energy resources are classified based on average annual wind speed or average annual specific power at 10 and 50 meters above ground level (Table 2).

Taking into account Europe's high population density, residential zones, valuable

agricultural lands, and protected areas, a significant portion of wind turbines are installed 100–200 meters offshore. In these zones, wind conditions are stable and there are no surface obstructions. However, due to the complexity of construction in such areas, the costs are considerably higher. The main challenge in this case is delivering the electricity from the generation site to consumers, which requires the construction of above-ground transmission infrastructure.

Regarding energy payback, as early as 2014, the School of Technical and Industrial Engineering at Oregon State University conducted a large-scale study using one of the most commonly used 2 MW Siemens wind turbines. The research showed that the energy payback period was just 5 to 7 months, even though the operational lifespan of wind turbines is at least 20 years.

The calculations in the study were based on conditions typical of the U.S. Northwest coast (with an annual yield of 6.12 GWh at 35% capacity factor), which is considered an average for the U.S. The methodology followed the international energy return on investment framework (ReCiPe 2008), which accounts not only for production costs but also for operational expenses over the full 20-year lifecycle.

The payback calculation took into account raw material extraction, manufacturing of turbine components, transportation from various factories, on-site installation, regular maintenance over the lifecycle (including the use of 273 to 546 tons of lubricating oil depending on the model), and eventual partial recycling and decommissioning. In contrast, fossil fuel power plants typically have longer payback periods, higher ongoing maintenance costs, and shorter operational lifespans compared to wind turbines.

Today, some of the largest wind turbines in mass production—despite an estimated cost of $14 million—achieve faster payback. At wind speeds of 13–15 m/s, these turbines can generate 7–8 MW and are considered ideal for coastal installation. The rotors of these giant turbines exceed 150 meters in diameter and are capable of operating at wind speeds as low as 3–5 m/s.

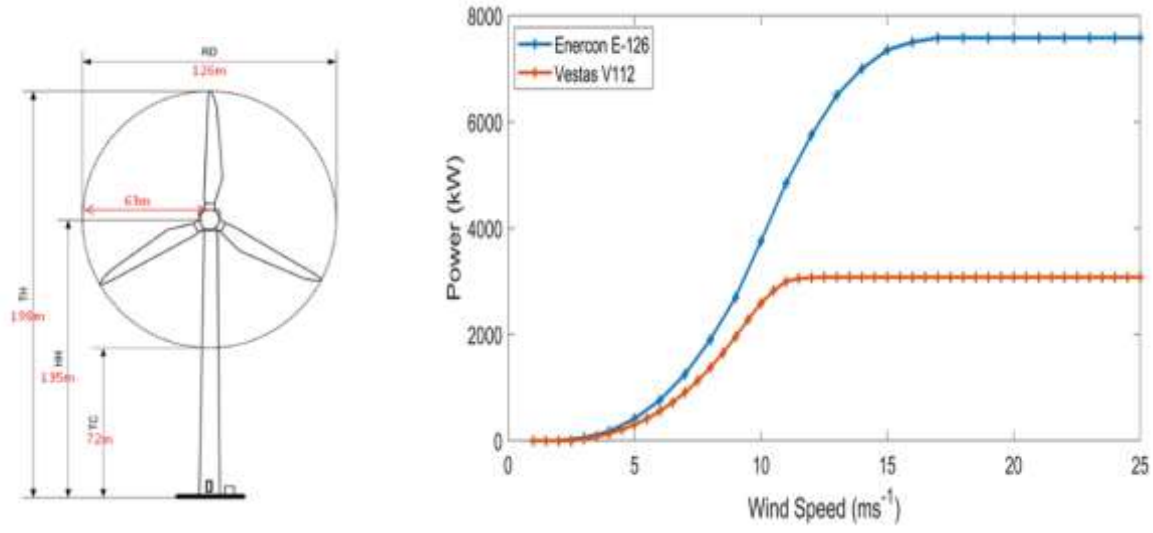


Figure 3: *Diagram of the Enercon E126 wind turbine installation (a). Power curves of Enercon E126 and Vestas V112 turbines (b). The E126 model is capable of generating electricity at wind speeds up to 34 m/s.*

When wind speeds reach 25 m/s, turbines are shut down for safety reasons. While it may seem that the blades should spin faster at higher wind speeds, that's not the case. In reality, depending on the wind speed, they rotate slowly—only about 5–11 revolutions per minute—and generate minimal noise. The reliability of these wind turbines stems from their simple design: they are gearless and use direct drive technology. One of the most powerful wind turbines—

though not the largest—is the German-made Enercon E126, with a capacity of 7.58 MW (see Figure 3). Many of these turbines have been installed in Sweden, where their combined capacity reaches 4 GW, accounting for 10% of the country's electricity production. Although renewable energy sources make up 60% of Sweden's energy mix, the country is not among the global top 10 producers of wind energy. That top spot is held by China, which leads the world in both wind and nuclear power plant construction.

As mentioned earlier, wind energy installations demonstrate the highest efficiency in coastal areas, where wind speed and stability are significantly higher. Before designing large-scale wind farms, it is essential to consider the wind map at the height corresponding to the turbine rotor's location, as well as the so-called "dead zone" of the generator—an area where airflow is distorted and weakened due to the proximity of turbines. Excessive density of turbine placement can result in a loss of power. Standard meteorological data are typically recorded at a height of 10 meters above the ground, while wind data at rotor height is critical for wind turbines. This justifies the need for launching specialized meteorological satellites for wind energy purposes.

The construction of large wind turbines is more cost-effective: both operational and capital costs for renewable energy remain low. According to the U.S. Energy Information Administration's 2021 report, solar and wind power plants are the most economical in terms of construction and operation.

Despite the obvious advantages, there are ongoing discussions in society regarding the environmental impact of wind energy: threats to birds, acoustic and infrasound pollution, as well as potential electromagnetic radiation. However, modern studies show that the number of birds killed by wind turbines is significantly lower compared to those killed by domestic cats, collisions with building glass, or electrocution from power lines. When accounting for 1 GW of generated energy, wind farms cause five times fewer bird fatalities compared to traditional fossil fuel power plants. The design of modern turbines includes low blade rotation speeds and the absence of attractive nesting sites, which reduces risks for birds.

As for noise and radiation, sanitary regulations in various countries stipulate a minimum distance between wind turbines and residential buildings—ranging from 500 to 1000 meters. Electromagnetic radiation levels rapidly decrease with distance, and even in close proximity to the installation, they do not exceed background levels that we encounter daily from Wi-Fi or mobile devices. In terms of noise, the turbine's sound is no louder than a lawn mower and significantly quieter than thermal power plants.

International studies (e.g., Resonate Acoustics commissioned by the Department of Environment of South Australia, as well as monitoring in Canada and Germany) have confirmed that the levels of infrasound and acoustic impact from wind farms are similar to those in other rural and urban areas and do not negatively affect humans, animals, or insects.

An issue that warrants attention is the potential microclimate change caused by large wind farms. While turbines in small-scale installations do not have a significant climate impact, a full transition to wind energy could alter local wind patterns and, potentially, air temperature. Since wind turbines partially absorb the kinetic energy of the airflow, weakening it, further research is needed to determine whether this effect can be used, for example, to combat soil erosion in regions with aggressive wind activity.

Offshore (marine) wind farms are of particular interest due to their smaller climate impact. Their main drawback remains the high installation costs and the need for underwater cables to transmit energy to land.

IV. Conclusion

Wind energy is a key element in the global transformation of the energy sector aimed at sustainable and environmentally safe development. The main advantages of this technology—renewability, low operational costs, minimal water consumption, and reduced dependence on fossil fuels—make it a strategically important factor in achieving energy independence and reducing greenhouse gas emissions.

Regression analysis revealed a high degree of correlation between wind energy growth rates and the level of government subsidies, tax incentives, as well as a reduction in capital costs due to technological progress. Statistically significant coefficients ($p < 0.01$) for investment variables in the capacity growth model confirm their critical role in accelerating the transition to green energy.

At the same time, sensitivity models showed that the growth in the number of installed turbines should be accompanied by strict adherence to environmental and spatial standards to minimize potential damage to the environment and public health.

Thus, with the integration of environmental standards and the maintenance of investment dynamics, wind energy remains one of the most promising forms of generation, ensuring economic growth while simultaneously reducing climate and environmental risks. Its role in the future energy system will depend on the ability of countries to adapt economic support tools and develop infrastructure to meet the needs of the rapidly growing sector.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DEVELOPING CHROMITE DEPOSITS IN THE MOUNTAINS OF AZERBAIJAN USING MOBILE PLANTS AND ENSURING ENVIRONMENTALLY AND ECONOMICALLY SUSTAINABLE MINING

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Abstract

This study focuses on developing chromite deposits in Azerbaijan's mountain regions using mobile processing plants to ensure environmentally safe mining. The main objective is to process high-quality chromite ore directly at the mine. This reduces transport and logistics costs, lowers environmental impact and brings economic and social benefits to local communities. The research analyses the technical and economic performance of mobile plants, including their energy use, carbon emissions, water usage and recycling systems. The results show that using mobile plants can reduce energy consumption and the carbon footprint. At the same time, water reuse and effective waste management help to protect the environment. The study also examines how well these activities align with Azerbaijan's laws and international standards. It makes recommendations for improving the legal and regulatory framework for mobile plant use. In conclusion, mobile processing plants can support the growth of Azerbaijan's metallurgical industry, protect the environment and boost the local economy in mining areas.

Keywords: Kelbajar-Lachin zone, chromite, platinum group elements, mineralization, geological sections, petrology, geochemistry

I. Introduction

Chromite minerals hold strategic importance for industry, as they are the primary raw material for the production of ferrochrome and stainless steel. The growth of global industrial demand and the need for efficient use of raw materials require a more sustainable and modern approach to the development of these mineral resources. This is especially relevant for chromitite deposits located in hard-to-reach mountainous regions with poorly developed infrastructure, where exploitation by traditional stationary mining and processing plants faces technical and economic difficulties. The mountainous regions of the Republic of Azerbaijan — in particular, the Kelbajar- Lachin geological zone — are rich in high-quality chromite minerals. However, the complex terrain and underdeveloped mining infrastructure significantly hinder the industrial development of these deposits. In this context, the use of mobile (portable) beneficiation plants serves as an alternative and promising technology. Mobile plants can be quickly installed and provide on-site raw material processing, reducing transportation costs and minimizing the impact on the natural environment. This study evaluates the possibilities for developing Azerbaijan's chromitite resources using mobile technologies and justifies transforming this approach into an environmentally 2 sustainable exploitation model. The article analyzes the technical advantages of mobile plants, ways to reduce

environmental risks, and techno-economic indicators. In addition, the study references international experience and demonstrates the effectiveness of applying these technologies in the mountainous regions of Azerbaijan.

II. Study area and geological conditions

The result of predicting the risk of a certain event is to determine when, where and with what (what) characteristics the event will occur. In general, non-parametric methods are often used in risk forecasting, such as the least squares method, which evaluates the accuracy of the forecast.

III. Engage experts

The mountainous regions in the southwestern part of the Republic of Azerbaijan — particularly the Kelbajar-Lachin geological zone — are characterized by the widespread occurrence of ophiolitic complexes rich in chromitites. These complexes were mainly formed within Mesozoic ultrabasic rocks of both mantle and crustal origin, including dunites, harzburgites, and serpentinites. Chromitite lenses in this zone are typically located in the central parts of dunite massifs and occur as natural bodies of varying size. The main deposits are concentrated in the areas of Gamishli, Karachinar, Khachikend, and Shekerchay (1.2.3). From a geological perspective, these territories belong to the Eastern Pontide–Kura–Araz ophiolite belt and include fragments of paleo-oceanic lithosphere complexes. Chromitite mineralization is mainly represented by aluminum-chromite type and, less frequently, by magnesium-chromite type. These minerals are considered to be high-quality industrial materials with Cr_2O_3 contents ranging from 40% to 54% and a low FeO/MgO ratio. The chemical composition of selected chromitite samples from the Kelbajar-Lachin zone was analyzed under laboratory conditions (Table 1), using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) techniques.

Table 1: *Chemical composition of selected chromitite samples collected from the Kelbajar- Lachin zone*

Sample	Cr_2O_3 (%)	FeO (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)
XLM-01	48.3	22.1	9.5	10.2	3.1
LM-02	50.5	20.8	8.9	11.0	2.5
XLM-03	46.7	24.2	10.1	9.8	3.4

As a result of geochemical analyses, it has been established that the quality characteristics of chromitites in these deposits meet international standards and, in most cases, can be used directly for ferrochrome production. The structure and mineralogy of the deposits indicate that they are suitable for industrial processing, particularly for primary beneficiation using mobile processing plants. In addition, minor concentrations of platinum group elements (PGE) — especially platinum (Pt), palladium (Pd), and gold (Au) — have been identified in several deposits, which provides an additional economic advantage for the integrated development of these sites. The locations of the studied areas, geological context, and sampling points are shown on the map (Fig. 1 and 2).

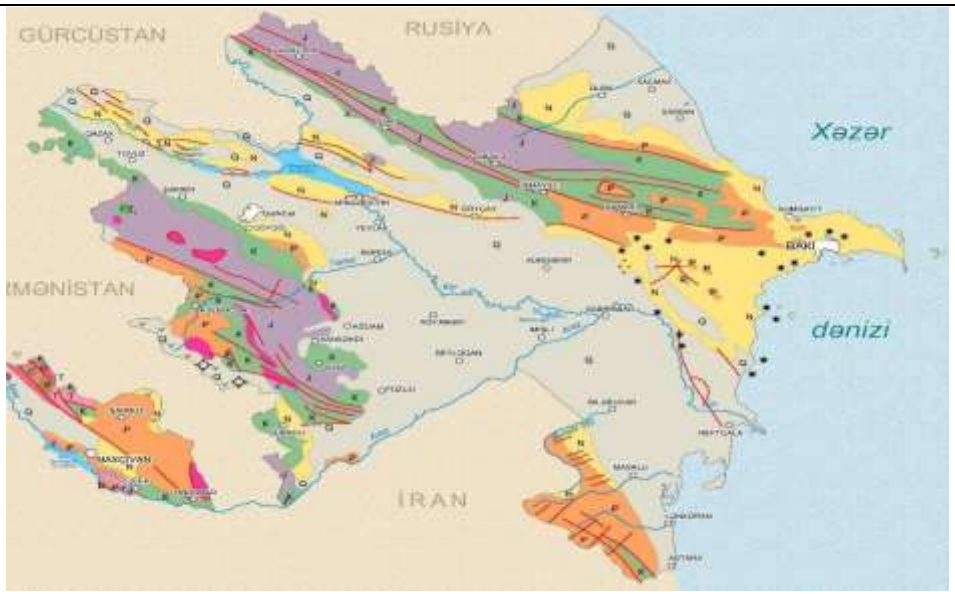


Figure 1: *Geological map of the republic of Azerbaijan*

To visualize the spatial distribution of chromite deposits, the geological context of the region, and the sampling points, a thematic geological map was developed. It highlights key elements, including:

- Ophiolite belts, marked by red structural lines on the geological map, indicating potential zones of chromite mineralization and deposits (Fig. 1);
- The main chromite deposits of the Kalbajar–Lachin zone (Kamishly, Karachinar, Shekerchai, Khachikend, etc.);
- Stratigraphic and lithological units, including ultramafic massifs and ophiolitic complexes;
- Coordinates of the sampling points at Kamishly, Shekerchai, and Khachikend (Fig. 2);
- Transport infrastructure elements and proposed sites for the deployment of mobile processing complexes, taking into account production efficiency and logistical accessibility.

The map serves as an important tool for analyzing geological and industrial conditions, as well as for the preliminary assessment of development prospects and the organization of chromite ore processing at specific sites.



Figure 1: *Cordinates of sampling points*

To provide a comprehensive view of the geological and structural conditions, spatial distribution of chromite deposits, sampling points, and infrastructure potential, a geological map of the region was created. It highlights key elements, including chromite deposits (Gamishly, Karachinar, Shekerchai, Khachikend, and others), major geological structures (ultramafic massifs

and ophiolite complexes), sampling points with coordinates, as well as potential sites for deploying mobile processing plants from a production perspective [4,5,6].

This map provides a schematic representation of the geological setting of the Kalbajar–Lachin zone, including geomorphological and infrastructure features. Chromite deposits in the region are mainly located within the ophiolitic complexes of the Lesser Caucasus. These formations, which represent remnants of ancient oceanic lithosphere, consist mainly of dunites, peridotites, and other ultramafic rocks, where chromite occurs in the form of lenses and veins. Two major groups are particularly distinguished (Table 2):

- The Goydarya Group (Kalbajar District) is characterized by lens-shaped bodies of chromite mineralization within dunites, with ore body thicknesses ranging from 0.5 to 15 meters and Cr_2O_3 content from 43.5% to 52.6%.
- The Ipek Group (Lachin District) is represented by lenses within hyperbasites, with Cr_2O_3 content ranging from 25.0% to 39.5% and ore body thicknesses from 0.5 to 5 meters.

The mineralogical composition of chromite ores includes the following major components:

- Chromite ($FeCr_2O_4$) – the primary ore mineral, with a high Cr_2O_3 content;
- Olivine ($(Mg,Fe)_2SiO_4$) – commonly associated with chromite, dominant in dunites;
- Pyroxenes (enstatite, diopside) – components of ultramafic rocks;
- Serpentine minerals – secondary phases indicating intense serpentinization of the rocks.

The combination of these minerals reflects the specific formation conditions of the chromite mineralization in the region.

Table 2: *Major chemical composition of chromite minerals in Azerbaijan.*

Component	Content (%)
Cr_2O_3	43,5–52,6
FeO	16,4
SiO_2	33,8
MgO	8,5
Al_2O_3	9,2
TiO_2	0,3
CaO	0,2

The chemical and mineralogical characteristics indicate a high industrial potential of chromite deposits in Azerbaijan (Table 3). The development prospects can be assessed as follows:

- In the Goydarya Group, the significant thickness of the ore bodies and the high Cr_2O_3 content create favorable conditions for industrial exploitation.
- In the Ipek Group, the lower Cr_2O_3 content and thinner lenses require additional geological exploration to evaluate economic feasibility.

To efficiently develop these deposits, further geophysical studies are needed, along with the implementation of modern processing technologies and strict environmental protection measures. A promising direction involves deploying mobile processing plants, tailored to the specific site conditions, while minimizing environmental impact.

Table 2: *Major chemical composition of chromite minerals in Azerbaijan.*

Parameter	Azerbaijan (Kalbajar–Lachin)	South Africa (Bushveld)	Kazakhstan (Kempirsai)	Turkey (Gülen, others)
Cr_2O_3 (%)	30–45	45–50	44–48	35–48
$FeO+Fe_2O_3$ (%)	15–25	12–16	14–18	16–24
Cr/Fe	1.8–2.5	2.8–3.5	2.6–3.2	2.0–3.0
Al_2O_3 (%)	10–20	10–15	10–17	12–20
MgO (%)	14–20	12–18	16–22	15–20
PGE (Pt, Pd)	trace/anomalies	high content	low–medium	trace
Deposit Type	ophiolites	intrusive complex	ophiolites/ultramafics	ophiolites
Mineral Association	chromite, olivine, serpentine	chromite, platinum, pyroxenes	chromite, olivine, magnetite	chromite, serpentine
Industrial Use	metallurgy, potential PGE	ferrochrome, PGE	ferrochrome	ferrochrome

III. Mobile processing plant technology

The process of primary processing of chromite ores to obtain ferrochrome (FeCr) is determined by the chromium oxide (Cr_2O_3) content in the original ore, as well as its physical and chemical properties. Up to 90% of the entire technological chain is focused on ore preparation and beneficiation prior to metallurgical reduction.

In the first stage, crushing and grinding are carried out, during which the chromite ore is processed into specified-size fractions using jaw and cone crushers. The goal of this stage is to release valuable components and form the optimal fraction for further processing.

Next, the material undergoes classification and screening, during which it is separated into fractions using hydrocyclones and vibrating screens. This ensures uniformity of the material for enrichment.

One of the most effective methods is gravity beneficiation, which takes advantage of the high density of chromite. Spiral separators and shaking tables are used. This stage significantly increases the Cr_2O_3 content — from an initial 20–30% to 40–50%.

Additional purification is achieved through magnetic separation methods, based on the paramagnetic properties of chromite, allowing it to be separated from silicates and other impurities. In the case of low-grade ores, flotation is applied using reagents that aid in the selective extraction of chromite.

After that, the concentrate undergoes thermal drying and preheating, which reduces the moisture content to less than 2%, preparing it for the metallurgical stage.

The final stage is reduction in electric furnaces, where at a temperature of 1500–1700°C, Cr_2O_3 is reduced to metallic chromium, forming a ferrochrome alloy (iron and chromium):

$$Cr_2O_3 + 3C \rightarrow 2Cr + 3CO\uparrow \quad (1)$$

The efficiency of the above stages directly affects the final quality of the product and the chromium recovery rate.

In this context, mobile processing plant technology becomes particularly relevant. These plants are modular constructions that can be quickly deployed at new mining sites, minimizing infrastructure and ore transportation costs.

Mobile solutions are characterized by a high level of energy efficiency, reduce the carbon footprint, and ensure flexibility of the production process. Their implementation in the mining industry opens prospects for local processing and rapid adaptation to the characteristics of specific raw materials, especially in remote or temporary development areas.

Examples from South Africa, Russia, and Canada demonstrate the high efficiency of mobile flotation and beneficiation units, capable of operating in complex geographical and climatic conditions.

Thus, mobile processing technologies are forming a new direction in the sustainable development of the mining industry, combining technical flexibility with environmental responsibility.

Table 4: *Estimated technological contribution at each stage (approximate data)*

Stage	Contribution to technological process
Crushing and grinding	20%
Screening and classification	10%
Gravity beneficiation	30%
Magnetic separation	15%
Flotation	10% (if necessary)
Drying and preheating	10%
Total	85–90%

IV. International Experience in Chromite Mining and Processing

When examining successful examples of chromite ore extraction in global practice, several countries stand out for their significant achievements, attributed to the adoption of modern technologies, efficient resource utilization, and a high level of organizational development.

South Africa remains the world's largest producer of chromite, with production volumes reaching 18 million tons in 2021. The primary mining enterprises are concentrated in the northeastern provinces of Mpumalanga and North West, forming part of the Bushveld Igneous Complex, the world's largest geological formation with substantial chrome reserves.

Finland showcases a successful model of sustainable production through the Kemi Mine, the only chromite mine in the European Union. Owned by Outokumpu Chrome Oy, the mine annually

extracts approximately 2.4 million tons of ore, which is supplied to the ferrochrome plant in Tornio. A distinctive feature of this project is its focus on carbon-neutral technologies and the transition to a closed-loop production cycle.

Turkey holds a leading position in the global chromite sector, producing 8.16 million tons of ore in 2023. The largest deposit, Guleman, accounts for nearly half of the national production and is notable for its high-quality metrics: a high Cr/Fe ratio and low silicon content, making Turkish ore competitive in the global market.

In **Zimbabwe**, chromite extraction is centered in the Great Dyke region, which boasts rich reserves of both chrome and platinum group metals. Major deposits are located in the Darwendale, Lalapanzi, and Mutorashanga areas. Leading companies in the region include Maranatha Ferrochrome, Zimalloys, and Zimasco, which actively implement ore beneficiation technologies and develop processing facilities.

Kazakhstan possesses the world's largest proven chromite reserves, approximately 230 million tons. In 2018, production volume reached 4.6 million tons. The country is actively advancing raw material processing, strengthening its leadership in the global market. Both manual processing lines equipped with crushing and sorting equipment and fully automated complexes with digital control systems and integrated safety modules are being implemented.

Modern approaches to chromite processing include the use of mobile plants, which offer several advantages. Energy efficiency is achieved through the use of diesel-electric hybrid installations and optimized technological processes, reducing overall energy consumption. The modular structure allows for the adaptation of production lines to various ore types and rapid configuration changes. The ability to relocate to new deposits is facilitated by the standardization of modules according to ISO container standards, simplifying transportation and equipment deployment in the field.

Implemented projects demonstrate the potential of mobile solutions. In South Africa, ProProcess developed a mobile flotation pilot plant for Anglo American, consisting of 16 modules designed for rapid ore processing in various concentration zones. In Russia, EVRAZ KGOK successfully implemented mobile processing complexes in challenging climatic and topographical conditions, significantly enhancing production indicators. Similarly, in Canada, mobile plants manufactured in South Africa are employed at remote mining sites, confirming the versatility and effectiveness of such solutions in the global mining industry.

V. Environmental Assessment and Principles of Sustainable Development in Chromite Mining and Processing

Sustainable development in the field of chromite mining and processing requires a systematic approach to minimizing environmental impact and ensuring rational use of resources. One of the key tools is the Environmental Impact Assessment (EIA), which is carried out before the start of project and operational activities. This process helps identify potential environmental risks, propose mitigation mechanisms, and ensure that project decisions comply with both national and international environmental standards.

An additional important tool is the Life Cycle Assessment (LCA), which evaluates environmental impacts at all stages of the technological chain—from ore extraction to disposal of final products. This supports decision-making aimed at reducing the overall environmental footprint and managing resources more efficiently.

Modern industry is increasingly implementing concepts of “green” and climate-resilient mining, relying on digital technologies and Industry 4.0 solutions. These technologies help reduce greenhouse gas emissions, automate sorting and processing operations, and adapt production processes to environmental constraints.

A progressive example is the use of sensor-based sorting technologies. These systems improve the quality of the raw ore, reduce the share of waste rock, and thus minimize the volume of generated waste. In response to rising environmental protection standards, biotechnological methods for waste processing are gaining importance, allowing for safe disposal and resource recovery without significant harm to ecosystems.

Transitioning to electric-powered mining and processing equipment instead of diesel-powered units helps reduce the carbon footprint and local air pollution. Special attention is also paid to waste-to-energy technologies, such as anaerobic digestion and thermal treatment, which simultaneously reduce landfill volumes and generate alternative energy sources.

Ferrochrome production processes are particularly energy-intensive: in submerged arc furnaces (SAF), up to 59 GJ of energy is required per ton of ferrochrome, which results in up to 5.5 tons of CO_2 emissions. However, the introduction of closed furnaces with preheating systems (CSAF+PH), as well as the use of hydropower, can reduce carbon emissions by 23–68%, depending on the configuration of the equipment and energy sources.

Water resources play a crucial role in chromite ore beneficiation, especially during washing and separation processes. In response to global water scarcity and pollution challenges, closed water circulation systems are being used. An example is the Sukinda mine in India, where Tata Steel Mining Ltd. implemented a comprehensive wastewater reuse system, achieving 100% return of water into the process cycle and eliminating harmful discharges.

Comprehensive environmental strategies include improving energy efficiency through heat recovery systems, modernizing equipment, and implementing programs for the reuse of process water. An important direction is the reuse of waste products, such as ferrochrome slags, in construction and other industries, which significantly reduces storage volumes and secondary pollution.

To mitigate the impact on local ecosystems, environmental monitoring systems are widely implemented, tracking air, water, and soil quality using automated stations. Noise and vibration are reduced through engineering damping systems, and dust control is achieved using water spraying and sealing of dust-generating zones. A critical element of a sustainable approach is biodiversity conservation, which includes land reclamation, vegetation restoration, and maintaining natural landscapes.

In Azerbaijan's legislative framework, environmental sustainability is supported by the Law "On Environmental Expertise" and regulations on Strategic Environmental Assessment. These govern procedures for analyzing and monitoring the effects of economic activities on public health and natural resources. Additionally, Azerbaijan is a party to several international agreements, including the Paris Agreement and the Espoo Convention, which facilitate integration into the global environmental agenda and the adoption of universal sustainability standards.

VI. International Experience in Chromite Mining and Processing

The techno-economic analysis (TEA) of mobile processing plants represents a key stage in assessing the feasibility of their implementation in the mining industry. A comparative analysis with traditional stationary facilities shows that mobile units offer several significant advantages, both in terms of capital investment and operational costs (15;16).

6.1. Capital and Operating Expenses

Mobile plants are characterized by significantly lower initial investments and operating costs compared to traditional stationary facilities. This is due to several factors: first, the modular design approach allows a considerable reduction in construction and installation costs; second, the mobility of the units reduces the need for infrastructure development; and finally, such plants usually have lower energy and water supply requirements, which decreases operating expenses.

Table 5 illustrates the main indicators of investment and operational efficiency for mobile processing plants of various scales, including the range of initial capital, daily expenses, and key parameters such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period.

Comparative data on the three types of mobile processing plants (small, medium, and large scale) involved in chromite ore processing—regardless of scale—show equally positive economic indicators: NPV is 12,627 USD, IRR is 25.76%, and the payback period is 2.34 years. These values indicate the high efficiency of mobile solutions, even with minimal investment. The presented data can serve as a benchmark for the preliminary evaluation of the investment attractiveness of similar projects in the mining industry (17).

Table 5. *Techno-Economic Indicators of Mobile Chromite Processing Plants*

Plant Scale	Initial Investment (USD)	Daily Operating Costs (USD)	NPV (USD)	IRR (%)	Payback Period (years)
Small Scale	500,000 – 1,000,000	230	12,627	25.76	2.34
Medium Scale	1,000,000 – 5,000,000	230	12,627	25.76	2.34
Large Scale	5,000,000 – 10,000,000	230	12,627	25.76	2.34

6.2. Logistical and Environmental Advantages

Among the key advantages of mobile processing plants are their modular design, rapid deployment, ease of relocation, and minimal environmental impact. The ability to quickly install the plant directly at the mining site allows for a significant reduction in transportation costs and a lower carbon footprint. These aspects are especially important in the context of tightening environmental regulations for mining operations.

Table 5. *Transport and Logistics Advantages*

Advantage	Description	Gained Benefits
Modular design and transportation	Plants are designed in modular format and can be easily transported to various mining sites.	Reduction of additional infrastructure costs and flexible site allocation.
Installation and operation	The time and resources needed for installation and operation are minimal.	Rapid start of operations and lower operational costs.
Reduced environmental impact	Plants are located close to mining sites, reducing transportation needs.	Lower carbon emissions and energy consumption.

Table 6 provides an analysis of the logistical benefits of mobile plants, showing how design and operational features affect the economics and sustainability of projects. It outlines the structured

key logistical advantages of mobile processing units in three areas: modular design and transportability, installation and operational features, and impact on environmental sustainability. Specifically, it states that fast assembly and commissioning allow for accelerated project launch, and proximity to raw material sources reduces logistics costs. It also highlights the reduction of carbon emissions, which is particularly relevant in the context of sustainable development and environmental compliance. This confirms the strategic value of mobile solutions for modern mining enterprises.

Locating mobile processing plants near deposits contributes to a multiplier effect in the regional economy. Positive outcomes include increased employment, growth in local production, higher tax revenues, and the development of supporting infrastructure.

Table 7 highlights the key socio-economic impacts of implementing mobile processing plants in a regional context, supported by quantitative examples from international practice, including Canada. In particular, the Ring of Fire project led to the creation of more than 5,500 new jobs, demonstrating the potential of such solutions for stimulating employment. Moreover, the use of local raw materials and labor resources fosters the development of local production and reduces dependence on imports (18;19). The presented data underline the significant role of mobile processing units as a driver of sustainable economic growth, especially in regions with underdeveloped industrial infrastructure.

Table 5. *Transport and Logistics Advantages*

Economic Indicator	Impact	Example
Job creation	Mobile plants generate new jobs for the local population.	"Ring of Fire" project in Canada created 5,500 jobs.
Growth in local production	Working with local resources increases local manufacturing.	Strengthening the local economy and reducing import dependency.
Increase in tax revenues	Job creation and production growth raise tax income.	Additional income sources for the state budget.

VII. Conclusion

The implementation of mobile processing plants, particularly for the treatment of chromite-containing raw materials, demonstrates significant potential in terms of technical efficiency, economic viability, and environmental sustainability. Analysis of investment and operational characteristics shows that mobile units require substantially lower capital expenditures compared to traditional stationary plants, while delivering high profitability indicators (NPV, IRR) and a shortened payback period.

The logistical advantages of mobile plants, reflected in their modular structure and mobility, allow for effective deployment in remote or hard-to-access regions. This reduces the need for costly infrastructure and minimizes environmental impact. As shown in the tables, the modular approach helps lower the carbon footprint and increases flexibility in production processes.

From a socio-economic perspective, mobile processing facilities can serve as catalysts for local development. Examples from international experience—particularly the *Ring of Fire* project in Canada—confirm their capacity to create jobs, stimulate local production, and boost tax revenues.

This is especially relevant for Azerbaijan, where such technologies could be implemented in newly liberated or industrially promising areas, including the Absheron Peninsula.

A key area for further development is the integration of innovative technologies and ensuring compliance with environmental and legal standards. Special attention must be paid to workforce training, the improvement of the regulatory framework, and additional research on the environmental impact of mobile production.

In a broader strategic context, the development of Azerbaijan's machine-building industry requires a sustainable and efficient supply of alloying elements, particularly ferrochrome. Advancing chromite mining and establishing ferrochrome production using modern, eco-friendly technologies will reduce import dependence, increase export potential, and strengthen the national industrial base.

Therefore, mobile processing plants represent a promising tool for sustainable industrial development, especially when combined with measures to modernize alloy metallurgy. Their application can contribute not only to economic diversification but also to the formation of an environmentally responsible approach to industrial growth.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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CONSTRUCTION WATERPROOFING MATERIALS BASED ON HOUSEHOLD TYRE WASTE

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Abstract

The research project aims to produce waterproof materials using tyres and cement glue. One method of disposing of domestic waste is to use secondary tyres. The presence of heavy metals in the waste materials used to construct waterproof materials (waste tyre powder, sand, cement, etc.) is of interest as it is an important environmental pollution issue. These materials are cheaper than similar products, simple to produce and stable against microorganisms. They also meet all modern requirements for construction materials. Sample preparation involves mixing the ingredients and then testing them. Typical recipes include a mixture of cement, sand and additives. New recipes are variations of old ones, obtained by changing the ingredients and their mass content. When preparing new samples, we added different percentages of finely dispersed waste tyre powder. This was added at the expense of reducing the quantity of sand. The waste tyre powder was added in quantities of 1%, 3%, and 5%. The standard sample was spread to a size of 24.5/24.5 cm in 1 minute for a self-levelling floor. The best results were obtained with the addition of 5% waste tyre powder. In addition to the waste tyre powder, the mixture contained 1% diethylene glycol monomethyl ether and methyl cellulose at various weight ratios.

Keywords: glue, rubber, composite

I. Introduction

Improvement of ecological state of the environment is one of the most important issues of modern times. In this regard, it is essential to deepen the knowledge of those environmental problems, which are related to application of polymeric materials. Environment protection from domestic waste pollution posing real threat to the environment has to become a main care for each member of the society. This work foresees familiarization with the second aspect of waste disposal and management – the opportunity of harmful waste transformation into useful products, which is realized through chemical and technological processes, as well. Plastic waste disintegrate into small pieces in rivers and are eaten by fishes. Afterwards these wastes hit human organism and have a harmful effect on health. Prevention of plastic pollution means salvation of water habitants as well and this fact is acknowledged well in the European Union. In March 2019, the European Parliament adopted the law prohibiting production of single use plastic, for example plastic plates, knives and forks, ear sticks and other similar products. At the same time, a new processing method has been instituted (collection of 90% of plastic bottles until 2029) and increased responsibility of manufacturers has been established. Plastic is one of the most stable environmental pollutants and over the last 50-60 years it has been collected in vast numbers worldwide. It should be noted that it is not a problem for humans only. Plastics remain stable for a

long time, and some of them – up to 100-500 years, so it is obvious that such type of waste creates a problem for the environment and represents one of the most stable pollutants. This work is important both from ecological viewpoint and in the light of receipt of new materials, in particular, receipt of new safe, ecologically clean composite waterproofing materials on the basis of household plastics, rubbers and glass waste, which are applicable in the construction industry [1-6].

Environment protection problem may be solved by two ways – waste destruction and disposal (recycling). The latter implies its transformation into useful products. Burial and incineration are among main destruction methods of solid domestic waste and packing materials. Burial of solid domestic waste requires allotment of large land areas for landfills. Obviously, these lands become unfit for further useful application. Roughly 90% of solid domestic waste are disposed at landfills (garbage dumps), which occupy more than 20 000 hectares of land area. So, each of these landfills "swallows" hectares of lands. In addition, valuable secondary raw materials (waste paper, plastic, glass, metals etc.), which necessarily must be involved in the beneficial industrial cycles, are brought to the landfills. Incineration may be applied both to solid and liquid waste. This method is neither rational nor cost-effective, since toxic gases (SO_2, NO_2, CO) are separated during burning. This process is accompanied by rapid wear of equipment (garbage furnaces), emission of harmful combustion products into atmosphere and therefore its recontamination, and penetration of heavy metals, toxic salts into soil and water, and thereby into human organism. Garbage burning equipment, as a rule is a complex and expensive device, since it has to be equipped with effective filters and gas traps. Due to this reason, this method of solid domestic waste destruction is not frequently used. Domestic and industrial residuals, which are suitable for further processing are called secondary polymer wastes. They include unprocessed goods made of polymers and other materials, composite materials, which have lost their consumer properties due to physical wear [7-10].

II. Experimental Part

Based on the household plastics, glass and rubber available in the Black Sea coastal area, as well as using renewable vegetable raw materials, new organosilicon binder and antipyrene for the first time there have been received new ecologically safe polymer composites. The mentioned composites as waterproofing materials may be used in construction materials, for manufacture of drawing and building paints and household goods. These composite materials have been studied regarding their water absorption, bending and tensile strength, impact strength (viscosity), physical-mechanical and thermal properties, and supramolecular structure of surfaces using SEM scanning electron microscope.

Sample preparation is a direct process and it includes mixing of different ingredients in an ordinary container. Selection of mixer, ingredients' blending and testing of obtained composite occurs depending on total mixture mass. Cement, sand and fillers are among typical main ingredients. New recipes are variations of old ones, with alteration of quantity of components, their mass content and change of ingredients (mainly fillers).We have prepared new samples, for which purpose we have added powdered glass in different quantities. Glass was added at the expense of sand amount reduction. 1, 3 and 5% of glass and in all cases 5% of grinded rubber tire powder were added (Table 1). In addition to waste tire powder, 1% of diethyleneglycol ethyl ether and methylcellulose were added to the mixture in different weight ratios.

In order to keep waste tire powder usability and for its safe use, we have determined the content of toxic elements established under the European Union regulations for polymeric materials.

The course of analysis: we removed moisture from the waste tire powder sample (using thermostat, at 105°C, down to permanent weight), took 1000g sample for analysis, which was

annealed in furnace at 300-350°C within an hour. A burnt sample was moved to cylindrical vessel, then 20 ml of aqua regia (3 volume fractions of HCl (37% merk) + 1 volume fraction of HNO_3 (65% merk)) was added and solution was dried over the electric stove until getting a dry residue. This procedure was repeated twice. 5 ml of dissolved HCl (in the ratio of 1:1) was added to obtained dry residue and this solution was held for 24 hours at room temperature. Solution was filtered and a filtrate was filled up to 100 ml with deionized water using measuring flask. We determined the content of some toxic heavy metals (As, Cd, Pb, Zn, Cr, Cu, Co, Ni, Mn etc.) as well as alkaline and alkaline-earth metals in the obtained filtrate with the use of microwave plasma- atomic emission spectroscopy (MP-AES) [11]. For measurements we used device of MP-AES 4210 series (Fig. 1). Obtained results are given in Table 2.



Figure 1: *Agilent 4210 MP-AES*

New composite materials were tested for adhesion ability. Adhesion is mainly determined on a periodical basis, depending on which sample is tested. In our case, an experiment was held in 7- or 28-day interval. Results are given in Table 3.

In order to test adhesion to waterproofing materials, square-shaped samples were prepared, which afterwards were attached to cement tile. Preparation process starts with cutting of large tiles, which is followed by tiles' inspection. Each tile has to have specific size in order to avoid erroneous results during an experiment, and they are checked using a ruler, respectively their size has to meet relevant rules and regulations. After preparation, tiles are glued to large cement tiles. It is necessary to prepare surfaces properly, typically a surface must have two layers, after putting the second layer we glue small tiles, put weight on them and then remove it in a given time. We are waiting for it to dry. After completion of this process we glue metal plates to attached tiles using epoxide. In a few days, using adhesiometer we measure a force needed to tile detachment. It should be noted that a great attention is paid to what a surface remained on a plate after detachment.

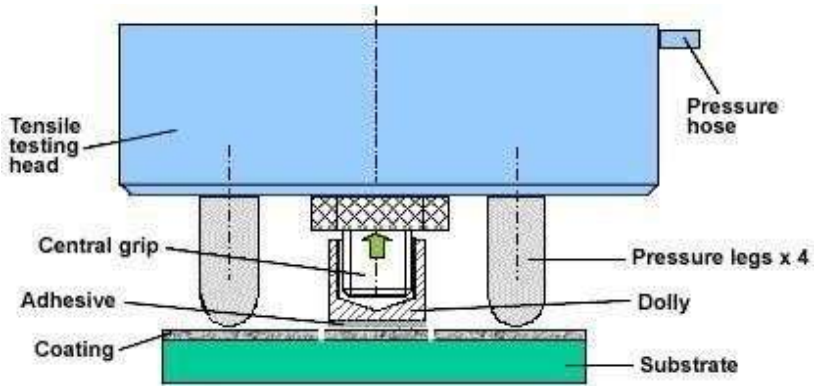


Figure 2: *Pressure device*

Experiment for fracture resistance and pressure resistance is conducted at the pressure device (Fig. 2). The role of this experiment lies in the fact of determination how many kilopascals are necessary to fracture the product and not to experience structural failure due to pressure. Special molds prepared in the special equipment are necessary for carrying-out the experiment. During an experiment, the fracture resistance is determined first and then we move to pressure using an interface of equipment. Then the fractured plates are thrown it the garbage. After obtaining results takes place their inventory, accounting and numeration in the journal. This experiment depends on the product, since cement glue working properties are totally different than those of such materials as liquid floor etc. As a rule, this experiment depends on visual perception of experimenter. For instance, for cement glue inspection, after mixing takes place determination of blending sensitivity with the use of spatula (putty knife), then by spatula hitting on the mixture is determined, whether an imprint is left on spatula or no, thereafter a strength of gluing to spatula is measured and then a quantity left on spatula is determined.

Surface spreading and cutting time. Experiment for surface spreading is carried out for liquid floors and is aimed to determination of time, after which a floor loses its liquid properties. Performance of experiment requires a flat, glossy surface, on which special round-shaped molds are placed. Molds are filled with a liquid floor, after definite period of time the molds open vertically, a floor is spread over the surface, then within 10-minute intervals a floor is cut with a spatula, and through visual observation we establish whether the cut surface has been filled or not. Also, it is necessary to measure surface spreading diameter using ordinary ruler. After obtaining results takes place their inventory, accounting and numeration in the journal. For experiment it is necessary to put a plate on horizontal surface, on which a weight is put after 2 minutes, thereafter a surface is stacked vertically for a definite time, during which a plate comes down by a definite distance. This distance is measured using special device, when a surface is put horizontally.

Correction time. Correction time is used for establishment of product petrification time, or else a time after which the constructional correction become impossible. This experiment is similar to adhesion with the only difference that tiles are attached to foam plastic and after a definite period of time they rotate by 180 degrees (do a U-turn).

Mold preparation. Preparation of mold is necessary for many experiments, they are prepared not only for establishment of compression degree, but also for determination of fracture resistance and pressure resistance. Molds are prepared in a special iron container consisting of 3 sections. A material has to be lubricated prior to its putting in order to avoid adhesion (gluing). Afterwards molds are placed in a special device and firmly attached to it. After attachment, we fill molds, switch on the device and wait until it finishes its work, following which we extract obtained mold and put it into archive. It has to be noted that they must be wrapped in cellulose film and wet cloth in order to keep the water content of the mold.

Compression test. Compression is a process experienced by a construction material after definite period of time, it is measured within 1-28-day interval. This is a simple process, as a rule 3 molds are prepared, which are placed on the pressure device (Fig. 1). After placement, it is measured to what extent the prepared mold is compressed.

III. Result and discussion

As is was mentioned in the experimental part, different percentages of glass and in all cases 5% of rubber tire powder were added for receipt of new composite materials. Results of mechanical parameters' determination for new composite materials are given in Table 1, from where is seen that a standard extension of a sample CN 68 equals to 24,5/24,5 cm after 1 minute. The best possible results close to this value are obtained when 5% of glass were added.

Results of different elements' determination in waste tire powder used for receipt of new waterproofing materials are presented in Table 2. Based on the obtained experimental data one may consider that the content of none of the toxically hazardous heavy metals in waste tire powder exceeds permissible standards established for heavy metals in polymeric materials. This fact points at the usability of waste tire powder and in addition, at its safe use as a raw material for receipt of waterproofing materials.

Table 1: *Results of mechanical parameters' determination for obtained composite (waterproofing) materials*

Sample	Bending, MPa	Compression, MPa	Extension (min)	Days	Storage conditions
CN68	1,74	7,2/7,2	24,5/24,5 cm	1	23°C/50% humidity
	5,17	18,1/18,6		28	23°C/50% humidity
CN68 + 5% glass + 5% rubber tire	1,7	7,6/7,5	23/23 cm	1	23°C/50% humidity
Powder	4,8	18,5/18,1		28	23°C/50% humidity
CN68 + 3% glass + 5% rubber tire	1,7	8,12/8,12	23,5/23,5	1	23°C/50% humidity
Powder	5,25	19,2/19,2		28	23°C/50% humidity
CN68+ 1% glass + 5% rubber tire	1,7	7,55/7,84	24/23,5	1	23°C/50% humidity
Powder	5,0	19,2/18,4		28	23°C/50% humidity

Table 2: *Content of some metals (mg/kg) in waste tire powder*

Element	**mg/kg**	**NF EN 71-3, mg/kg [12]**
Aluminum (Al)	1 530	70 000
Antimony (Sb)	21	560
Arsenic (As)	1.4	47
Barium (Ba)	21	18 750
Cadmium (Cd)	1.0	17
Calcium (Ca)	4 710	-
Chromium (Cr total)	5.4	Chromium (III) - 460 Chromium (VI) - 0.2
Cobalt (Co)	26.3	130
Copper (Cu)	517.0	7 700
Iron (Fe)	4 909.9	-
Lead (Pb)	36.6	160
Lithium (Li)	2.0	-
Magnesium (Mg)	1 010	-
Manganese (Mn)	53.8	15 000
Molybdenum (Mo)	1.0	-
Nickel (Ni)	11.8	930
Sodium (Na)	571.4	-
Silica (Si)	53.0	-
Potassium (K)	944.6	-
Zinc (Zn)	6 417	46 000

Results of new composite (waterproofing) material tests for adhesion ability are presented in Table 3, from where is seen that adhesion ability is the best possible in case of adding 5% of glass compared to application of 1 and 3% of glass. In addition, 5% of glass content provides the best mechanical properties of composite materials obtained by us.

Table 3: *Test of new composite samples for adhesion ability*

CM 11 + adhesion in standard condition after 14 D.	
Test method	EN 12004-2:2012/2018
Storage conditions	23 ^{0}C/ 50% (humidity)
Standard	1.07 MPa
1% glass	1.1 MPa
3% glass	1.1 MPa
5 % glass	1.2 MPa
Comment	Glass addition at the expense of sand

IV. Conclusion

New recipes of cement glues, which are variations of old ones, have been developed. We have changed quantities of components entering cement glue and added new components, which respectively lead to percentage change of components and improvement of properties. Ethyl silicate, household plastic and rubber articles waste have been added to new samples prepared by us, which opens up the opportunity of harmful waste transformation into useful products using chemical and technological processes. None of the toxically hazardous heavy metals' content in waste tire powder exceeds permissible standards established for heavy metals' content in polymeric materials, which points at usability of waste tire waste as well as at its safe use as a raw material for receipt of waterproofing materials. One may draw conclusion that prepared new samples of cement glue, to which 1, 3, 5% of glass powder have been added and 5% of rubber waste have been taken in all interest cases, have improved their mechanical properties. The best results have been obtained when 5% of glass and 5% of powdered rubber tire have been added.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of.

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FINANCING OF INNOVATIVE PROJECTS FOR THE DEVELOPMENT OF REGIONAL INFRASTRUCTURE

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Abstract

The study aims to develop and justify a risk management system for infrastructure enterprises, with the goal of minimizing the negative impact of risks on their activities. This article examines existing risk management approaches, analyses modern scientific publications from 2020 to 2025, and proposes an original risk management system adapted for infrastructure enterprises. The main results of the study include the definition of the concept of a 'risk management system for infrastructure enterprises', an analysis of how such enterprises operate, the development of the main directions and measures to reduce risks, and the author's proposal for a risk management system. The article also describes the system's formation stages, funding sources, and tools and methods for assessing its efficiency. The study's findings demonstrate that implementing a risk management system increases the sustainability of infrastructure enterprises, reduces financial losses, and improves service quality. The proposed system can be used to optimize risk management processes within infrastructure enterprises, ultimately having a positive impact on their long-term competitiveness and sustainability.

Keywords: risk management, infrastructure enterprises, management system, risk assessment, indicators, efficiency

I. Introduction

Risk management is an important element of strategic management in infrastructure enterprises, which play a key role in ensuring the functioning of the economy and society. The risks faced by such enterprises include financial, operational, environmental, technological and regulatory threats. In an unstable external environment and increasing competition, effective risk management becomes critical to ensuring the sustainability and competitiveness of infrastructure enterprises.

The existing views on risk management methods in infrastructure enterprises can be divided into traditional and modern. Traditional approaches, such as insurance and reservation, are aimed at minimizing the consequences of risks that have already been realized. Modern approaches, including risk-based management and integrated risk management systems, involve predicting and preventing risks at early stages. However, research shows that many infrastructure enterprises still use outdated methods, which reduces their efficiency in a rapidly changing environment.

A review of scientific publications for the period 2020-2025 allows us to identify several key trends in the field of risk management. For example, Smith et al. (2020) emphasize the importance of integrating risk management into the strategic planning of infrastructure enterprises [14].

Cea, L. and Costabile, P. (2022) investigated flood risks in urban areas considering modelling, management and adaptation to climate change [11].

Sotamaa T., Reiman A. and Kauppila O. (2020) conducted a systematic review of the literature on risk management in manufacturing small and medium-sized enterprises in the modern era of digitalization and artificial intelligence development [15].

Aliyev A. G. (2022), Porath U. (2023) prove that organizations that effectively use digital technologies reduce risks, increase their security, gain a competitive advantage by optimizing resource allocation and more effective decision-making [9; 12].

Currently, researchers pay much attention to the issues of managing environmental risks of enterprises in the context of "green" development [13].

The issues of risk management efficiency in the public and state sectors are always relevant, affecting the interests of many categories of the population Aliyev A. G. (2022) [10].

Similar topics are also in the field of attention of Russian researchers. For example, Adamenko A. A., Avanesova R. R., Tsysov A. S., studied the conceptual foundations of creating effective risk management systems taking the characteristics of our country into account [16].

The integrated risk management model was proposed by I. P. Skobeleva, N. V. Legostaeva, N. E. Kalashnik [7].

Various aspects of risk management in relation to projects are considered by O. B. Ivanenko, S. I. Ponikarov, A. V. Semenov [18; 5; 6].

For infrastructure enterprises, it is of interest to study the relationship between risks and conditions of high uncertainty in the activities of companies [4], as well as to develop ways to prevent threats of their influence [8].

The study by T. A. Golovina, I. L. Avdeeva, D. A. Sukhanov (2022) analyzes risk assessment methods using big data and artificial intelligence [17].

However, despite significant progress in this area, many issues remain unresolved, including the lack of universal approaches to risk management for infrastructure enterprises.

The need to apply a risk management system in infrastructure enterprises is caused by several factors. Firstly, such enterprises are often monopolists or oligopolists, which makes them vulnerable to regulatory changes and public pressure. Secondly, their activities are associated with high capital expenditures and long payback periods, which increases financial risks. Thirdly, infrastructure enterprises often face environmental and social risks that can lead to significant reputational and financial losses.

Thus, the development and implementation of an effective risk management system is an urgent task for infrastructure enterprises. This article proposes an original approach to the formation of such a system, which considers the specifics of the functioning of infrastructure enterprises and modern trends in risk management.

II. Methods

Analysis of the current state of risk management systems at Russian enterprises of the infrastructure sector reveals an urgent need for their significant modernization. Historically, risk management has been perceived as a utilitarian, secondary function, remaining outside the scope of academic research. As a result, independent initiatives of enterprises to implement risk-oriented management systems often were limited to the formal reproduction of other people's models, borrowed primarily from the financial and investment fields, without considering the specifics of infrastructure activities. Rare attempts at scientific analysis of risk management were episodic and failed to form a holistic conceptual understanding of the problem.

Mainly universal approaches and research methods were applied within the framework of the stated topic: systemic approach, synthesis, methods of economic analysis, analysis of management systems, comparative analysis.

III. Results

Infrastructure is an integral element of any integrated economic system, acting as its necessary subsystem. It is a component of the economic structure, playing a supporting role and ensuring the smooth functioning of the economic or political system as a whole.

Market infrastructure is a complex set of organizational and legal forms that regulate the movement of goods and services, the processes of purchase and sale, as well as a set of institutions, systems, services, organizations and enterprises that serve the market and ensure its stable and efficient operation. Without a developed infrastructure, the modern market would not be able to perform its key functions of organizing commodity exchange. Infrastructure serves as a tool for implementing these functions, uniting interconnected economic entities, institutions and substructures into a single system.

Risk is an invariable element of the functioning of infrastructure enterprises, a condition for the manifestation of uncertainty factor of the outcome of future events in the external and internal environments. It is capable of giving three different meanings to the results of enterprises' activities:

- negative, when the risk turns into financial losses and damages;
- neutral (zero), in which economic indicators remain practically unchanged;
- positive, when the risk transforms the situation into economic benefits.

The risks inherent in this area of activity of the infrastructure enterprise can increase the impact of threats from the external and internal environment, weaken its competitiveness. In this regard, the implementation of measures to minimize the negative impact of risks becomes not only desirable, but also a necessary condition for the survival of the enterprise. This emphasizes the significant impact of risks on the activities of enterprises, which necessitates the regular development and implementation of practical actions to reduce their potentially negative impact at the micro level. At the same time, before starting to implement such measures, it is necessary to carefully identify and assess all possible risks, the consequences of their negative impact, and determine the effectiveness of their implementation.

Existing approaches to risk assessment can be divided into quantitative and qualitative. Quantitative methods include analysis of the probability and consequences of risks using statistical data. Qualitative methods are based on expert assessments and scenarios. In recent years, methods based on the use of big data and artificial intelligence have become increasingly widespread, allowing for more accurate risk prediction.

Infrastructure enterprises have a number of characteristics that affect their risk profile:

1. High capital costs – infrastructure enterprises often require significant investments in fixed assets, which, as a rule, leads to long payback periods.

2. Regulatory dependence means that the activities of such enterprises are often largely regulated by the state, which creates additional risks.

3. Social responsibility – infrastructure enterprises play a key role in ensuring the functioning of society, which increases their vulnerability to reputational risks.

4. Technological complexity – the use of complex technologies increases the probability of operational risks.

To maintain their competitiveness, infrastructure enterprises are forced to regularly determine the main directions and sets of measures to reduce risks.

To minimize the negative impact of risks on infrastructure enterprises, the following areas can be identified (Table 1):

Table 1: *Some directions for minimizing the negative impact of risks on infrastructure enterprises*

Title of the risk management direction	Contents
Financial risk management	Diversification of funding sources, creation of reserves, insurance
Operational risk management	Implementation of monitoring and control systems, automation of processes
Regulatory risk management	Interaction with regulators, lobbying for the interests of the enterprise
Environmental risk management	Implementation of environmental standards, monitoring of environmental impact

The infrastructure enterprise risk management system (IERMS) is a set of methods, tools and processes that, taken together, ensure the identification and study of factors that can influence the strategic goals of the enterprise, as well as measures to reduce their destructive impact.

The IERMS is aimed at identifying, assessing, minimizing and monitoring risks that may affect the achievement of the enterprise's strategic goals.

The IERMS includes the following mandatory elements: detection, identification and systematization of risks; risk assessment, development of new risk management strategies, implementation of measures and realization of selected risk management strategies at the infrastructure enterprise; monitoring and control.

Let's define the main content of the elements of an infrastructure enterprise risk management system.

1. Detection, identification and systematization of risks in the IERMS includes the definition of all possible risks that an enterprise may face.

The process begins with a thorough analysis of internal and external factors that can negatively affect the achievement of the enterprise's strategic goals. Internal factors include operational processes, financial condition, personnel management, and technological infrastructure. External factors include changes in legislation, economic instability, actions of competitors, natural disasters, etc.

Risk identification requires the use of various methods, such as brainstorming, historical data analysis, SWOT analysis and expert assessments. It should be considered that each identified risk should be clearly formulated, indicating the probability of occurrence and potential consequences for the enterprise.

Systematization of risks for use in the IERMS involves their classification by various criteria, such as risk type (financial, operational, strategic), level or area of occurrence (e.g. federal, regional, local), area or industry of impact (production, services, marketing, logistics), degree of

impact on the enterprise's activities. This allows for prompt and more effective risk management, and development of adequate measures to minimize their impact. The summary result of the process of detecting, identifying and systematizing risks at an infrastructure enterprise is the formation of a risk register, which contains detailed information on each risk, including its description, causes of occurrence, potential consequences, probability of implementation and measures for managing it. The risk register can serve as a basis for developing a risk management strategy containing reasonable measures to reduce the negative consequences of their influence.

2. Risk assessment in the IERMS means a detailed analysis of the probability of occurrence and consequences of each risk.

Risk assessment is a determining step in the risk management process, aimed at determination of the probability of occurrence for each identified risk and the potential impact of its consequences on the project or organization. At this stage, both qualitative and quantitative analysis is carried out, providing a comprehensive understanding of the risk situation. Qualitative risk analysis, using such techniques as expert assessments, brainstorming, and scenario analysis, focuses on subjective assessment of the probability and consequences of risks occurring. The result of the analysis is a risk matrix that classifies risks according to their degree of severity. Quantitative analysis, on the other hand, uses statistical methods and modeling to numerically assess the probability and impact of risks. Methods include sensitivity analysis, Monte Carlo simulation, and decision trees.

Risk assessment results are used in the IERMS to develop risk response strategies, such as avoiding, reducing, transferring or accepting risk. Effective risk assessment enables enterprises to make informed decisions and minimize potential damage from adverse events.

3. Development of new risk management strategies in the IERMS includes the selection of risk minimization methods (avoidance, reduction, transfer, acceptance).

The choice of risk minimization methods is an essential condition for developing an effective risk management strategy. Each of the methods used (avoidance, reduction, transfer and acceptance) has its own advantages and disadvantages, so the choice of the most acceptable one depends on the nature of the risk, the value of its potential impact and the available resources.

Risk avoidance involves the complete elimination of the type of activity that may lead to the emergence of risk. This method may be effective for risks with unacceptably high potential losses, but it can limit the profit opportunities for the infrastructure enterprise.

Risk reduction aims to reduce the probability of risk occurrence or mitigate its consequences. It may include implementing additional security measures, improving processes, and training personnel.

Risk transfer involves shifting responsibility for a risk to another party, for example, through insurance or risk transfer contracts.

Risk acceptance is a conscious decision to accept a risk and its potential consequences. This method is typically used for low-impact risks or when the cost of risk reduction or transfer exceeds the potential loss.

4. Implementation of measures and realization of selected risk management strategies at the infrastructure enterprise.

The implementation of risk management measures involves the development and implementation of a set of specific actions in the risk management system that reduce the probability of adverse events occurrence, as well as minimizing their potential consequences for the infrastructure enterprise. This process includes identifying the most significant and dangerous risks, developing plans and projects to respond to them, and allocating resources to plans and projects for their effective implementation. The implementation of selected risk management strategies requires clear coordination between various departments of the enterprise and the

involvement of competent specialists in the IERMS. An important aspect is monitoring the efficiency of the implemented measures and timely adjustment of strategies if necessary.

Successful implementation of risk management strategies requires adequate training of staff, development of communication procedures and establishment of specific reporting forms. Regular assessment of the efficiency of the implemented measures in the IERMS allows identifying weak points and making adjustments to increase the resilience of the infrastructure enterprise to various types of risks.

The implementation of risk management measures and selected strategies is carried out as a dynamic and continuous process that requires comprehensive analysis and appropriate optimization. Only with such a systematic approach an enterprise can protect its assets from threats, create conditions for uninterrupted functioning and achieve its strategic goals in full.

5. Monitoring and control in the IERMS mean methods of continuous monitoring of risk factors, as well as adjustment of planned action for the implementation of new strategies for managing identified risks at an infrastructure enterprise.

Monitoring and control are an integral part of the risk management process, ensuring timely detection of unacceptable deviations from the intended targets, as well as prompt response of the enterprise management to emerging threats. The monitoring system provides for regular collection and analysis of data on the presence of risks, their current state, as well as an assessment of the efficiency of measures implemented to reduce their negative impact.

For the IERMS, a mandatory element of monitoring is the definition of clear criteria and indicators that allow for a quantitative assessment of the risk level and tracking the dynamics of its change. These indicators may include the frequency of risk incidents, the amount of potential damage, the degree of readiness to respond to emergency situations, and other relevant parameters. Control, in turn, involves taking corrective measures based on the results of monitoring, for example, in the form of reviewing risk management strategies, making adequate and timely changes to action plans, and allocating additional resources. It is important that the control process be flexible and adaptive, allowing infrastructure enterprise employees to respond quickly to changing external conditions and the emergence of new risks.

Implementation of an effective monitoring and control system requires the active participation of all stakeholders, including the enterprise management, risk management personnel, external experts and consultants. Regular meetings, trainings and exercises help to increase the awareness of the infrastructure enterprise personnel about risks and prepare them for actions in case of emergency situations.

In a graphic form, the system can be represented as a cyclic model that includes all the stages considered above.

The core of the risk management system is formed by the following elements:

- goals, which are aimed at minimizing the negative impact of risks on the enterprise activities;
- tasks, that include identification, assessment, management and monitoring of risks;
- principles, i.e. systematicity, complexity, continuity, adaptability;
- functions – risk analysis, strategy development, implementation of measures, control.

The stages of forming a risk management system may be determined by the state and characteristics of the infrastructure enterprise. The following stages may be considered as mandatory stages of forming a risk management system:

1. Preparatory stage – analysis of the current situation, determination of goals and objectives.
2. System development – creation of methodology and risk management tools.
3. Implementation of the system – personnel training, integration of the system into business processes.

4. Monitoring and improvement – continuous monitoring of the system efficiency and its adjustment.

Financing the creation and ensuring the current functioning of the risk management system can be carried out using the enterprise's own funds, government subsidies, and also by attracting external investors.

In the risk management system of an infrastructure enterprise various tools can be used, which it is reasonable to combine into functional groups:

- a group of analytical tools including SWOT analysis, PEST analysis, scenario modeling;
- a group of technological tools, including monitoring systems, risk analysis software, etc.;
- a group of financial instruments (insurance, hedging, creation of reserves).

The enterprise should regularly assess the effectiveness of the risk management system, based on the results of which management decisions are made on the expedience of its adjustment.

The efficiency of the risk management system can be assessed using key performance indicators (KPI), such as the level of loss reduction, the degree of strategic goals' achievement, and stakeholder satisfaction.

IV. Discussions

The results of the research show that the proposed risk management system allows to effectively minimize the negative impact of risks on infrastructure enterprises. Comparison with the results of other authors shows that the proposed approach is more comprehensive and adaptive, which makes it applicable in various conditions. However, for the further improvement of the system, it is necessary to consider the specifics of each enterprise and constantly update risk management methods and tools.

V. Conclusions

1. The author's risk management system for an infrastructure enterprise has been developed, which includes identification, assessment, management and monitoring of risks.

2. The proposed system allows to minimize the negative impact of risks on the enterprise's activities.

3. The implementation of a risk management system helps to increase the sustainability and competitiveness of infrastructure enterprises.

4. The efficiency of the system can be assessed with the help of key performance indicators.

The proposed system can be used for optimization of risk management processes at infrastructure enterprises, which will ultimately have a positive influence on their long-term competitiveness and sustainability.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INVESTMENTS IN INFRASTRUCTURE AS A STRATEGIC TOOL FOR ECONOMIC DEVELOPMENT AND SOCIAL WELL-BEING IN THE CONTEXT OF DIGITAL TRANSFORMATION

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Abstract

This article examines the multifaceted nature of infrastructure investments as a strategic tool for economic development and social well-being. It analyses the relationship between infrastructure investment and economic growth at macro and micro levels, paying particular attention to the multiplier effects of infrastructure projects. It also considers current issues of infrastructure financing, including public–private partnerships and attracting institutional investors. Furthermore, it analyses modern approaches to assessing the effectiveness of infrastructure investment, taking into account long-term socio-economic effects and environmental aspects. Particular attention is paid to the digital transformation of infrastructure and the integration of innovative technologies into traditional systems.

Keywords: infrastructure investment, infrastructure, investment, economic growth, public-private partnership, sustainable development, digital infrastructure

I. Introduction

Infrastructure is a complex of interconnected service structures, systems and objects that provide the basis for the functioning of the economy and the life of society. In a broad sense, infrastructure is a fundamental material, technical and institutional base that creates conditions for the implementation of production, social, managerial and other types of activities. From an economic point of view, it is characterized by a number of specific properties: high capital intensity, long life cycle, significant positive external effects, network nature, scale effect and indivisibility of objects [[1]]. Infrastructure often has the characteristics of a public or quasi-public good, which determines the specifics of its financing and management.

Infrastructure is a fundamental basis for the functioning of the modern economy and the life of society, acting as a necessary condition for the efficient production of goods and services, the free movement of people, goods and information. High-quality infrastructure creates a mechanism for a multiplier effect on economic growth by reducing transaction costs, increasing labor and capital productivity, expanding access to markets and resources, and creating conditions for technological innovation. Research by the World Bank and the IMF shows that an increase in infrastructure investment by 1% of GDP can lead to long-term GDP growth of 1.5%, which confirms the exceptional importance of infrastructure as a driver of economic development [[6]]. Moreover, infrastructure plays a key role in addressing today's global challenges, including urbanization,

climate change and digital transformation, determining not only current economic dynamics but also long-term prospects for sustainable development.

II. Methods

The social significance of infrastructure is no less important, since it directly affects the quality of life of the population, determining the availability of education, health care, cultural goods and other social services, as well as shaping the quality of the environment and living space. Access to basic infrastructure remains one of the key factors in reducing inequality and increasing social mobility, which is especially important for developing countries, where infrastructure limitations often become an insurmountable barrier to the socio-economic development of entire regions. According to the UN, investment in infrastructure is directly related to the achievement of at least 9 of the 17 Sustainable Development Goals [[7]], including poverty eradication, food security, health and well-being, quality education and gender equality. Infrastructure development is therefore not just a technical or economic issue, but a key condition for social progress and the formation of an inclusive society oriented towards meeting the needs of all its members.

The classification of infrastructure objects is presented in Fig. 1.

INFRASTRUCTURE FACILITIES		
Transport infrastructure	**Energy infrastructure**	**Public utilities infrastructure**
❑ Highways and bridges ❑ Railway infrastructure ❑ Ports and waterways ❑ Airports and air navigation systems ❑ Pipeline transport ❑ Multimodal logistics complexes	❑ Electricity generation facilities (thermal power plants, nuclear power plants, hydroelectric power plants, renewable energy facilities) ❑ Electrical networks and substations ❑ Gas transportation systems ❑ Heating systems ❑ Energy storage facilities ❑ Energy efficient technologies	❑ Water supply and sanitation systems ❑ Waste management facilities ❑ City Lighting ❑ Improvement of territories
Telecommunications infrastructure	**Social infrastructure**	**Institutional infrastructure**
❑ Multi-generation communication networks ❑ Data centers ❑ Broadband Internet Access ❑ Satellite communication systems ❑ Infrastructure for Internet of Things technology	❑ Educational institutions ❑ Healthcare facilities ❑ Sports facilities ❑ Cultural institutions ❑ Social security facilities	❑ Public administration systems ❑ Development financial institutions ❑ Legal and regulatory mechanisms

Figure 1: *Classification of infrastructure objects*

III. Results

The modern understanding of infrastructure also includes the concept of "critical infrastructure" – systems and facilities whose disruption could lead to a significant negative impact on national security, the economy and public welfare [[5]]. In the context of the digital transformation of the economy, the concept of "smart infrastructure" is of particular importance. It is characterized by the integration of physical objects with digital technologies, including the Internet of Things, big data and artificial intelligence, which allows optimizing the operation of infrastructure facilities, increasing their efficiency and adaptability to changing conditions.

Thus, infrastructure is a multidimensional economic phenomenon, covering a wide range of tangible and intangible assets, ensuring the functioning and development of the economic system and social sphere of the state. In the context of global economic challenges and increasing international competition, investments in infrastructure are acquiring strategic importance for ensuring the sustainable development of national economies.

Infrastructure investments are long-term capital investments in infrastructure facilities with the aim of creating, modernizing or expanding material and technical and organizational and economic systems that provide fundamental conditions for the functioning of the economy and the life of society. This type of investment has a number of specific characteristics that determine their special place in the economic system:

- long-term nature – infrastructure investments imply a long payback period, often measured in decades, which requires a strategic approach to planning and implementing such investments;
- high capital intensity – the implementation of infrastructure projects requires significant initial capital investments, which creates significant barriers for private investors and determines the need for state participation;
- multiplier effect – infrastructure investments generate significant economic effects, stimulating the development of related industries and creating conditions for long-term economic growth;
- social significance – the results of infrastructure investments have wide public use and affect the quality of life of the population, often going beyond purely economic criteria of efficiency;
- network nature – many infrastructure facilities function as parts of a single system, which requires coordination of investment decisions and an integrated approach to infrastructure development;
- significant positive externalities – infrastructure investments create positive externalities that cannot always be monetized by the investor, which determines their underfunding under the conditions of a market mechanism [[2]].

The essence of infrastructure investment is not only the creation of physical assets, but also the formation of fundamental conditions for economic growth, increased productivity and competitiveness of the economy as a whole. In modern conditions, they are also considered as a tool of countercyclical regulation: during economic downturns, states often increase the volume of infrastructure investment to stimulate aggregate demand and create jobs. Infrastructure investment is characterized by significant diversity and can be classified according to various criteria (Fig. 2).

Infrastructure investments play a key role in the economic development of states and regions, forming the basis for sustainable growth and improving the quality of life of the population. Depending on the goals, scale and nature of the objects, four main types of infrastructure investments can be distinguished, each of which has its own characteristics, advantages and areas of application.

Thus, greenfield investments are aimed at creating completely new infrastructure facilities "from scratch" [[4]]. These projects are implemented in previously undeveloped territories or in areas where the corresponding infrastructure was absent. Key features of investments in infrastructure greenfield projects include: high initial costs, significant freedom in design and

planning, no restrictions associated with existing facilities, a long payback period (usually 15-30 years), and increased risks due to the lack of operational history. Examples of such investments are the construction of new airports, the laying of new railway lines, the construction of new power plants, the creation of new reservoirs.

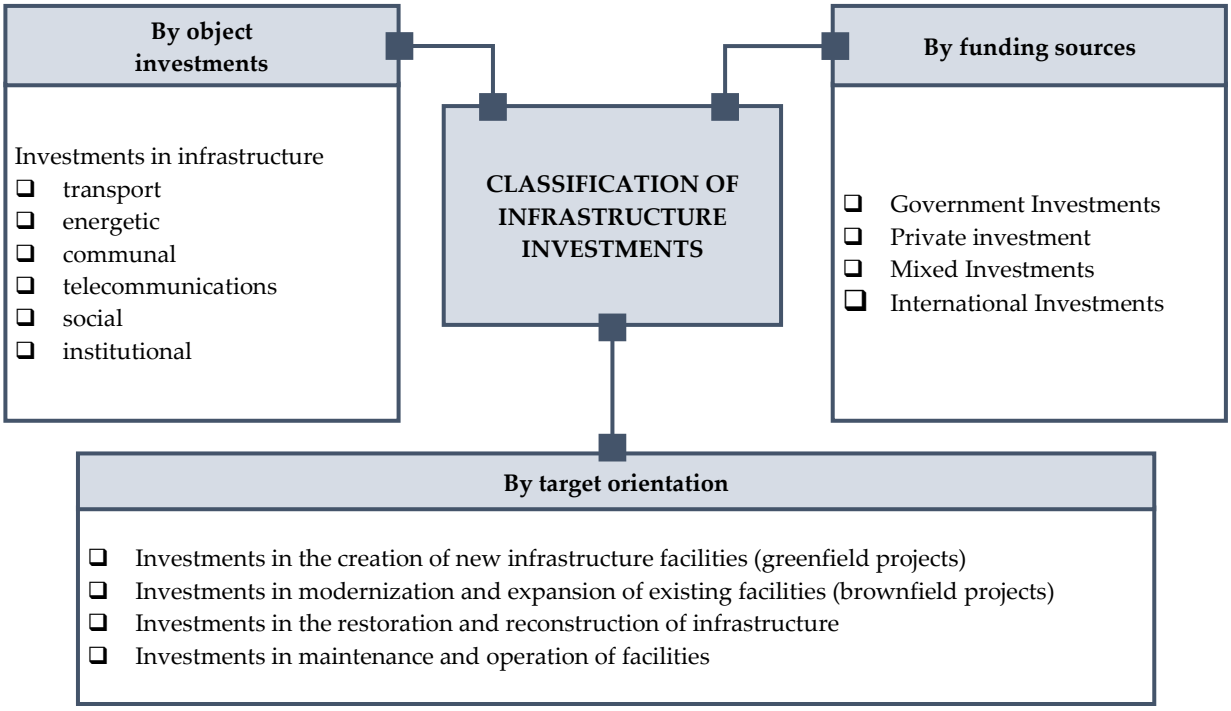


Figure 2: *Classification of infrastructure investments*

IV. Discussion

Brownfield investments are aimed at expanding, modernizing, or refurbishing existing infrastructure facilities to improve their efficiency or increase their capacity. The features of such infrastructure investments are lower initial costs, shorter implementation periods, more predictable risks due to the presence of an operational history, a relatively quicker achievement of the break-even point, and some limitations associated with the existing infrastructure. Examples of such investments include investments in the expansion of port terminals, modernization of electrical networks, expansion of highway capacity, and updating of telecommunications equipment.

Significant infrastructure investments also include investments in restoring the functionality and upgrading obsolete or damaged infrastructure facilities to extend their service life or adapt them to new requirements. The main characteristics of such investments are their focus on extending the life cycle of infrastructure systems, upgrading the technological base, and reducing operating costs in the long term. This type of investment often includes elements of modernization and may involve improving the environmental performance of the relevant facilities. Examples of such projects include: reconstruction of bridges, restoration of historic buildings while maintaining their functionality, upgrading urban sewer systems, and reconstruction of obsolete industrial facilities.

Investments in maintenance and operation are aimed at maintaining the current functioning of infrastructure facilities, preventing their premature wear and tear, and ensuring uninterrupted

operation. The features of this category of infrastructure investments are the regularity and repeatability of investments, relatively small amounts compared to other types of investments, critical importance for preventing more expensive repairs, direct impact on operational efficiency, and ensuring user safety. Such investments include scheduled road surface repairs, regular maintenance of water supply systems, maintenance of equipment at power plants, and seasonal preventive maintenance on utility networks.

Ensuring adequate financing for infrastructure projects is one of the key problems of economic development for both developed and developing countries. The diversity of sources of infrastructure financing reflects the complexity and comprehensive nature of infrastructure projects, as well as the diversity of mechanisms for attracting capital to this sector of the economy.

Public investment has traditionally played a dominant role in financing infrastructure projects, which is due to a number of objective factors. First of all, many infrastructure projects are public or quasi-public goods, characterized by non-excludability and/or non-rivalry in consumption [[3]]. These characteristics make private financing of such objects economically inexpedient and determine the need for state participation. State financing of infrastructure is carried out through various channels and mechanisms: direct budget investments, state infrastructure funds, investment programs of state companies and natural monopolies, targeted state programs for infrastructure development.

Direct budget investments are the most traditional and widespread mechanism, whereby infrastructure projects are financed directly from federal, regional or municipal budgets. This mechanism is especially relevant for socially significant infrastructure facilities, such as educational institutions, healthcare facilities, and public road networks. The advantages of direct budget financing are the relative simplicity of administration and the possibility of implementing projects with low commercial but high social returns; the disadvantages include budget constraints and the risks of inefficient use of funds in the absence of market incentives.

State infrastructure funds are specialized financial institutions created by the state for the targeted financing of infrastructure projects. These funds can be formed from various sources, including tax revenues, income from the export of natural resources, income from privatization, and others. Examples of such funds are the National Welfare Fund in Russia, infrastructure funds at the level of individual states in the United States, and the National Infrastructure Fund in the United Kingdom. The advantage of creating specialized funds is the possibility of long-term planning and financing of infrastructure projects, regardless of short-term fluctuations in budget revenues [[2]].

Investment programs of state-owned companies and natural monopolies are an important channel for financing infrastructure, especially in strategic sectors of the economy. State-owned companies in the energy, transport and telecommunications sectors implement large-scale investment programs aimed at developing the relevant infrastructure. The mechanisms for financing such programs may include both the companies' own funds and debt financing under state guarantees, as well as various forms of state support, including interest rate subsidies and tax incentives.

Targeted state infrastructure development programs involve a comprehensive approach to financing interrelated infrastructure projects within a single development strategy. Such programs are often implemented at the national level and cover both the modernization of existing and the creation of new infrastructure. Examples of such programs are National Projects in Russia, the Infrastructure Investment and Jobs Act in the United States, and the TEN-T transport infrastructure development program in the European Union.

Attracting private capital to infrastructure projects allows not only to overcome the limitations of public financing, but also to increase the efficiency of project implementation by introducing market incentives, advanced technologies and management practices. Corporate investments are investments of private companies in the creation and modernization of infrastructure facilities necessary for their production activities. This mechanism is most common in sectors with a high

degree of commercialization, including telecommunications, energy, and port infrastructure. Corporate investments can be made both at the expense of the companies' own funds and by attracting debt financing on market terms.

Infrastructure funds allow attracting funds from institutional investors to infrastructure projects, including pension funds, insurance companies, sovereign wealth funds, which are characterized by a long-term investment horizon corresponding to the life cycle of infrastructure facilities. Infrastructure bonds are a specialized financial instrument that allows attracting funds from a wide range of investors to finance infrastructure projects. Bonds can be issued both by private companies implementing infrastructure projects and by specialized project companies within the framework of public-private partnerships. Infrastructure bonds often imply the presence of certain state guarantees or tax benefits that increase their attractiveness to investors.

Project financing is a mechanism for attracting long-term debt financing for large infrastructure projects, where the main collateral is future cash flows from the project. This mechanism involves the creation of a special project company (SPV), which is responsible for the implementation of the project and servicing the attracted financing. Project financing allows structuring complex financial schemes involving various types of investors and creditors, as well as optimally distributing project risks between its participants.

Venture capital investments have become a significant source of financing for innovative infrastructure projects in recent years, especially in the field of digital infrastructure and smart cities. Venture capital funds and business angels invest in startups developing technological solutions for infrastructure problems, which contributes not only to financing, but also to the technological modernization of the infrastructure sector. Despite the growth of private investment in infrastructure, their share in the total volume of infrastructure investment remains relatively low, which is due to a number of limitations, including high risks of infrastructure projects, regulatory uncertainty, difficulty in assessing long-term projects, and other factors.

Public-private partnership (PPP) has become one of the key mechanisms for attracting private capital to infrastructure projects while maintaining strategic control by the state. PPP is an institutional and organizational alliance of the state and business, created for a certain period to implement a specific project and ceasing to exist after its completion. The development of PPP mechanisms requires the formation of an adequate institutional environment, including legislative regulation, dispute resolution mechanisms, a system of guarantees for investors, as well as the development of the competencies of government agencies in the field of structuring and managing PPP projects.

International investment plays an important role in financing infrastructure projects, especially in developing countries that face limited domestic sources of capital. Thus, international development finance institutions, including the World Bank, regional development banks (Asian Development Bank, African Development Bank, Inter-American Development Bank, etc.), provide concessional financing and technical assistance for the implementation of infrastructure projects in developing countries. Financing can be carried out both in the form of direct loans and through co-financing mechanisms with private investors, provision of guarantees and other instruments. International financial institutions also play an important role in developing standards and best practices in the field of sustainable infrastructure development.

New international financial institutions, in particular the Asian Infrastructure Investment Bank (AIIB) and the New Development Bank of the BRICS, initiated by China, are actively increasing financing of infrastructure projects in Asia, Africa and Latin America. These institutions focus on financing projects in the fields of transport, energy, digital infrastructure and social development. National external infrastructure financing programs, such as China’s Belt and Road Initiative, Japan’s Partnership for Quality Infrastructure, and the US’s Build Back Better World initiative, provide financing and technical support for infrastructure development in partner countries. Such programs often combine economic goals with the geopolitical interests of donor countries.

International infrastructure funds, including sovereign wealth funds, pension funds, and insurance companies from developed countries, are increasingly investing in infrastructure projects on a global scale, viewing them as a source of stable long-term income and a way to diversify their investment portfolio. Cross-border infrastructure projects are a special category of international infrastructure investments implemented jointly by several countries. Such projects are especially common in the areas of transport (international transport corridors), energy (cross-border power grids, international gas pipelines), and telecommunications (underwater communication cables). Financing of such projects is often carried out through complex international consortia involving public and private partners from different countries.

At the present stage, the infrastructure financing sector faces a number of significant challenges that determine the evolution of capital raising mechanisms:

1) Global infrastructure gap – various international organizations estimate that infrastructure investments of USD 3.5 – 4.5 trillion annually are required to meet the growing needs of the global economy and achieve the UN Sustainable Development Goals, while actual investments amount to approximately USD 2.5 – 3 trillion, creating a significant funding gap [[7]];

2) Fiscal constraints – high levels of public debt in many countries limit the ability of public sector infrastructure financing and necessitate more active involvement of private capital;

3) Regulatory barriers – the complexity and instability of the regulatory environment, especially in developing countries, creates significant risks for private investors and increases the cost of capital for infrastructure projects;

4) Technological transformations – digitalization and decarbonization of the economy require large-scale investments in new types of infrastructure (digital, “green” infrastructure), as well as the modernization of existing infrastructure systems.

In response to these challenges, new trends in infrastructure financing are emerging:

1) Development of innovative financial instruments, including “green” and “social” bonds, sustainability-linked bonds, blended finance, which allows combining commercial financing with grant support for projects with high social or environmental impacts;

2) Creation of specialized platforms for connecting investors and infrastructure projects, including digital platforms that facilitate the process of structuring and financing projects, as well as reducing transaction costs;

3) Standardization of infrastructure projects and development of infrastructure as an asset class, which allows for increased transparency and comparability of projects for investors, as well as reduced investment risks;

4) Integration of ESG (Environmental, Social, Governance) criteria into the process of making investment decisions and assessing infrastructure projects, which reflects the growing attention to issues of sustainable development and social responsibility;

5) Development of new PPP models that take into account the lessons of previous experience and allow for a more effective distribution of risks and responsibilities between the public and private sectors.

Thus, infrastructure financing is a complex and dynamically developing area at the intersection of public policy, financial markets and the real sector of the economy. An effective combination of various sources of financing, including public, private, mixed and international investments, is a key condition for bridging the global infrastructure gap and ensuring sustainable development in the long term.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ASSESSMENT OF THE RELATIONSHIP BETWEEN PHYTOMASS AND PHYSICAL-GEOGRAPHICAL FACTORS IN THE FOREST LANDSCAPES OF GEORGIA

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Abstract

This paper examines the relationship between phytomass, one of the most essential landscape-geophysical parameters, and the physical and geographical factors of forest landscapes in Georgia. Relief, climate and soil conditions are discussed to reveal the features of phytomass distribution in different physical-geographical environments and explain the reasons behind them. Additionally, the study establishes the limiting factors that determine favourable natural conditions for the accumulation of maximum phytomass. The study primarily uses materials from field expeditions, but also makes use of published scientific works and archive materials from various agencies. The data were processed using GIS technologies and a number of thematic maps were created.

Keywords: landscapes, phytomass, field work, Georgia

I. Introduction

The study of forest resources is a critical issue aimed at addressing various problems facing humanity. The solutions must be based on these resources' economic and environmental functions [Lakida, 1996]. Due to the continuous growth of population, industries, and urbanization, forest cover is steadily declining, leading to significant negative impacts on the climate [1]. The sustainable use of forest resources has become especially important and can only be achieved through a comprehensive assessment of all components of forest ecosystems [2, 3].

Phytomass is one of the best indicators for analyzing processes occurring in a landscape, such as humidification—aridification, preservation—degradation, stability—sensitivity, and others. Based on this, it becomes possible to identify the natural potential and productivity patterns of various physical-geographical environments and the trends of their changes and other related aspects.

Numerous studies on phytomass content have been conducted and published in the world literature, including issues related to the dynamics and structure of phytomass [3-7], their estimates, carbon reserves [8-10], etc. However, estimates of the extent of phytomass in the former Soviet Union have been limited in their publication within Western literature [11].

Some scientific studies have been dedicated to researching phytomass in Georgia [12-15]. These works focus on studying the phytomass of Caucasian landscapes at high taxonomic levels (subclass,

types, subtypes) and address issues related to the dynamics of phytomass based on data from the Martkopi physical-geographical station. A map of the phytomass of Caucasian landscapes has also been compiled [Tediashvili, 1984, stock materials], and the average amounts of phytomass have been determined at the level of landscape genera.

II. Materials and Methods

The study is primarily based on field data collected by the Research Laboratory of Studying Conditions of Environment by Aerial Methods from 1977 to 2005 (Fig. 1). Field data from 2013 to 2015 and 2021 to 2025 were also used in various scientific projects. Results from stationary observations (Martkopi Physical-Geographical Lab.) and semi-stationary observations (Amtkeli, Bakuriani, Bevreti, Kovaluki, Lagodekhi, and Kazbegi semi-stations) across different regions of Georgia were also utilized (Fig. 1). These studies were mainly conducted during the summer, providing a solid basis for data comparison. Moreover, data from various literary sources (primarily related to timber stock and biomass productivity) and archival materials preserved in different institutions were used.

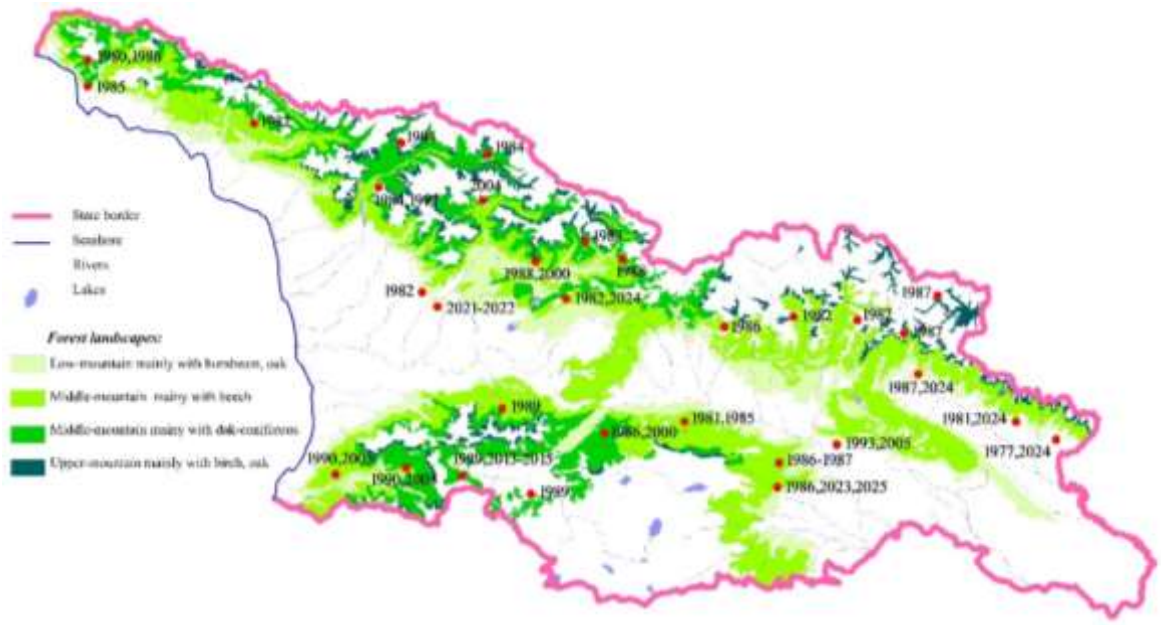


Figure 1: *Fieldwork in the forest landscapes of Georgia*

The research focuses on the concept of spatio-temporal analysis and synthesis of natural-territorial complex (NTK), developed by N. Beruchashvili in 1983 [13].

The identification of the spatial distribution characteristics of the geomass in Georgia's forest landscapes was carried out from various perspectives:

- Changes in the amount of phytomass across different physical-geographical environments;
- Identification of the physical-geographical factors that determine the accumulation of maximum geomass in specific conditions;

- Correlation of phytomass quantities with other geomasses (lithomass, pedomass, mortmass).
- Determination of the total amount of phytomass by landscapes of various ranks (types, subtypes, genera) and by types of the vertical structure of geosystems (average amount, variation range, and reserves).

III. Main Results

The general patterns of phytomass distribution in the mountain forest landscapes of Georgia.

The average amount of phytomass in Georgia's landscapes is 230 tons per hectare (t/ha), but it varies significantly, ranging from 0.1 t/ha to 1200 t/ha. Landscapes of mid-mountain beech-dark coniferous forests rank first in terms of average phytomass amount (over 500 t/ha) [Nikolaishvili, 2009], while semi-desert and high mountain subnival landscapes rank last (0.1 t/ha). Forest landscapes also differ in terms of phytomass quantity, although the variation is not as extreme as in the previously mentioned cases.

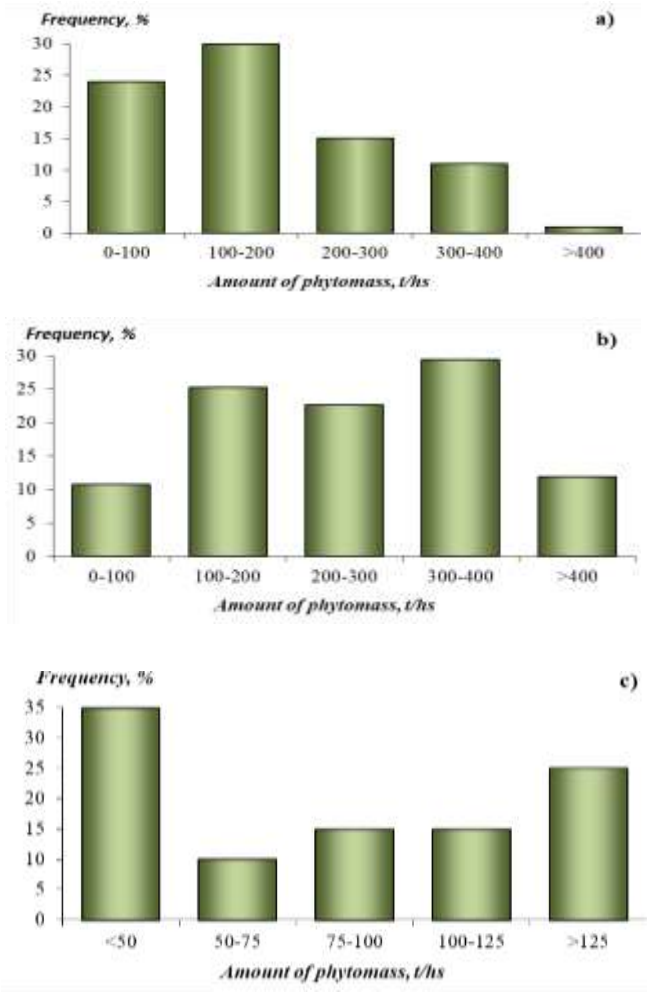


Figure 2: *Frequency of phytomass in mountain forest landscapes of Georgia Forest landscapes: a) low-mountain, b) middle-mountain, c) upper-mountain*

Non-forested areas, often resulting from anthropogenic transformation, are also present within forest landscapes. Accordingly, undisturbed and minimally altered areas have high phytomass amounts, whereas degraded forests and secondary meadows lag significantly behind. Another observation is that this variability is expressed with less intensity in relatively undisturbed environments.

The lower mountain forest landscapes are characterized by extensive phytomass quantities, with forest stands ranging from 75-100, 100-200, and 300-400 t/ha. However, their distribution is highly uneven. Forest stands with 300-400 t/ha are much rarer in these landscapes (Fig. 2a). The reason for this is easy to explain. These landscapes are relatively close to densely populated lowlands, and due to their less complex terrain, they are more accessible and better utilized. As a result, the scale of anthropogenic impact in these areas is significant. Alongside undisturbed forest stands, whose area continues to decline, there are transformed landscapes and those under intense anthropogenic pressure.

A completely different situation is observed across the entire hypsometric spectrum of mid-mountain forest landscapes. These are some of the most well-preserved landscapes, maintaining much of their original natural appearance. The reason for this lies in the predominance of steep and moderately sloped terrains (20-35°), which, in turn, have resulted in sparse population settlement. In these areas, forest stands with phytomass amounts ranging from 100-400 t/ha account for nearly 70% (Fig. 2b).

The upper mountain forest landscapes also exhibit a wide range of phytomass quantities (Fig. 2c). This can be explained by the fact that these landscapes border both forested and sparsely forested or completely non-forested landscapes, resulting in the presence of vegetation types characteristic of both.

Field studies have also shown that in all forest landscapes of Eastern Georgia, the range of phytomass quantities is higher, as within the boundaries of a single subtype, one can find not only extrahumid (with relatively limited distribution) and humid but also semihumid, semiarid, and even arid geosystems [14]. This is less common, or not observed at all, in the relatively evenly humid landscapes of Western Georgia.

Topographic factors

The relief conditions significantly affect the amount of phytomass – absolute altitude, surface slope, exposure, type of relief, and location on ridges or slopes, among others. This, in turn, is determined by the differences in heat and moisture that various geosystems, located in different relief conditions, receive. The relief factor is especially evident in mountain landscapes, unlike in lowland landscapes, because all the aforementioned relief conditions act as limiting factors in highly fragmented mountain-valley landscapes. In such situations, the relief primarily determines the migration, transit, and accumulation of substances. Consequently, different conditions form for the development of vegetation cover and the accumulation of phytomass.

The correlation between phytomass and elevation is not very stable within the boundaries of a landscape taxonomic unit. There are landscapes with different amounts of phytomass at the same elevation [15]. The correlation between phytomass and absolute elevation is more evident in mid-mountain forest landscapes, while it is weaker in lower mountain forests and even less so in upper mountain forest landscapes. This can be easily explained by the fact that mid-mountain forest landscapes have a much broader hypsometric range than the other two.

For most of Georgia's mountain landscapes, the maximum amount of phytomass is characteristic of slopes with moderate inclinations under a transeluvial migration regime. This is

especially evident in the lower and mid-mountain forest landscapes. Geosystems under the transeluvial migration regime occupy the largest area in Georgia (49'000 km²), where the transit of substances exceeds the eluvial processes. This accounts for more than 65% of the country's total area. The proportion is even higher in forest landscapes. About three-quarters of the total area comprises geosystems under the transeluvial regime, where the surface slope ranges from 30° to 45°. In such conditions, the amount of phytomass varies significantly (from 5 to 500 t/ha and more). Despite this, due to less anthropogenic impact, the maximum amount of phytomass is observed under exactly this migration regime.

A low amount of phytomass is observed on ridges, especially in areas under anthropogenic impact. The dryness of ridges and ridge-adjacent slopes hinders the natural regeneration of vegetation cover and the accumulation of significant amounts of phytomass. This feature is characteristic of almost all mountain forest landscapes in Georgia. The situation is quite the opposite in geosystems under the transeluvial migration regime. Here, the amount of phytomass is high, despite the presence of geosystems that are particularly vulnerable to deforestation. It is obvious that deforestation is inadvisable in such conditions, and only selective (sanitary) cutting should be considered. Otherwise, the diversification, degradation, and destruction of natural complexes are likely.

Climatic factors

It is known that mountain landscapes in Georgia are greatly influenced by air temperature, while plain landscapes are significantly affected by precipitation [15]. This general characteristic manifests differently across various landscapes, depending on the degree of anthropogenic transformation in the area. In forest landscapes with minimal human impact, the amount of phytomass correlates well with the balance of heat and moisture. Specifically, an increase in atmospheric precipitation corresponds to the rise in phytomass. Notably, a significantly higher amount of phytomass accumulates in landscapes where precipitation is evenly distributed throughout the year, with no drastic reductions in summer and no extreme fluctuations in air temperature. For instance, in the middle-mountain forest landscapes of western Georgia (dominated by beech forests), the maximum amount of phytomass (over 400 t/ha) is observed in areas where annual precipitation exceeds 1,000 mm. In similar landscapes in eastern Georgia, the maximum phytomass is found where precipitation exceeds 780-800 mm. Under conditions of relatively low atmospheric precipitation, the amount of phytomass is closer to the lower limit of the range typical for the landscape, while in areas with abundant rainfall, it approaches the upper limit. Additionally, landscapes with minimal anthropogenic impact are not characterized by a wide range of phytomass variation.

The situation is different in landscapes with a high degree of anthropogenic transformation. In such areas, it is more challenging to establish a correlation between the balance of heat and moisture and the amount of phytomass. This balance no longer acts as a limiting factor, and anthropogenic influences take precedence.

A significant correlation is also observed between the amount of phytomass and atmospheric precipitation during the growing season (from May to November). This is one of the main reasons why mountain forest landscapes in western Georgia typically have a higher phytomass than those in eastern Georgia. The only exception to this trend is the mountain forest landscapes of the Kakheti Caucasus, where precipitation is distributed more evenly throughout the year.

Edaphic factors

Soil thickness, moisture, texture, humus content, and stoniness are physical characteristics of the soil that significantly influence the productivity of the vegetation cover. These characteristics, in turn, are determined by various physical-geographical factors [16].

In this regard, soil thickness plays one of the most critical roles. An increase in soil thickness corresponds to the rise in phytomass [17]. However, this characteristic does not exhibit uniform patterns across all landscapes. For instance, in the eastern part of the distribution of mid-mountain forest landscapes, there is a relatively pronounced direct proportional relationship between the amount of phytomass and soil thickness. This, however, cannot be said for mid-mountain forest landscapes formed on karst substrates. In these areas, ecosystems with large amounts of phytomass are found even on relatively thin soils, while complexes with comparatively low phytomass are frequently observed on thicker soils.

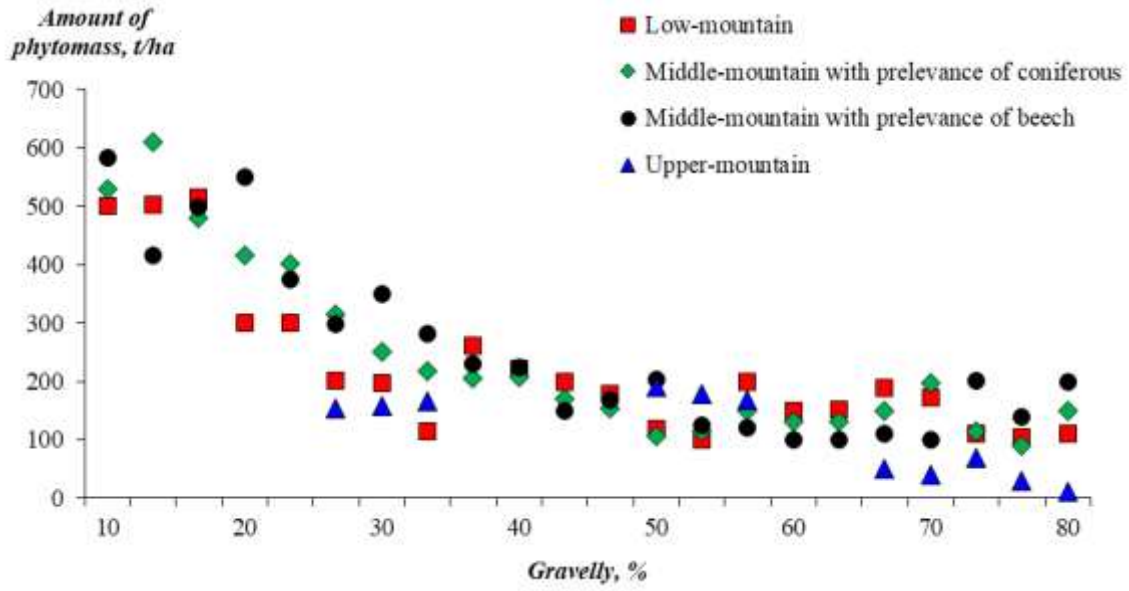


Figure 3: *Relationship between phytomass and the soil's gravelly*

Soil stoniness also has a specific influence on the amount of phytomass. Logically, an increase in stoniness should correspond to a decrease in phytomass [18]. However, it is impossible to definitively argue for an inversely proportional relationship between them, as low phytomass levels are observed in ecosystems where the lithomass's projected cover varies widely within the soil profile (10-60%). The most remarkable diversity in this regard is characteristic of the lower mountain forest landscapes (Fig. 3). When lithomass's projected cover is high in the landscape, ecosystems with 100-150 t/ha phytomass levels are more common. In mid-mountain forest landscapes with a predominance of beech forests, phytomass levels reach 100-200 t/ha. In mid-mountain forest landscapes with a predominance of beech and dark coniferous forests, levels rise to 250-350 t/ha. In upper mountain forest landscapes, phytomass levels range from 60-110 t/ha. Regarding ecosystems with high phytomass levels, in nearly all cases, the lithomass's projected cover does not exceed 20-25% [18].

IV. Conclusions

The study identified the relationships between relief, climatic, and edaphic conditions and the amount of phytomass in the mountain forest landscapes of Georgia. Specifically:

- The territorial distribution patterns of phytomass were revealed in various physical-geographical environments, considering factors such as absolute altitude, surface slope, the balance of moisture and heat, and depth and stoniness of soil.
- Limiting factors determining favorable natural conditions for the maximum phytomass accumulation were also identified.

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CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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GREEN ECONOMY DEVELOPMENT

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Abstract

Environmental risks are becoming increasingly relevant to the economy due to environmental degradation, climate change, resource exhaustion, and growing demands from the government and consumers. The solution to this problem lies in developing a green economy. This requires studying issues related to creating a state support mechanism for non-profit organisations' activities in green finance, as well as their participation in environmental projects through developing instruments of this type of financing. Education and raising awareness of the importance of sustainable development also play a key role in this process.

Keywords: green economy, responsible investment, environmental projects

I. Introduction

The rapid growth of the world economy in the 20th century put industry at the top of the list of development priorities [1]. This led to the strengthening of various types of economic growth, depending on the resources used. As a result, the environmental situation around the world became significantly less favorable. An awareness was formed of the narrowing of opportunities to continue economic growth based on the existing production and technological conditions.

In this regard, the need to review innovation policy was recognized, which should increase the activity of enterprises in terms of innovation and ensure economic growth. In such conditions, the concept associated with changing financial mechanisms on an ecological basis, with "green" financing, has become increasingly important. This concept provides for the need to generate demand for innovation.

Demand for innovations can be stimulated by the state [2]. The state has the ability to solve the corresponding problem by introducing special requirements, including labor regulations,

changes in legal and regulatory frameworks.

The measures implemented by the state are aimed at generating demand for innovations and integrating investment and scientific and technical solutions in the implementation of investment projects that are particularly significant.

II. Methodology

To ensure the equivalence of environmental and economic benefits, today it is necessary to form mechanisms for sustainable development that are comprehensive, environmental and economic.

A number of leading approaches have been formed in economic theory.

It should be noted that the participation of representatives of neoclassical economics in the study of relevant issues is significant, primarily as a result of studies in the middle of the last century [3]. Within the framework of these studies, many economic externalities were correlated with environmental resources. At the same time, researchers pointed to free access to a number of natural resources that are not owned by anyone (air, oceans, etc.)

The neoclassical approach is based on the interchangeability of all resources and on the optimal allocation of resources through the action of market forces. The possibility of caring for future generations is ensured through discounting. Additional challenges in maintaining a sustainable state of the natural environment are characterized as "market failures". To solve these problems, mechanisms in the form of permit trading and taxation are proposed. In fact, this approach examines two key issues related to environmental protection, related to the management of environmental assets through policy instruments and the valuation of these assets.

The formation of the concept of ecological economics took place at the turn of the sixties and seventies of the last century. This concept was formed in its basic form by R. Costanza, G. Daly, J. Martinez-Alier, P.R. Hay [12]. The corresponding researchers proposed to interpret the economic activity carried out by people as an element of the natural system. They pointed to the need for the economy to correspond to the complex of natural limitations. The fundamental assertions on which this concept is based are as follows:

- it is necessary to recognize that nature is of great importance;
- it is necessary to consider the demographic changes that are taking place and how these changes affect ecological and socio-economic systems;
- the ethical aspects of economic activity should be taken into account, primarily how this activity affects the state of the natural environment, contemporaries and future generations;
- the sustainability of unlimited economic growth in ecological and social terms is low;
- there is a need for a more detailed analysis of the hidden value inherent in economic growth;
- it is necessary to recognize that from the point of view of sustainability, well-being in social, environmental, and economic terms, all types of capital (social, natural) are significant;
- more careful consideration of changes in economic and social systems is required, since the consequences of such changes may be unpredictable and irreversible.

Peter Robert Hay describes this approach in economics as a practical problem-solving approach that differs from the neoclassical school in its disdain for abstract modeling. It shifts attention from the micro-perspective to macro analysis and from short-term to longer-term perspectives. This school complements ecological actions and interactions harmoniously, making its approach more holistic and considering dynamic processes and changes, avoiding stagnation. Certain aspects of this approach seem impossible from a practical and ethical point of view, as the

integration of economic principles into the original context requires structured commitments to manage contextual connections.

This school of thought considers the size of the economy relative to the ecosystem as a key issue, with a particular focus on environmental challenges [7]. Ecological economists see the economy as part of the ecosystem and believe that it cannot be isolated from its context. Since ecosystems have limits and the economy belongs to them, it is necessary to limit economic growth to address environmental challenges.

They note the advisability of reducing the tax burden on all production resources except natural resources, and increasing it in relation to natural resources.

The policy measures they propose to implement are similar to those proposed by neoclassicists. At the same time, the post-Keynesian approach emphasizes that state participation in ensuring sustainable development should increase.

The corresponding approach assumes the identification of a number of environmental problems as fundamental. These problems are associated with limited replacement, uncertainty, and financial support for new investments.

The measures proposed within this approach are related to:

- the introduction of environmental standards, the direction of state expenditures to ensure the sustainability of the economy, including the need to protect the natural environment, and the stimulation of the transformation of consumer habits;
- the increase of the role of banking organizations in maintaining a favorable state of the natural environment based on increasing financial support for “green” projects and technologies with the provision of state guarantees for this financing (this measure is consistent with post-Keynesian ideas, according to which an increase in demand supported by investments contributes to economic growth);
- overcoming uncertainty through the formation of a strategy for preserving natural capital and the definition by the state of strategic goals in the form of low inflation and a balanced budget.

According to the neoclassical approach, environmental problems are presented in the form of externalities, and measures to solve them are presented in the form of permits and taxes.

Representatives of the concept related to ecological economics believe that due to the fact that the ecosystem is limited, economic growth is problematic. In this regard, it is proposed to control this growth, but in a market-type economy, the solution to this problem is associated with difficulties.

According to post-Keynesians representatives, “green” growth is limited due to a number of problems associated with insufficient investment in environmental projects and fundamental uncertainty

III. Results

Over the last decade, the topic of the “green economy” has become widespread. In a narrow sense, the “green” economy is understood as types of economic activity that, along with modernization and increased production efficiency, contribute to the improvement (or preservation) of the human living environment, including the reduction of technogenic emissions, and the adaptation of the population and the economic complex to changing climatic conditions. Today, such activities cover energy conservation and energy efficiency, development and exploitation of alternative energy sources, transport, agriculture and forestry, water management, solid waste management, construction of smart buildings and cities and a number of other areas, i.e., in a general sense, economic activity that improves people's well-being and ensures social justice, while significantly reducing environmental risks and depletion of nature.

The following principles can be considered as the main principles of the green economy:

- the principle of well-being;
- the principle of justice;
- the principle of planetary boundaries;
- the principle of efficiency and sufficiency;
- the principle of good governance;

The principle of well-being. The green economy is primarily people-oriented and its main goal is to create true prosperity for people. The main focus is on the growth of wealth, which will then lead to well-being. This is not only the growth of financial wealth, but also other types of human, social, material and natural capital. Priority in investments is given to stable natural systems and infrastructure, to education and knowledge. The direction is based on collective action to achieve public goods, while also considering and respecting the individual choices of each person.

The principle of justice. The green economy should fairly share the decision-making process, taking into account all benefits and costs, and avoiding the capture of goods and the emergence of elites. It should support the empowerment of women. That is, the green economy is non-discriminatory and inclusive. It is aimed to reduce differences between people, to create harmony between people and wildlife. It is based on solidarity and social justice, strengthening trust and social ties between people. It considers the interests and rights of workers, indigenous peoples and minorities.

The principle of planetary boundaries. A green economy must protect, restore and invest in nature. It recognizes and supports the various natural values, including the functional values that underlie the economy, the cultural values that form the basis for society and the ecological values that are fundamental for life on Earth. It invests in protecting and restoring natural diversity, the ecology of soil, water, air and all-natural patterns.

The principle of efficiency and sufficiency. The green economy should be aimed at supporting sustainable consumption and production. The green economy is low-carbon, resource-efficient, variable and cyclical. It implies new models of economic development; it seeks to limit the consumption of natural resources to acceptable levels. At the same time, it recognizes the importance of the need for a certain social level to ensure human well-being.

The principle of good governance. The green economy must be guided by sustainable, integrated and accountable institutions. It is evidence-based. Governance operates on the principles of transparency, social dialogue, democratic accountability and freedom from vested interests. The financial system of the green economy is designed in such a way that it can ensure the well-being, sustainability and security of public interests.

The term “green” finance refers to a set of financial products and services that focus on both reducing climate and environmental threats and increasing resource efficiency. These instruments include “green” investments, bonds, loans, insurance, funds, etc.

Historically, “green” bonds are considered as the most ancient and widespread form of “green” financing. These securities assume the receipt of fixed income, and are debt securities.

This is a type of fixed-income debt security that can raise money from investors in exchange for an obligation to repay it within a specified period of time and at a specified interest rate.

Issuers pledge to use the proceeds of these bonds to support or refinance projects that have a positive environmental or climate impact. These bonds are traded on specialized exchanges at a reduced interest rate and attract the attention of large financial institutions. Often, state and central banks subsidize interest rates on “green” initiatives, and pension funds are eager to invest in them. The “green” bond market has expanded significantly in recent years and includes such types as general issue bonds with guarantees, project and income bonds, asset-backed and covered bonds. The first “green” bonds were issued by the International Development Banks in 2007–2008,

and following the rapid growth of this market, the International Capital Markets Association launched the "Green Bond Principles" in January 2014.

At the same time, the "green" credit market is actively developing. Such a loan is a financial instrument intended for full or partial support of new and existing environmental projects. Unlike bonds, the market of "green" loans is relatively young both at the global and the national levels.

"Green investments" are presented in the form of property, securities, and cash that are invested in activities aimed not only at making a profit, but also at reducing the negative impact on the natural environment. These investments can, accordingly, be considered as financial instruments allowing to ensure a reasonable balance between the economy and the natural environment, increase the energy efficiency of economic activity, optimize production, and reduce the negative impact on the natural environment. The corresponding financial instruments can act as an effective means of implementing state policy, since they are characterized by the presence of a social element.

"Green" Insurance

The securities must be certified for compliance with certain criteria to be considered as "green", which in turn gives them the opportunity to secure government support and a number of preferences. Active development of legislative regulation of "green" financing in the Russian Federation began in 2020. The state corporation VEB.RF was appointed as a methodological center for green financing. On September 21, 2021, the Government of the Russian Federation, in cooperation with the mentioned organization, adopted Resolution No. 1587, which provides a set of requirements for projects related to sustainable development and the criteria by which these projects are assessed. The Resolution provides, among other things, for a set of priorities and goals related to sustainable development.

In 2012, the vector of development of the domestic green economy was defined. The Head of the State approved a policy for Russia's development in terms of environmental protection for the period up to 2030. This document provides a set of fundamental requirements, goals, and objectives related to sustainable development. The relevant key provisions are intended to meet the needs of the country's population while preserving the natural environment, including for future generations.

This policy is primarily aimed at solving socio-economic problems, maintaining environmental safety, promoting economic development with a focus on environmental protection, strengthening law and order in the area of environmental protection, maintaining a favorable state of the natural environment, creating conditions under which each person could exercise the right to have a favorable environment, preserving natural resources and biodiversity taking into account the needs of existing and future generations.

The fundamental requirements for the implementation of environmental policy include the need to:

- respect the rights of citizens to receive reliable information on the state of the natural environment;
- respect the human right to a natural environment that is favorable;
- proceed from the fact that the proposed economic and other activities may threaten the natural environment;
- ensure living conditions that are favorable for citizens;
- ensure the responsibility of government bodies at the federal and regional levels, bodies operating at the municipal level, for ensuring environmental safety and a favorable environment;
- combine on a scientific basis the social, economic, and environmental interests of the state, society, and individuals to ensure environmental safety, a favorable environment, and sustainable development;
- preserve natural complexes, landscapes, and natural ecological systems as a priority;

- use natural resources reasonably, carry out their reproduction and protection to ensure environmental safety, a favorable environment, etc.

Sustainable development criteria apply to a variety of areas: wastewater disposal, water supply, energy, construction, transport, waste management, agriculture, etc.

IV. Discussion

The Russian economy has shown poor readiness for the transition to sustainable development, while remaining with an unstable and ineffective structure [19]. The level of negative impact on nature in the country is significantly higher than in technologically advanced countries, which is expressed by significant discrepancies and low use of available natural, scientific, technical and cultural resources. Many production facilities do not meet modern environmental standards, and ecologically unfavorable areas account for 16% of the country, where more than half of its population lives. Without the introduction of environmentally oriented approaches into the economy within the framework of institutional and structural reforms, it is impossible to achieve the goals of the concept of sustainable ("green") development. It is necessary to widely implement environmentally oriented management practices, mass use of energy- and resource-saving technologies, and also to radically change the structure of the economy and consumer practices, the attitude of citizens to nature. Russia has all the resources needed to achieve the goals of the Sustainable Development Concept.

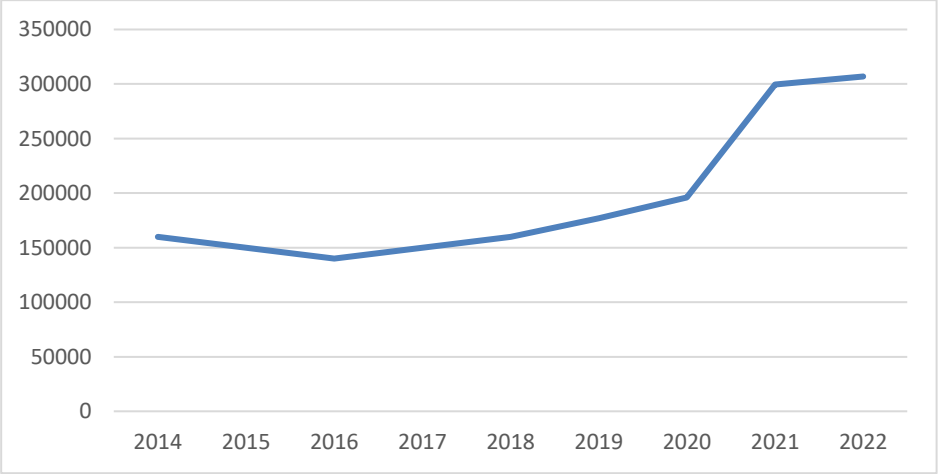


Figure 1: *Investments in fixed capital aimed at environmental protection and rational use of natural resources, million rubles.*

The latest programs aimed at increasing energy and environmental efficiency, improving resource conservation and developing alternative energy sources in the country are focused on introducing modern approaches to the "green" economy, considering national characteristics. Russia's transition to a sustainable path requires time and the solution of complex socio-economic and environmental problems, as well as significant financial resources and compliance with certain restrictions. In the current conditions, it is worth considering the "green" economy as the basis for the sustainable development of world civilization. Sustainability is a progressive development that ensures rational use of natural resources and harmonious cooperation with nature, as opposed to stability, which only leads to stagnation.

Even the most advanced technology should not be implemented if it does not meet the criteria of "green" technologies and harms the environment. Only by following this ecologically

and socially oriented doctrine the humanity will be able not only to survive, but also to rapidly develop in the future.

It is also worth to note that the dynamics of environmental investments in the Russian Federation over the past decade (Fig. 1) allows us to conclude that the responsible investment market is progressing and the "green economy" is becoming a vector for innovative projects.

Based on the study of investments in fixed capital related to the reasonable use of natural resources and environmental protection from the point of view of the dynamics of their volume, it should be noted that the system of financial support for environmental projects is characterized by successful development.

The volume of relevant investments in 2022 was equal to 306,887 million rubles; the main areas of investment were related to land protection and their reasonable use, protection of the air and water environments. Investments in projects in these areas amounted to 27,806, 139,273 and 110,560 million rubles.

As an example of the implementation of the concept related to green financing, it is worth mentioning the platform "Sustainable Development Sector". This is the first domestic platform aimed at providing financial assistance to projects of an environmental nature.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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EMPLOYMENT OF DISABLED PEOPLE AS A TOOL FOR DEVELOPING THE REGIONS OF THE NORTH CAUCASUS

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Abstract

This article analyses the integration of disabled people into the labor market as a strategic tool for the socio-economic development of North Caucasian regions. The study aims to identify the key factors influencing the employment level of this demographic group, taking into account demographic trends such as population ageing and a shrinking working-age population. In the context of demographic change and the need to make better use of labor resources, employing disabled people is becoming important for maintaining regional economic activity. The study identified the main mechanisms and barriers hindering the professional development of disabled individuals. The results of the analysis showed that the successful employment of young disabled people requires a systemic approach involving the coordination of the efforts of all parties concerned. It is important not only to ensure the availability of specialized jobs, but also to provide comprehensive support at all stages of professional adaptation and work activity. Government agencies must recognize the need to select suitable work and subsequently monitor, support and evaluate the effectiveness of disabled people's adaptation to the work environment.

Keywords: regional development projects; demographic dividend; disabled people, individuals with disabilities

I. Introduction

Over the past decades, humankind has made active efforts to ensure inclusion and the implementation of basic rights and freedoms for disabled people and individuals with disabilities, including the right to work and education. "Disabled person" is a person who has a health impairment with a persistent disorder of body functions caused by diseases, consequences of injuries or defects, leading to a limitation of life activities and causing the need for his social protection. Disorders can be physical, sensory, and cognitive, and include physical, mental, and chronical diseases.

According to the World Health Organization (WHO), the number of people with disabilities exceeds 650 million people, which is about 10% of the world's population [1]. The Convention on the Rights of Persons with Disabilities, adopted by the UN General Assembly in 2006 [2], defines disability as "the interaction that occurs between persons with impairments and the environmental barriers that hinder their full and effective participation in society". Thus, the problem of disability is considered not only as a medical phenomenon, but also as a social phenomenon that requires a comprehensive approach to its solution.

The relevance of this study is due to the need to revise approaches to understanding the effective use of labor resources in individual regions of the country. Changes in the demographic composition of the working-age population lead to the need to restructure the employment system. The labor market is a fundamental element in the system of national and regional

economic development. Its evolution must be synchronized with the dynamics of social transformations, adequately responding to modern challenges and trends. The key task of business is to create an inclusive environment that provides access to jobs for people with disabilities, which facilitates the integration of this category of citizens into the labor activity.

In the early 2020s, there was an urgent need to update the system of job quotas for disabled people and individuals with health limitations (HL).

The problem of updating the system of job quotas for disabled people and persons with health limitations (HL) is multifaceted and requires a comprehensive approach. So, it was important to consider both regulatory and legal aspects and socio-economic factors influencing the effectiveness of employment of this population group. In this regard, it was necessary to develop methodological recommendations that would facilitate the creation of optimal conditions for the integration of people with disabilities into the workforce.

This included not only the adaptation of workplaces to the specific needs of this category of citizens, but also the development of comprehensive programs for professional training and retraining, which contributed to increasing their competitiveness in the labor market.

II. Methods

The following methodological approaches were used in the study: a monographic method that allows for a detailed study of individual aspects of the problem; a comparative analysis to identify patterns and differences between the objects under study; and a logical analysis aimed at systematizing and generalizing the data obtained. The integrated application of these methods ensured a thorough study of the topic and made it possible to achieve the stated research goals. As an empirical base and analytical material data from the Federal State Statistics Service were used, including information on official disability for the period from 2019 to 2024, data on the employment of disabled people reflected in the state statistical accounting system, as well as the results of sample surveys conducted by Rosstat. In addition, the regulatory legal acts governing the area under consideration were analyzed.

III. Results

The state policy of the Russian Federation in the area of promoting employment of disabled people and individuals with health limitations (HL) is aimed at ensuring that they have equal rights with other citizens in realizing their labor potential. Regardless of the current economic situation, in the medium and long term, the shortages of skilled workers remain the biggest brake on growth for Russia.

The introduction of comprehensive measures to increase the employment of disabled people can contribute to an increase in the growth rate of the Russian Federation's GDP by 0.5 percentage point annually [3]. This emphasizes the importance of this social initiative not only from the point of view of social justice, but also from an economic perspective.

In recent years, there has been a positive trend in the employment of disabled people, but the results achieved are still insufficient to fully use their labor potential.

The concept of disability, as a multifaceted phenomenon, has evolved in line with social, cultural and political changes. In historical retrospect, one can observe a transformation of approaches to defining disability, which reflects the dynamics of social norms and values. The modern paradigm of disability emphasizes a comprehensive analysis of the phenomenon, including objective medical disorders, functional limitations and social barriers that hinder the full integration of individuals into society.

In the context of the Russian Federation, where there is a significant number of people with disabilities and individuals with health limitations (HL), including young people with disabilities,

the urgent task of state policy is the development and implementation of programs aimed at promoting their employment and vocational education. One of such programs is the subprogram "Promoting employment of disabled persons, including young people with disabilities in obtaining vocational education and subsequent employment, as well as disabled persons in need of accompanied employment assistance" [4]. Along with this legislation, there was a concerted effort to improve the living conditions of people with disabilities. This led to the development of policies aimed at reducing institutional care and replacing it with community living. There are many questions and problems surrounding inclusion in the disabled and individuals with health limitations (HL) community. People with disabilities often have valuable qualifications and represent a good – and to date underutilized – resource. They are often better qualified than unemployed people who aren't severely disabled, although they have a poorer record in finding employment. If businesses, the federal employment agencies and the Job centers work more closely together in this area, more employers will be able to make use of their potential

From September 1, 2024, the following rule applies to the allocation of job quotas for disabled people and people with health limitations. If the number of employees exceeds 35 people, the quota for hiring disabled people is from 2 to 4 percent of the average number of employees (paragraph 1 of Article 38 of the Federal Law of 12.12.2023 No. 565-FZ "On Employment of the Population in the Russian Federation").

Employers can receive a subsidy for the employment of certain categories of citizens. Applications are now open for employers to receive a subsidy for disabled persons' employment. The program of state support for employers in the employment of certain categories of citizens is included in the federal project "Active Measures to Promote Employment" of the national project "Personnel" and is implemented in accordance with the order of the Social Fund of Russia dated 29.12.2024 No. 2714 [5]. The purpose of granting a subsidy is to partially compensate the employer's costs for paying wages to employees from among certain categories of employed citizens. Categories of citizens whose employment is eligible for subsidies: combat veterans; family members of combat veterans; disabled persons, etc.

Employers who are individual entrepreneurs or disabled persons can receive an increased subsidy when employing disabled individuals. The payment for one employed disabled person is 6 minimum living wages. Three payments are provided: after the first month – 1 minimum wage, after the third month – 2 minimum wages, after the sixth month – 3 minimum wages [4].

If the income of a person with disabilities is below the subsistence minimum, then he or she has every right to benefit from the privileges of the social contract for the "Job Search" event.

To conclude a social contract for "Job Search" it is necessary:

- to register with the employment authorities in order to find suitable work or be recognized as unemployed;
- to find a job;
- to be employed for at least one year after the end of the social contract.

The size of the social contract for the "Job Search" event in 2025 is:

- 19 522 rubles when concluding a social contract;
- from 300 to 3 000 rubles per month for the period of job search within the framework of the social contract;
- 19 522 rubles within 3 months from the date of employment confirmation.

In accordance with Article 20 of the Federal Law "On the Social Protection of Disabled Persons in the Russian Federation", disabled people are provided with guarantees of employment by federal government bodies and government bodies of constituent entities of the Russian Federation by implementing the following special measures to enhance their competitiveness in the labor market:

- establishment of quotas in organizations for hiring disabled people and a minimum number of special jobs for disabled people, regardless of organizational and legal forms and forms of ownership;

- reservation of jobs in professions most suitable for the employment of disabled people;

Despite the wide range of social support measures provided by Russian legislation, disabled people and individuals with health limitations (HL) continue to face serious barriers to their integration into the labor market. These barriers can be classified as follows:

1. Discriminatory practices in employment, expressed in the biased attitude of employers towards candidates with disabilities.

2. Physical and technical inaccessibility of most workplaces, which significantly limits employment opportunities for people with disabilities. Infrastructure limitations, such as the lack of ramps, elevators, specialized equipment and adapted workplaces, create insurmountable obstacles to employment for this category of citizens.

3. Limited access to quality vocational education and socio-cultural services. Insufficient development of inclusive educational programs and the lack of specialized vocational training centers lead to the fact that persons with disabilities do not receive the necessary competencies and skills for successful employment. This, in turn, worsens their social and economic situation.

These and other problems faced by young disabled people and individuals with health limitations (HL) at the stage of professionalization and employment highlight the need to conduct a comprehensive study of the youth segment of the labor market, considering its specific features and factors influencing its functioning.

According to Rosstat data for 2024, there are 11.1 million people with disabilities living in Russia. Among them, 1.2 million are disabled persons of group I, 4.5 million of group II, and 4.64 million of group III. 779 thousand of the total number are children. Since 2016, the total number of disabled people in the country has decreased by 85 thousand, but the number of children with disabilities has increased by 162 thousand.

According to Rosstat, since 2015, the employment of disabled people in Russia has significantly decreased, from 2.4 million to 1.6 million employed people with health limitations. The main diseases for all disability groups are neoplasms and diseases of the circulatory system – about 30% each. Diseases of the musculoskeletal system affect 7% of citizens recognized as disabled. Injuries (including industrial ones) and other external causes are the reason of disability of about 30 thousand people per year (4% of the total number of those recognized as disabled).

The main difficulties for Russians with disabilities are that a citizen can be recognized as disabled in Russia only if three conditions are met (incurability of a disease, limitation of life activities, need for rehabilitation). Accordingly, citizens who do not have at least one condition do not have the status of a disabled person, but systemic health disorders are already present, which is not considered and no work is being done to reduce the risk of further health deterioration of these citizens.

Based on data from the Federal State Statistics Service (Rosstat) for 2022, the employment rate of disabled people of working age was 15%. This index is significantly lower than the employment rate among the working-age population without disabilities, which reached 67.3%.

According to the results of 2023, the employment rate of disabled people of working age in Russia was 19.8%. In the countries of the Organization for Economic Cooperation and Development (OECD), the share of employed disabled people is significantly higher and amounts to approximately 30%, which indicates significant potential for improving the situation in Russia.

Analysis of the situation in the sphere of employment of persons with disabilities at the all-Russian level shows insignificant dynamics of changes. In 2020, the share of employed persons with disabilities of working age was only 26.7%, which indicates the persistence of significant barriers to their integration into the labor market. The leading position in terms of employment of this category of citizens is occupied by St. Petersburg, where 37.2% of disabled people of working age are employed. In six constituent entities of the Russian Federation, including Belgorod, Kursk, Moscow regions, as well as the Nenets, Khanty-Mansiysk and Yamalo-Nenets Autonomous areas, the share of employed disabled people exceeds 30%, which indicates more effective

implementation of employment support measures in these regions.

In the context of the implementation of quotas for the employment of disabled people, the number of citizens employed in 2023 reached 424.9 thousand people, including 34.2 thousand people employed in specially equipped workplaces. This index shows an increase of 3.1% compared to 2022, which amounts to 12.8 thousand people. It is important to note that the total number of organizations, which are subject to the obligation to establish quotas for the employment of disabled people increased by 4.6%, which amounts to 5.5 thousand organizations, compared to the previous year [6].

The occupancy rate of jobs allocated within the quota, as well as special jobs, has increased significantly by the end of 2023 compared to 2022. Thus, in 2023, compared to 2022, the absolute number of jobs occupied by disabled people increased by 24.3 thousand units (by 8.1%), including special ones by 3.8 thousand units (by 20.6 %). At the same time, the share of jobs filled under the quota in the total number of jobs allocated under the quota increased by 3.5 percentage points, amounting to 76.2 percent in 2023, and the share of special jobs occupied by disabled people in the total number of special jobs increased by 8.5 percentage points and amounted to 65.3 percent. In organizations with state (municipal) participation, the occupancy rate of jobs allocated under the quota amounted to 84.5 percent in 2023.

The most successful results in fulfilling the quota for hiring disabled people (the occupancy rate over 90 %) were achieved in the Republic of Dagestan, the Republic of Ingushetia, the Kabardino-Balkarian Republic, the Karachay-Cherkess Republic, the Republic of North Ossetia-Alania, the Chechen Republic, as well as in the Novosibirsk, Kursk and Penza regions.

Among the disabled people who were working as of January 1, 2024, the largest share of those employed was in manufacturing (13.2 %), education (12.7 %), healthcare and social security (11.9 %), wholesale and retail trade, and repair of motor vehicles and motorcycles (11.1 %). According to monitoring data, almost half of all working disabled people are concentrated in these types of economic activity.

The low level of employment of people with disabilities is influenced by many factors, acting both on the demand side and on the supply side.

Increasing the level of employment of disabled people is a promising direction for increasing the demographic dividend in the Russian Federation, which is especially relevant in the context of a reduction in the share of the working-age population. The demographic dividend, as an economic category, reflects the impact of changes in the age structure of the population on the dynamics of economic growth, expressed in the growth rate of real gross domestic product (GDP) per head of the population. Under global population aging and a similar trend in Russia, there is an annual decline in the share of the working-age population, which creates significant potential for compensating for losses in the labor market through the integration of people with disabilities into work activities.

According to the Social Fund of Russia, there are approximately 907 258 disabled people of working age living in the North Caucasian Federal District (NCFD), of which only 25% have jobs (see Table 1).

In the North Caucasus, the most common disability group is II group – more than 500 thousand of the disabled people. Then follows the group III – 252 163 thousand disabled people, and the number of disabled people of the group I is 114 545 thousand people. The age group of people with disabilities in the North Caucasian Federal District varies from 18 to 60 years. The largest group is 60 years old, more than 300 thousand disabled people. The category of disabled people goes in descending order: from 50 years old – 213 481 disabled people; from 40 years old – 152 300 disabled people; from 30 years old – 108 356 people with disabilities; from 18 years old – 85 561 young disabled people.

Today, three quarters of working-age citizens with disabilities are not involved in the labor market.

According to the results of the latest 2021 population census, only 25.2% of Russians live in

rural areas. To prevent people from leaving villages and countryside, the state introduces benefits and support programs for them.

The share of the rural population in the subjects of the North Caucasian Federal District (NCFD) exceeds the Russian average, and in some republics, it is twice as high. Thus, as of January 1, 2023, in all seven constituent entities of the Russian Federation that are part of the North Caucasian Federal District, the actual value of the indicator "Share of rural population in the total population of the Russian Federation" exceeds the Russian average (25.1%)," the report says. It is noted that in the Republic of Dagestan the share of the rural population is 54.8%, in the Republic of Ingushetia – 45.2%, in the Kabardino-Balkarian Republic – 48.2%, in the Karachay-Cherkess Republic – 58.6%, in the Republic of North Ossetia-Alania – 36.8% (see Table 1), in the Chechen Republic – 61.9%, in the Stavropol Territory – 39.3% [7].

Table 1: *Number of disabled people by disability group in the constituent entities of the Russian Federation*

	2019	2020	2021	2022	2023	2024
	Total excluding children with disabilities	Total excluding children with disabilities	Total excluding children with disabilities	Total excluding children with disabilities	Total excluding children with disabilities	Total excluding children with disabilities
RF	11 277 668	11 188 902	10 928 989	10 601 586	10 210 793	10 285 405
NCFD	883 957	907 458	911 926	915 101	907 258	936 823
The Republic of Dagestan	291 892	302 080	307 505	311 189	304 508	316 384
The Republic of Ingushetia	51 627	57 338	59 049	60 472	60 664	62 739
The Kabardino-Balkarian Republic	56 478	57 272	56 439	55 341	52 749	54 195
The Karachay-Cherkess Republic	49 958	51 342	51 604	51 387	51 230	52 228
The Republic of North Ossetia-Alania	66 537	62 571	56 820	52 872	56 988	59 358
The Chechen Republic	154 743	165 663	172 965	180 746	184 004	195 826
The Stavropol Territory	212 722	211 192	207 544	203 094	197 115	196 093

According to data as of May 1, 2025, in Digora among permanent residents, 1 462 people have disabilities, which is 7.97% of the total population. 12% of disabled people are employed.

The number of disabled people living in the municipality of Chikola as of 01.01.2023 is 1 909; the number of people in need of employment is 36 people.

The number of disabled people living in the municipality of Elkhotovo as of 01.01.2023 is 832 people; the number of people in need of employment is 112 people.

There are more than 63 thousand disabled people living in the Republic of North Ossetia-Alania, of which 26 thousand are of working age. Almost 6 thousand are employed (22% in total).

In the future, disabled people as a social group of society will occupy a fairly large place in the structure of productive forces. For example, in the economy of Stavropol Territory, 26.5 thousand disabled people are currently employed, or 31.8% of their working age population. In particular, in the North Caucasian Federal District (NCFD) there is a shortage of effective personnel, as well as an increase in the labor mobility of the young working population. In this regard, there is a need to consider the model of employment of people with disabilities as a tool for developing the human resource potential of enterprises, including small and medium businesses.

This demographic group may have significant potential to meet the labor needs of a region experiencing labor shortage. In the context of the need to revise traditional approaches to the formation of labor resources and their diversification, this group represents a promising source of replenishment of the shortage of qualified specialists.

Particular attention should be paid to the integration of previously unused categories of human resources into the existing employment structure of the region, which will optimize the distribution of labor potential and increase the efficiency of human capital use. The most common vacancies for employment of people with disabilities who have recommendations for work in accordance with an individual rehabilitation or habilitation program are teacher, manager, educator, engineer, design engineer, programmer, storekeeper, picker, sales floor cashier, security guard, sales floor worker, cleaner, janitor.

People with disabilities in the NCFD have strikingly low employment rates compared to the rest of the population. As a comparison, in some parts of the United States working from home has already increased the number of people with disabilities in full-time employment by more than a quarter of a million. Given the aging of the population, the impact could be much greater in the long term as more workers become disabled as they age. Is the sharp increase in the number of people with disabilities in paid employment caused by the increase in working from home? It is difficult to assess causality for several reasons. First, there was a large influx of people diagnosed with cognitive dysfunction during the pandemic. If these people with health limitations who become disabled have higher work ability because they have less severe impairments, then this change in population composition may explain the increase in the number of disabled people in paid employment [5]. Hybrid and fully remote work could increase the labor supply by hundreds of thousands of people. Second, reverse causality may be present if workers with disabilities experience high demand for remote work. Analysis of statistical data on the choice of remote employment among disabled people and workers with health limitations (HL) provides an opportunity to study in detail the employment prospects of this social group. This approach allows not only to identify new employment models, but also to assess their influence on the socio-economic situation in regions characterized by high unemployment and employment difficulties. As a result, it can be assumed that the introduction of flexible forms of employment for persons with disabilities can help reduce social tension and improve the quality of life of this category of citizens in the North Caucasian Federal District. Third, let's not forget that the labor market strains caused by the pandemic could potentially lead to companies being more willing to hire workers with disabilities.

Remote work explains sharp rise in employment of people with disabilities.

One might wonder whether the significant increase in employment among disabled people and people with health limitations in 2024 is due to the supply of labor or the demand for it. In terms of supply, remote working reduces the burden of commuting and also allows for greater control over the work environment. This should increase the labor supply among people with disabilities who want to work. In terms of the demand, remote work can reduce companies' costs of accommodating employees, increase the productivity of workers with disabilities, and possibly make it harder for employers to discriminate if interviews are conducted on social media. This should increase companies' demand for workers with disabilities.

Rural areas of the NCFD are struggling to retain and attract young people for a number of reasons. The dual demographic trends of youth out-migration and aging of the population make it especially important for rural towns to implement strategies to retain and engage youth. The major part of the rural population (as well as the city population) in the Russian Federation is oriented towards wage employment. The share of employed disabled people in rural areas is usually lower than in cities. But, in 2024, for the first time this ratio changed in favor of rural areas. Based on Rosstat data for 2020, 47.1% of employed disabled people in rural areas are not employed in their specialty (in cities this index is equal to 45.3%). Only 32.1% of them were retrained (in cities – 39.1%) [7].

Among disabled people aged 15–72:

- 20.8% are employed in agriculture (5.8% of the total population);
- 12.6% – in manufacturing;
- 11.7% – in education;
- 10.9% – in trade and repair;
- 9.4% – in the field of health care and social services.

It is important to understand that rural youth and youth working in agriculture are not the same thing. Foremost, young people in rural areas are not necessarily employed in agriculture. For example, in some developed countries, the vast majority of people living in rural areas earn their income in the non-agricultural sectors of the economy.

High unemployment in rural areas is due to insufficient diversification of the economy. Disabled people and individuals with health limitations can contribute to the agro-industrial complex by participating in organic production, digitalization and precision farming. They are important for rural lifestyle, rural tourism and folk crafts. Further education should take their needs into account.

In less developed countries the process is slower, but nonfarm activities are expanding. Urban youth can also be involved in agriculture, especially in smaller towns.

To integrate disabled people into the economy, it is necessary to create conditions for education and employment, support traditional and innovative activities, and develop rural areas.

Globalization and urbanization are changing the socio-economic structure, making it difficult for people with disabilities to professionally integrate. In rural communities, they are often engaged in specialized tasks, but with the transition to mechanization of agriculture, their opportunities are narrowing.

This, in turn, reduces employment opportunities for disabled people who do not have the necessary skills and competencies to work under new economic conditions. Mechanization of agricultural production also limits opportunities for physical labor, making traditional forms of employment inaccessible for this category of the population [8].

The benefits of developing a model for employing people with health limitations in rural areas of the North Caucasian Federal District (NCFD) include:

1. Reducing the shortage of qualified personnel in key sectors of the regional economy.
2. Reducing dependence on shuttle migration of labor.
3. Reducing the level of economic tension in families of people with disabilities.
4. Creation of a favorable environment for living and career growth of this social group.

These measures contribute to the sustainable development of the region and improvement of the quality of life of the population. Optimization of the employment model considering the regional characteristics of the North Caucasian Federal District will lead to the formation of a new employment standard and improvement of socio-economic conditions in the region.

The individual employment program for persons with disabilities is a multifaceted approach based on a comprehensive analysis of the strengths, needs and interests of this category of citizens. This process includes the development and implementation of various strategies aimed at adapting workplaces, stimulating self-employment and entrepreneurship, as well as other restructuring and development methods that allow for the effective integration of people with disabilities into the workforce.

A key aspect of such programs is the provision of reasonable accommodations and necessary support, which allows for individualization of working conditions and minimization of barriers to the full performance of professional duties. Thus, individual employment programs are aimed at creating an inclusive work environment that promotes successful professional development of individuals with health limitations [9].

Thus, the integration of young people with disabilities into the labor market requires a comprehensive approach, including measures for professional training, creating conditions for employment and support in the workplace. Only through systematic interaction between all

participants in the process can we achieve significant results in increasing the level of employment of this category of citizens and contribute to the sustainable socio-economic development of the regions of the North Caucasus.

In modern Russia, the employment scenario for disabled people is rapidly changing (entrepreneurship, remote work, etc.). Combined with the abilities of young disabled people as a technologically savvy cohort who care about work-life balance, these are the conditions that can meet the needs of these young disabled people, which also meets the expectations of employers, helping to create dynamically developing regions for both work and life for healthy people and disabled people (see Fig. 1).

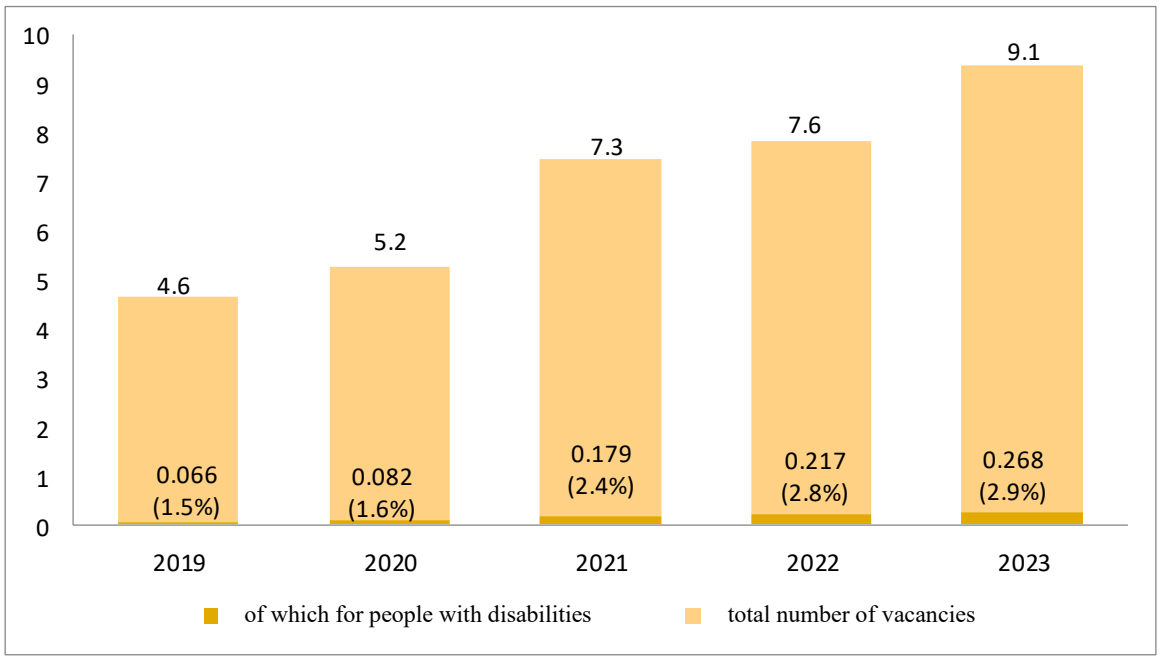


Figure 1.: *Share of vacancies accessible to people with disabilities*

Economists from the North Caucasian Federal District have determined that another factor in the sustainable employment of disabled people is the active cooperation of universities with executive authorities and employers. More than 80% of educational institutions in the NCFD interact with regional specialized ministries and departments, which allows for the development of interdepartmental target programs to support and facilitate employment. Also important is the proposal to provide career guidance support to 9th and 11th grade graduates with disabilities for admission to pedagogical specialties in universities and colleges [10].

There are positive examples in the region when graduates with disabilities get jobs in schools of the region. It is necessary to tell about such examples, as they can serve as an additional incentive for today's schoolchildren.

An important aspect is the participation of universities in the implementation of regional programs to support young disabled people, including career guidance activities, internships and practical training directly at enterprises. Most graduates with disabilities are employed or involved in business. So, 17 universities reporting annual employment of their graduates. However, it should be noted that, despite the positive dynamics, there are universities where the proportion of employed graduates remains low. There are also universities that do not have employed graduates with disabilities; there are 10 such universities in the North Caucasus.

Regional experts emphasize the need for further development of support programs and adaptation of curricula considering the specifics of the labor market in the regions. The list of organizations where graduates with disabilities and health limitations work after receiving their diplomas includes executive authorities, employment centers, educational organizations, industrial, agricultural and medical enterprises.

IV. Discussion

Thus, state policy regarding the employment of disabled people and persons with health limitations is based on the recognition of equal rights and opportunities for all citizens, regardless of their health status, which is an important step towards building an inclusive society.

Methodological recommendations should include an analysis of existing quota practices, an assessment of their effectiveness and the identification of problem areas.

The obtained data indicate that in the Russian Federation, disability is perceived as a multifaceted and complex problem with different approaches to the provision of services based on the understanding of health disorders and disabilities. Much attention is paid to the health problems of young able-bodied disabled people and the negative attitude towards them. Development of the employment capacity of people with disabilities and health limitations can not only contribute to raising awareness of the opportunities for urban and rural youth with disabilities, but also to the development of the region and thereby change the negative attitude towards people with disabilities to a positive one. A better understanding of the needs of young people with disabilities will help employers rethink disability in the broader context of equal opportunities.

V. Conclusion

Changes in the labor market, such as increased automation and new forms of employment, may negatively impact the employment prospects of people with disabilities. Major changes bring both risks and opportunities, and it is up to employers and regional leaders to realize the potential of a more efficient labor market that works for everyone, including people with health limitations. Regions should strive to improve the quality and flexibility of employment to reduce the wage gap for disabled people, better meet the needs of workers with disabilities, improve access to social protection for non-standard forms of employment, and use technological advances to integrate people with disabilities by promoting inclusive technologies.

Thus, the analysis of problems of employment and vocational education of persons with disabilities requires an interdisciplinary approach, including the study of social, economic, political and legal aspects, as well as the development of scientifically based recommendations for overcoming them.

The integration of persons with health limitations into society is a complex and multifaceted process, the key element of which is their work activity. However, this process, characterized by the wide involvement of significant human and natural resources, represents a significant economic burden for any society. In conditions of limited resource base, the issue of financing costly social programs to support people with disabilities not only remains relevant, but also shows a tendency to further increase in significance.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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DIGITALIZATION OF AGRICULTURE: ECONOMIC EFFECTS AND IMPLEMENTATION CHALLENGES

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Abstract

The rapid advancement of digital technologies is reshaping agricultural systems worldwide at an increasing rate. This article examines how the adoption of precision farming, Internet of Things (IoT) devices, remote sensing and data-driven analytics is affecting the economic performance of the sector, particularly in developing and transitional economies. Drawing on empirical data and regional case studies, the paper evaluates the impact of digital adoption on production costs, labour efficiency and farm profitability. While the benefits of these innovations are well documented — ranging from reduced input expenses to improved market access — implementation remains uneven. Barriers such as limited rural infrastructure, low levels of digital literacy among farmers and the absence of adequate financing mechanisms continue to impede progress. The study emphasizes that meaningful digital transformation in agriculture requires more than technology alone; it depends on coordinated policy action, targeted investment in digital capacity and the development of inclusive innovation ecosystems. These findings contribute to a deeper understanding of the structural changes occurring within agricultural economies and provide practical insights for accelerating sustainable digital integration.

Keywords: digital agriculture, precision farming, IoT, rural development, technological adoption, food security

I. Introduction

Digitalization is transforming traditional industries, and agriculture is no exception. The integration of digital technologies into agricultural practices offers opportunities to increase productivity, reduce resource losses, and promote sustainable economic growth in rural areas [1][2]. However, in many developing and transition economies, the adoption of these technologies is constrained by various structural and financial problems [3][4]. For example, in China, Technological entrepreneurship is developing in an evolutionary way and requires a large academic sector.

In India, Technological entrepreneurship is developing in many ways due to the low level of socio-economic development. The potential of many technology companies is limited by the fact that their product complements or serves traditional businesses and does not create new ones.

In Central and Eastern European Countries, the nature of technological entrepreneurship is determined by the disproportion between academic potential and resource provision. Therefore, technology firms are concentrated in the field of virtual and digital technological entrepreneurship. The objective of this study is to examine the economic implications and challenges of digitalization in agriculture and to provide recommendations to overcome existing

barriers. The relevance of this topic lies in the growing need to address food security, climate change adaptation and improving the efficiency of agricultural systems in light of population growth and shrinking arable land [5].

The implementation of digital solutions in agriculture can significantly transform agrifood systems, improving transparency, traceability, and resilience against external shocks such as pandemics or geopolitical disruptions [6][7]. Additionally, digitalization opens new markets and value chains, enabling even small-scale farmers to access digital platforms and engage in more competitive trade [8][9].

Literature Review

The growing body of literature on digital agriculture highlights its transformative potential in improving agricultural productivity and sustainability. Scholars have emphasized the role of precision farming, IoT devices, and AI-based tools in enabling data-driven decision-making at the farm level [1][10]. Wolfert et al. [1] argue that big data analytics facilitates not only optimized crop management but also enhances supply chain coordination. Furthermore, Liakos et al. [3] provide a comprehensive overview of machine learning applications in agriculture, ranging from pest detection to yield prediction.

However, the literature also reveals significant disparities in adoption levels. In high-income countries, advanced digital tools are increasingly integrated into farming operations, whereas in developing economies, digital penetration remains limited [4][11]. According to the FAO [5], many smallholder farmers face difficulties in accessing even basic technologies due to infrastructural and financial constraints. Moreover, the OECD [6] stresses that the lack of digital skills among rural populations is a key factor inhibiting adoption. Several studies also touch upon the broader implications of digitalization on rural livelihoods and agrarian structures. Eastwood et al. [11] discuss the ethical and social dimensions of smart farming, emphasizing the risk of marginalizing traditional knowledge and excluding digitally illiterate farmers. Rotz et al. [14] highlight the impact on labor and rural communities, while Carolan [15] focuses on public perception and data ethics. El Bilali and Allahyari [16] explore the sustainability aspects of digital transformation, and van der Burg et al. [17] examine its implications for responsible innovation. Bronson [18] and Ingram & Maye [19] further investigate how digital tools affect knowledge dissemination and social inclusion in farming systems.

II. Materials and methods

This study employs a mixed-method research design combining quantitative and qualitative approaches. Quantitative data were obtained from national agricultural statistics, international development reports, and datasets provided by organizations such as FAO, World Bank, and ITU [4][5][9]. Key indicators examined include average production cost per hectare, yield per hectare, net income per farm, and digital tool adoption rates across different regions and farm sizes.

In parallel, qualitative insights were collected through semi-structured interviews with 28 farmers, agronomists, and policymakers from selected countries in Eastern Europe and Central Asia. These interviews aimed to identify real-world challenges and economic effects associated with digital technology implementation in agriculture [13][20]. Respondents were selected to reflect a diversity of farm sizes, levels of technological adoption, and agroecological zones. The data were analyzed using comparative methods to assess the before-and-after effects of adopting digital tools such as GPS-guided machinery, smart irrigation systems, and mobile-based market access platforms. of predicting the risk of a certain event is to determine when, where and with what (what) characteristics the event will occur. In general, non-parametric methods are often used in risk forecasting, such as the least squares method, which evaluates the accuracy of the forecast.

III. Results and discussion

The findings indicate a strong positive correlation between the adoption of digital tools and key economic indicators such as crop yield, production efficiency, and profitability.

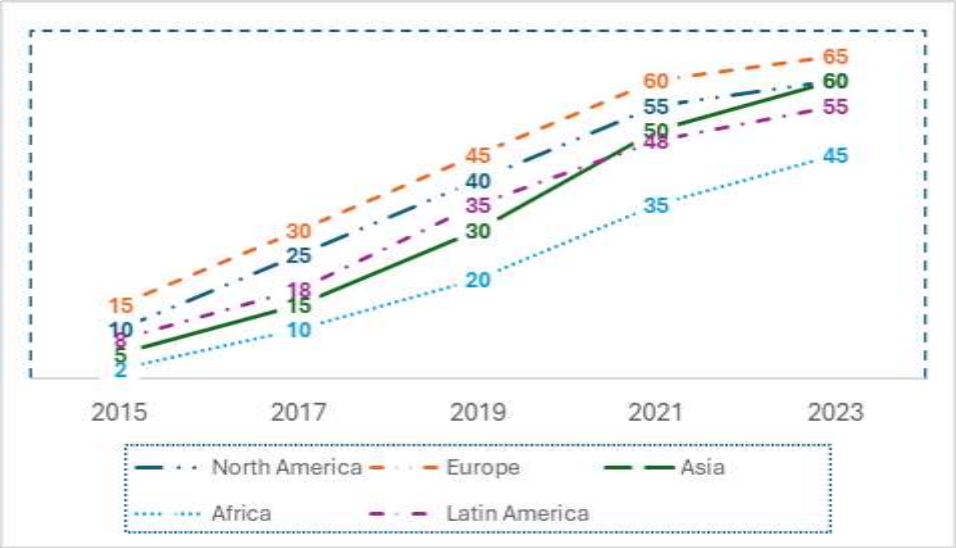


Figure 1: *Growth in Digital Technology Adoption in Agriculture by Region (2015–2023)*
Source: compiled by the author based on [4], [5], [9], [10].

As shown in Fig. 1, digital adoption in agriculture has shown positive progress in all regions over the past decade. North America and Europe lead the way in digital penetration in agriculture, reaching over 60% by 2023. Asia has also shown growth, particularly in countries such as China and India, where government initiatives and private sector innovation have accelerated digital integration. Latin America is following closely behind, benefiting from the expansion of mobile connectivity and digital service platforms tailored to smallholder farmers. Africa, while lagging behind other countries in the index, has made notable progress, from 2% in 2015 to 45% in 2023. Despite this positive trend, the regional disparities highlight the urgent need for inclusive infrastructure development and capacity building to ensure equitable access to digital technologies across all farming communities.

As shown in Fig. 2, farms implementing precision technologies experienced an average 15% decrease in input costs and up to a 30% increase in yields compared to traditional farming practices [1][7][9]. Notably, the deployment of IoT-based irrigation systems led to a 25% reduction in water usage and enhanced crop uniformity.

Digital tools have not only increased productivity but also improved market access and risk management, especially through the use of mobile platforms and predictive analytics. It is thanks to digital tools that farmers have been able to bypass middlemen and achieve higher prices for their produce [8][19]. Weather forecasting applications and sensor networks have helped reduce crop losses by allowing timely interventions. Overall, digitalization has increased the economic resilience of agricultural enterprises, especially in the face of climate uncertainty and market volatility. Fig. 2 shows the measurable economic effects of digitalization in agriculture. An analysis of the index values reveals a clear trend: digitalization leads to a significant reduction in production costs – by about 15%. The most significant cost savings are observed in farms using smart irrigation systems, GPS-guided tractors and precision application technologies. At the same time, crop yields typically increase by up to 20%, thanks to improved monitoring, better

prediction of pest outbreaks, and the ability to adjust management practices in real time using digital tools. However, the most significant shift is in per hectare income, which can increase by as much as 30% thanks to increased market access through e-commerce platforms. The chart shows that while digitalization requires an initial investment, the returns on this investment are tangible in terms of economic efficiency, productivity, and market competitiveness.

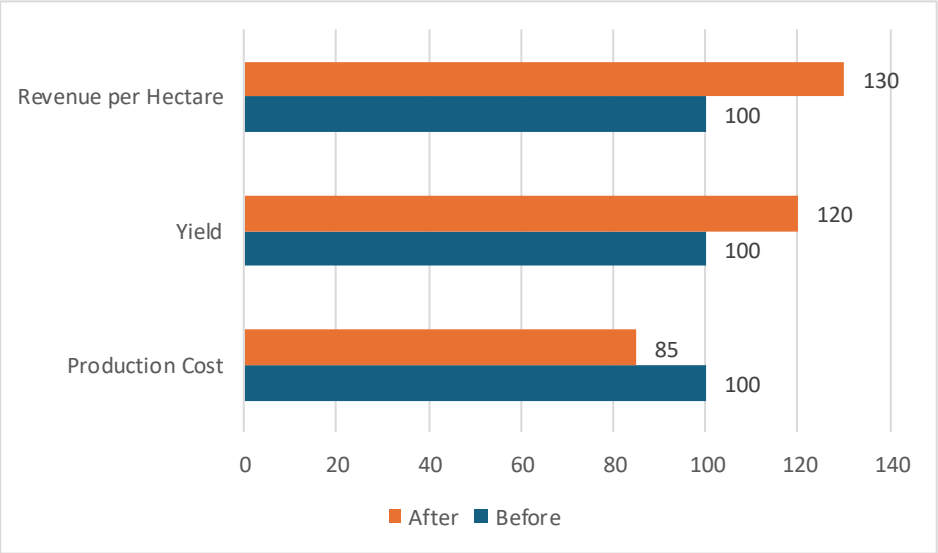


Figure 2: *Economic Impact of Digitalization: Before and After Technology Adoption*
Source: compiled by the author based on Bayer (2023) and supporting literature [6], [10], [13], [18].

Implementation Challenges

Despite these benefits, the study reveals several barriers to widespread digital adoption.

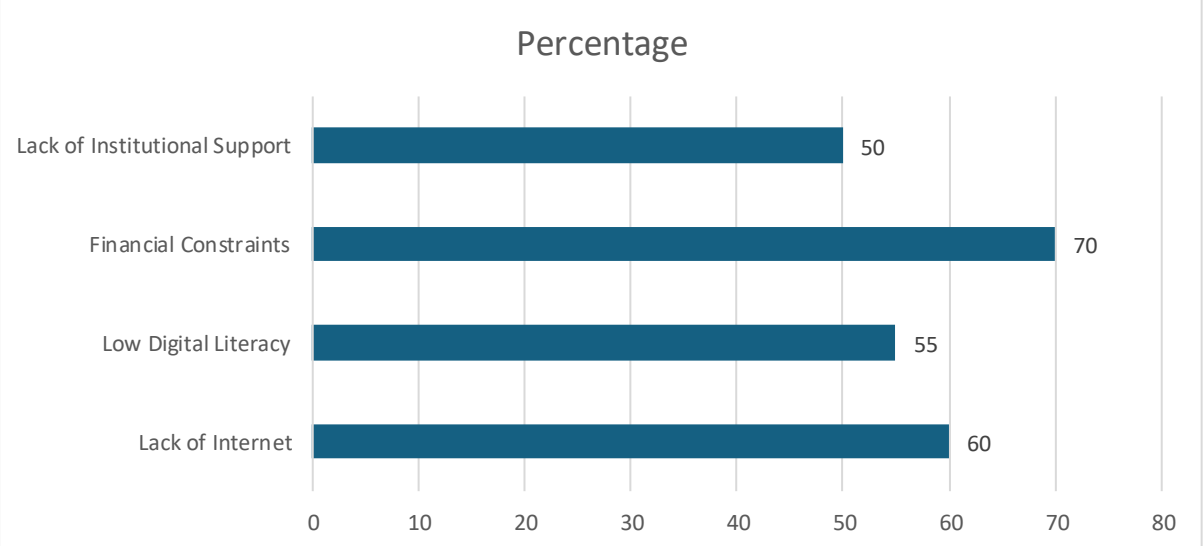


Figure 3: *Key Barriers to Digitalization in Agriculture (Survey of Farmers, 2023)*
Source: compiled by the author based on [6], [10], [13], [18].

Fig. 3 presents the most significant barriers that affect digital adoption. In a 2023 farmer survey, 70% of respondents cited financial constraints as the main limiting factor. Many small and medium-sized farmers do not have the funds to invest in digital equipment, subscription services, or the necessary upgrades to existing systems.

The second major challenge is the lack of internet connectivity in rural areas, cited by 60% of participants. Despite global improvements in mobile phone coverage, many agricultural areas still suffer from poor or unstable access.

The next most important is low levels of digital literacy (55%). Finally, 50% of respondents cited institutional weaknesses such as a lack of government coordination, fragmented policies, and limited access to technical support. To bridge the digital divide in agriculture, technological advances need to be accompanied by a comprehensive strategy, Thus, the successful implementation of technologies in agriculture requires not just the introduction of advanced solutions, but the implementation of large-scale and targeted scientific, technical and innovative programs that take into account all aspects and goals of sustainable development.

The most critical issue identified is the lack of reliable internet connectivity in rural areas, affecting over 60% of farmers surveyed [10][12]. Financial constraints are also significant, with many smallholders unable to afford the initial investment required for equipment and software licenses [13][14].

Furthermore, the lack of digital literacy and tailored training programs poses a major challenge [6][15]. Many farmers are unaware of available technologies or lack the skills to use them effectively. Institutional fragmentation and the absence of coherent national strategies further hinder integration efforts [18]. Lastly, interview data suggest that cultural resistance to changing traditional farming practices continues to slow adoption in some communities [20].

To effectively harness the economic potential of digital agriculture, a multi-faceted policy approach is essential. First, investment in rural digital infrastructure—particularly broadband internet—is crucial [12]. Public-private partnerships can be instrumental in accelerating infrastructure development and ensuring affordability for end users.

Second, governments should promote financial inclusion mechanisms such as microloans, subsidies, and leasing schemes to lower the entry cost for small and medium-scale farmers [14]. Establishing agri-digital innovation hubs and incubators can further stimulate local entrepreneurship and adaptation of technology to local needs.

Third, integrating digital literacy programs into agricultural extension services is critical [15][17]. These programs should include hands-on training and localized content to ensure relevance and accessibility. Special attention must be paid to including women and youth in digital training initiatives, as these groups often face disproportionate access barriers.

Fourth, national strategies must address regulatory clarity and foster interoperability standards among digital platforms [18]. This can enhance market competition, prevent monopolization, and enable seamless data integration across devices and services.

V. Conclusion

The findings of this study highlight both the potential and the challenges of integrating digital technologies into agricultural systems. On the other hand, tools such as precision irrigation, IoT-based crop monitoring, and mobile marketplaces have demonstrated clear benefits: reduced input costs, increased productivity, and improved access to markets. However, these benefits are not universal. In many regions, farmers face significant barriers to digitalization, including poor internet infrastructure, limited access to training, and weak institutional support. This shows that the success of digitalization depends not only on the availability of technology, but also on broader socio-economic and political conditions. Closing this gap requires more than innovation; targeted support measures are needed – public investment in rural connectivity, financial products tailored to smallholders, and education programs that take into account local realities. What works in one region may not be practical or relevant in another. For example, a farmer in rural Tajikistan faces different constraints and incentives than a farmer in northern France. It is worth noting that there is no universal model that suits everyone, and cannot exist. When

developing a strategy for the development of digital agriculture, it is necessary to take into account the specific features and complexities of the industry. For example, in animal husbandry, in contrast to industrial production, individualization and demand orientation are linked to the needs, health and well-being of each animal. Further research should focus not only on whether digital tools are effective, but also on the extent to which their true potential will be realized. Only if they are implemented in an inclusive, adaptive and in line with the daily realities of those, can they be fully successful.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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STATISTICAL ANALYSIS OF THE NUMBER OF DAMAGING LANDSLIDES IN MUNICIPALITIES AND REGIONS OF GEORGIA AND THEIR RELATIONSHIP WITH ATMOSPHERIC PRECIPITATION IN 2015-2024

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Abstract

Landslides are one of the most widespread types of natural disaster, occurring almost everywhere, including in Georgia. Landslides can destroy residential buildings and other structures, damage roads and bridges, disable utility lines and pose a threat to human life and health. They can also cause significant material damage. The occurrence of landslides depends on various stationary factors, such as slope steepness, lithology, soil and vegetation cover. At the same time, intense or extreme precipitation can be a key factor in landslide activation. Furthermore, precipitation can have both short-term (hours, days or months) and long-term (years or the climate scale) effects on landslide activation. This work presents the results of a statistical analysis of re-activated and new cases of damaging landslides in 11 Georgian regions and their constituent municipalities, as well as the relationship between landslide processes and atmospheric precipitation from 2015 to 2024. The municipalities vary in size from 56.7 km² (Kutaisi) to 3,104 km² (Mestia). The total area under study is 56,364 km². Over a ten-year period, 6,998 damaging landslides were recorded out of a total of 9,978. The following results were obtained in particular. Based on the number of landslides per year, normalized to 100 km² (LS100), the following five danger categories are proposed: 'Low' (LS100 = 0.02–1), 'Moderate' (LS100 = 1–2), 'High' (LS100 = 2–3), 'Very High' (LS100 = 3–4) and 'Extreme' (LS100 = 4). It was found that 28 municipalities belong to the "Low" landslide hazard category, 10 to the "Moderate" category, 9 to the "High" category, 6 to the "Very High" category, and 6 to the "Extreme" category. As the average annual precipitation increases, so does the number of landslides. The connection between LS100 values and the mean annual sum of atmospheric precipitation in municipalities and regions of Georgia follows a power-law function.

Keywords: landslides, natural disaster, risk assessment, atmospheric precipitations, statistical analysis

I. Introduction

Landslide processes, as one of the types of natural disasters, are widespread almost everywhere [1-3], including in Georgia [4-7]. Landslides destroy residential buildings and

structures, damage roads and bridges, disable utility lines, pose a threat to human life and health, cause significant material damage, etc. [8-10].

For example, some results of statistical analysis of parameterized landslide (LS) data (the number of landslides and their areas) for 11 regions of Georgia from 1900 to 2022 are presented in [7]. Landslides count for Georgia is 1325, total area - 526.3 km^2. The area of individual landslides varies in the range from 0.0005 km^2 (Imereti, Samegrelo-Zemo Svaneti, Samtskhe-Javakheti) to 12.0 km^2 (Shida Kartli). In particular, the following results were obtained. Map of distribution of landslides number and their areas for different regions of Georgia is presented. Repeatability of the number of landslides and also their total area for different ranges of LS areas is study; the highest frequency of landslides in the study area falls on the range of their areas 0.0005-0.05 km^2 (41.5%), the smallest - on the range 5.01-12.0 km^2 (0.38%); the highest frequency of the total area of landslides falls on the range of their areas 1.01-2.0 km^2 (26.1%), the smallest – on the range 0.0005-0.05 km^2 (1.8%). The average annual shares of the total area of landslides from the area of study regions is calculated; this share in Guria (0.288%) and Adjara (0.281%) is significantly higher than in other regions - respectively, 5.05-4.9 times more than in Shida Kartli and 28.8-28.1 times more than in Samegrelo-Zemo Svaneti, etc.

The activation of landslide processes depends on many stationary factors - slope steepness, lithology, soil and vegetation cover, etc. At the same time, intense or extreme precipitation can be one of the main reasons for the activation of landslides [11].

Recently, a number of studies have been conducted in Georgia to assess the short-term (hours, days, months) [12-15] and long-term (years, climate scale) impact of precipitation on the occurrence of landslides [16-18].

For example, in [16] preliminary results of the study of the relationship between the variability of the mean annual sum of atmospheric precipitation and landslide processes in Georgia for 32 years are presented. In particular, it was found that with an increase in the annual sum of atmospheric precipitation, the tendency of increase in the number of landslides is observed in accordance with a second power of polynomial.

This work is a continuation of previous studies. Below are presented the results of statistical analysis of the number of re-activated and new cases of damaging landslides in 11 regions of Georgia and 59 municipalities included in them, as well as the relationship of landslide processes with atmospheric precipitation in the period from 2015 to 2024.

II. Study area, material and methods

Study area – 11 region of Georgia including 59 municipalities with registered re-activated and new of damaging landslide number: Autonomous Republic of Adjara – /Adj/ - (Keda, Khelvachauri, Khulo, Kobuleti, Shuakhevi); Guria – /Gur/ - (Chokhatauri, Lanchkhuti, Ozurgeti); Imereti – /Im/ - (Baghdati, Chiatura, Kharagauli, Khoni, Kutaisi, Sachkhere, Samtredia, Terjola, Tkibuli, Tskaltubo, Vani, Zestaphoni); Kakheti - /Kakh/ - (Akhmeta, Dedoplistskaro, Gurjaani, Kvareli, Lagodekhi, Sagarejo, Signagi, Telavi); Kvemo Kartli – /KK/ - (Bolnisi, Dmanisi, Gardabani, Marneuli, Tetritskaro,Tsalka); Mtskheta-Mtianeti – /MM/ - (Dusheti, Kazbegi, Mtskheta, Tianeti); Samegrelo-Zemo Svaneti – /S-Z S/ - (Chkhorotsku, Khobi, Martvili, Mestia, Senaki,Tsalenjikha, Zugdidi; Racha-Lechkhumi and Kvemo Svaneti – /R-L KS/ (Ambrolauri, Lentekhi, Oni, Tsageri); Samtskhe-Javakheti – /S-J/ - (Adigeni, Akhalkalaki, Akhaltsikhe, Aspindza, Borjomi), Shida Kartli - /Sh K/ - (Gori, Kareli, Kaspi, Khashuri), Tbilisi - /Tb/.

The data of Department of Geology at Georgian National Environmental Agency about registered re-activated and new of damaging landslide number and annual sum of atmospheric precipitations for these municipalities are used [9,19]. It should be noted that the analysis of precipitation data in relation to this study was carried out in the work [19]. Period of observation: 2015-2024 (10 years).

The area of the municipalities varies from 56.7 km² (Kutaisi) to 3104 km² (Mestia). The total area under study is 56364 km². Over a ten-year period, 6998 damaging landslides were recorded (out of a total of 9978) [9].

In the proposed work the analysis of data is carried out with the use of the standard statistical analysis methods [20].

The following designations will be used below: Mean – average values; Max - maximal values; Min – minimal values; St Dev - standard deviation; St Err - standard error; C_v, - coefficient of variation, %; LS_N – landslide number in year; LS_{100} – landslide number in year normed to 100 km²; R^2 – coefficient of determination; R – coefficient of linear correlation; R' - correlation index for nonlinear regression; α - the level of significance; Lat - north latitude, °N; Lon - east longitude, °E.

The degree of correlation was determined in accordance with [20]: very high correlation ($0.9 \le R \le 1.0$); high correlation ($0.7 \le R < 0.9$); moderate correlation ($0.5 \le R < 0.7$); low correlation ($0.3 \le R < 0.5$); negligible correlation ($0 \le R < 0.3$).

Based on the number of landslides in year, normed to 100 km², it is proposed to introduce the following five danger categories: "Low" (LS_{100} = 0.02÷1), "Moderate" (LS_{100} = >1÷2), "High" (LS_{100} = >2÷3), "Very High" (LS_{100} = >3÷4), "Extreme" (LS_{100} = >4).

III. Results and discussion

Information on landslides number in year and landslides number in year normed to 100 km² by municipalities of Georgia in Fig. 1 and Table 1 are presented.

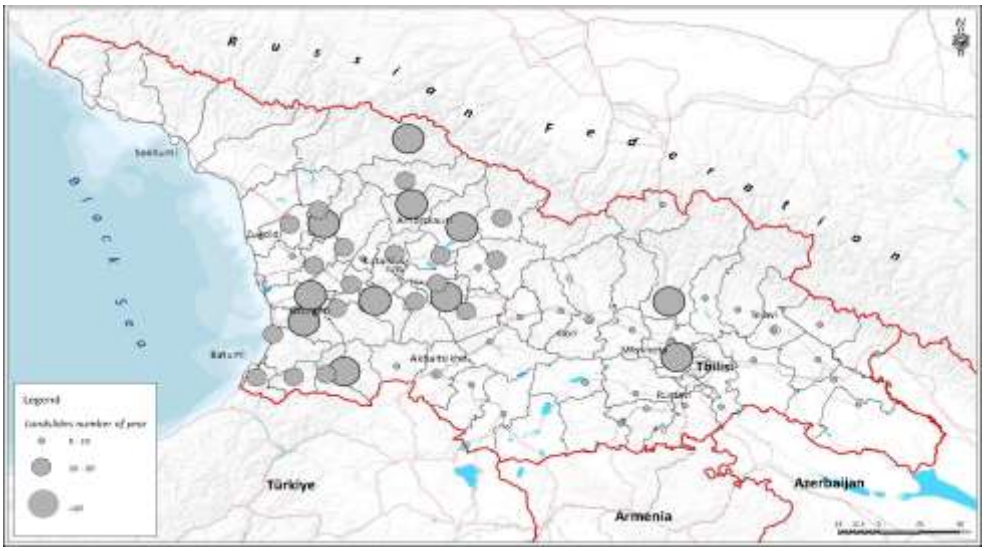


Figure 1: *Distribution of landslides number in year by municipalities of Georgia in 2015-2024.*

As follows from Fig. 1 and Table 1 values of LS_N change from 0.2 (Akhalkalaki, S-J) to 45.9 (Ozurgeti, Gur) and values of LS_{100} – from 0.02 (Akhalkalaki, S-J) to 7.00 (Lanchkhuti, Gur).

The various municipalities are characterized by the following landslides danger categories (Table 1):

LS_{100} = 0.02÷1 ("Low" category, 28 municipalities): Akhalkalaki (S-J), Dedoplistskaro (Kakh),

Kvareli (Kakh), Lagodekhi (Kakh), Gori (Sh K), Marneuli (KK), Kareli (Sh K), Bolnisi (KK), Kaspi (Sh K), Signagi (Kakh), Tsalka (KK), Akhmeta (Kakh), Dmanisi (KK), Telavi (Kakh), Kazbegi (M-M), Sagarejo (Kakh), Akhaltsikhe (S-J), Aspindza (S-J), Gardabani (KK), Borjomi (S-J), Gurjaani (Kakh), Tianeti (M-M), Mestia (S-ZS), Tetritskaro (KK), Khoni (Im), Dusheti (M-M), Oni (R-L KS), Mtskheta (M-M).

LS_{100} = >1÷2 ("Moderate" category, 10 municipalities): Khashuri (Sh K), Lentekhi (R-L KS), Adigeni (S-J), Khobi (S-ZS), Sachkhere (Im), Chiatura (Im), Kobuleti (Adj), Martvili (S-ZS), Tskaltubo (Im), Kutaisi (Im).

LS_{100} = >2÷3 ("High" category, 9 municipalities): Chokhatauri (Gur), Ambrolauri (R-L KS), Tsalenjikha (S-ZS), Kharagauli (Im), Baghdati (Im), Shuakhevi (Adj), Senaki (S-ZS), Keda (Adj), Zugdidi (S-ZS).

LS_{100} = >3÷4 ("Very High" category, 6 municipalities): Khelvachauri (Adj), Chkhorotsku (S-ZS), Terjola (Im), Tsageri (R-L KS), Khulo (Adj), Tkibuli (Im).

LS_{100} = >4÷7 ("Extreme" category, 6 municipalities): Vani (Im), Tbilisi (Tb), Samtredia (Im), Zestaphoni (Im), Ozurgeti (Gur), Lanchkhuti (Gur).

Table 1: *Data on landslides number in year and landslides number in year normed to 100 km² by municipalities of Georgia in 2015-2024.*

Location	LS Numb in year	LS Numb in year/100 km²	Location	LS Numb in year	LS Numb in year/100 km²
Keda (Adj)	12.7	2.88	Gardabani (KK)	4.6	0.44
Khelvachauri (Adj)	11.3	3.03	Marneuli (KK)	1.1	0.12
Khulo (Adj)	26	3.76	Tetritskaro (KK)	9.5	0.81
Kobuleti (Adj)	11.6	1.55	Tsalka (KK)	2.4	0.23
Shuakhevi (Adj)	15	2.60	Dusheti (M-M)	26.8	0.90
Chokhatauri (Gur)	16.7	2.04	Kazbegi (M-M)	3.1	0.29
Lanchkhuti (Gur)	39.2	7.00	Mtskheta (M-M)	7	0.95
Ozurgeti (Gur)	45.9	6.87	Tianeti (M-M)	6.7	0.74
Baghdati (Im)	19	2.35	Chkhorotsku (S-ZS)	21.3	3.34
Chiatura (Im)	8.4	1.53	Khobi (S-ZS)	7.7	1.12
Kharagauli (Im)	19.5	2.15	Martvili (S-ZS)	14.7	1.64
Khoni (Im)	3.4	0.84	Mestia (S-ZS)	23.7	0.76
Kutaisi (Im)	1.1	1.94	Senaki (S-ZS)	15.1	2.85
Sachkhere (Im)	10.7	1.18	Tsalenjikha (S-ZS)	14.2	2.15
Samtredia (Im)	16.6	4.78	Zugdidi (S-ZS)	19.8	2.99
Terjola (Im)	12.7	3.59	Ambrolauri (R-L KS)	24.3	2.13
Tkibuli (Im)	18.3	3.86	Lentekhi (R-L KS)	14.8	1.10
Tskaltubo (Im)	12.1	1.75	Oni (R-L KS)	15.4	0.90
Vani (Im)	26	4.44	Tsageri (R-L KS)	27.9	3.69
Zestaphoni (Im)	28.6	6.57	Adigeni (S-J)	8.9	1.11
Akhmeta (Kakh)	6	0.25	Akhalkalaki (S-J)	0.2	0.02
Dedoplistskaro (Kakh)	0.6	0.02	Akhaltsikhe (S-J)	4.2	0.42
Gurjaani (Kakh)	5	0.59	Aspindza (S-J)	3.5	0.42
Kvareli (Kakh)	0.6	0.06	Borjomi (S-J)	5.7	0.48
Lagodekhi (Kakh)	0.9	0.10	Gori (Sh K)	1.5	0.12
Sagarejo (Kakh)	4.4	0.29	Kareli (Sh K)	1.6	0.15
Signagi (Kakh)	2.8	0.22	Kaspi (Sh K)	1.6	0.20
Telavi (Kakh)	3.3	0.28	Khashuri (Sh K)	6.2	1.10
Bolnisi (KK)	1.5	0.18	Tbilisi (Tb)	23.1	4.58
Dmanisi (KK)	3.3	0.28			

With a high level of reliability, relationship between the values of LS_{100} by municipalities and the latitude and longitude of the area in Georgia can be represented by the following regression equation (the corresponding regression coefficients are presented in Table 2):

$$Y = a+b*x1+c*x1^2+d*x1^3+e*x1^4+f/x2+g/x2^2+h/x2^3+i/x2^4+j/x2^5$$

x1 – Lon °E, x2 – Lat °N, $R^2 = 0.524$, R' = 0.88, high correlation.

Table 2: *Coefficients of the equation for the relationship between the landslides number in year normed to 100 km² by municipalities and the latitude and longitude of the area in Georgia in 2015-2024.*

Coefficient	Value	Coefficient	Value
a	-8.70E+08	f	1.84E+11
b	4.22E+04	g	-1.56E+13
c	-1.44E+03	h	6.58E+14
d	2.17E+01	i	-1.39E+16
e	-1.23E-01	j	1.18E+17

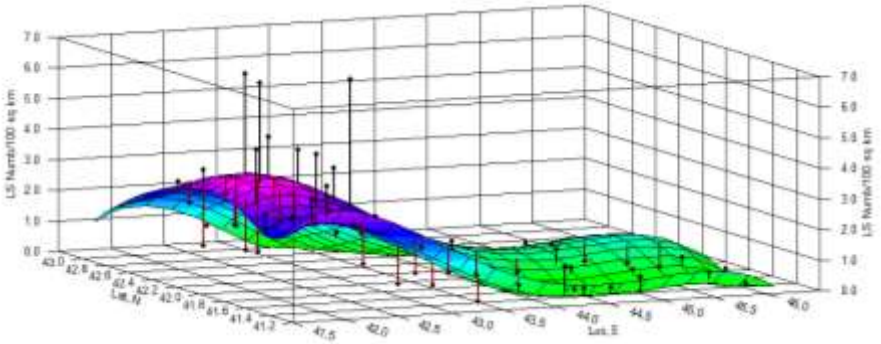
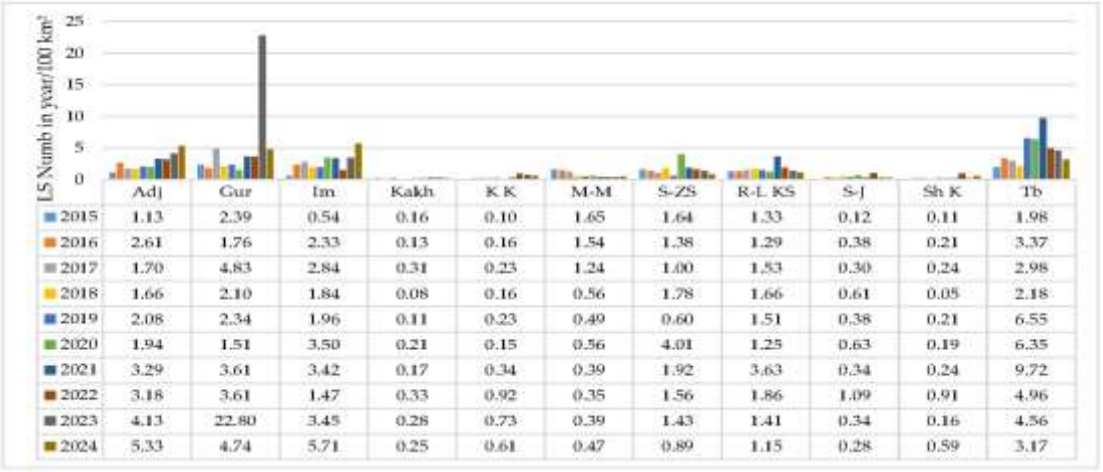


Figure 2: *Calculation model of distribution of landslides number in year normed to 100 km² by municipalities of Georgia in 2015-2024.*

In Fig. 2 calculation model of distribution of landslides number in year normed to 100 km² by municipalities of Georgia is presented, the actual data of which are given in Table 1. This Figure clearly demonstrates the decrease in the LS_{100} values in the eastern direction of the study area.



	Adj	Gur	Im	Kakh	K K	M-M	S-ZS	R-L KS	S-J	Sh K	Tb
2015	1.13	2.39	0.54	0.16	0.10	1.65	1.64	1.33	0.12	0.11	1.98
2016	2.61	1.76	2.33	0.13	0.16	1.54	1.38	1.29	0.38	0.21	3.37
2017	1.70	4.83	2.84	0.31	0.23	1.24	1.00	1.53	0.30	0.24	2.98
2018	1.66	2.10	1.84	0.08	0.16	0.56	1.78	1.66	0.61	0.05	2.18
2019	2.08	2.34	1.96	0.11	0.23	0.49	0.60	1.51	0.38	0.21	6.55
2020	1.94	1.51	3.50	0.21	0.15	0.56	4.01	1.25	0.63	0.19	6.35
2021	3.29	3.61	3.42	0.17	0.34	0.39	1.92	3.63	0.34	0.24	9.72
2022	3.18	3.61	1.47	0.33	0.92	0.35	1.56	1.86	1.09	0.91	4.96
2023	4.13	22.80	3.45	0.28	0.73	0.39	1.43	1.41	0.34	0.16	4.56
2024	5.33	4.74	5.71	0.25	0.61	0.47	0.89	1.15	0.28	0.59	3.17

Figure 3: *Data on landslides number in year normed to 100 km² by regions of Georgia in 2015-2024.*

Data on landslides number in year normed to 100 km² by regions of Georgia in 2015-2024 in Fig. 3 are presented and the statistical characteristics of these data in Table 3 are presented.

In particular, generally in the separate regions of Georgia the range of change and average of landslides danger categories is a following (Table 3): Adj: "Moderate" – "Extreme", "High"; Gur: "Moderate" – "Extreme", "Extreme"; Im: "Low" – "Extreme", "High"; Kakh: "Low" – "Low", "Low"; KK: "Low" – "Low", "Low"; M-M: "Low" – "Moderate", "Low"; S-ZS: "Low" – "Extreme", "Moderate"; R-L KS: "Moderate" – "Very High", "Moderate"; S-J: "Low" – "Moderate", "Low"; Sh K: "Low" – "Low", "Low"; Tb: "Moderate" – "Extreme", "Extreme".

Table 3: *Statistical characteristics of the landslides number in year normed to 100 km² by regions of Georgia in 2015-2024. NC - negligible correlation (0 ≤ R < 0.3).*

Variable	Adj	Gur	Im	Kakh	KK	M-M	S-ZS	R-L KS	S-J	Sh K	Tb
Max	5.33	22.8	5.71	0.33	0.92	1.65	4.01	3.63	1.09	0.91	9.72
Min	1.13	1.51	0.54	0.08	0.1	0.35	0.6	1.15	0.12	0.05	1.98
Mean	2.71	4.97	2.71	0.20	0.36	0.76	1.62	1.66	0.45	0.29	4.58
St Dev	1.29	6.38	1.43	0.09	0.29	0.51	0.94	0.72	0.27	0.26	2.41
St Err	0.43	2.13	0.48	0.03	0.10	0.17	0.31	0.24	0.09	0.09	0.80
C_v, %	47.8	128.3	52.8	42.8	78.9	66.3	57.7	43.5	60.7	89.4	52.5
	Correlation Matrix										
Adj	1	0.47	0.77	0.42	0.73	-0.53	NC	NC	NC	0.52	NC
Gur	0.47	1	NC	0.43	0.53	NC	NC	NC	NC	NC	NC
Im	0.77	NC	1	0.30	NC	-0.44	NC	NC	NC	NC	NC
Kakh	0.42	0.43	0.30	1	0.71	NC	NC	NC	NC	0.63	NC
KK	0.73	0.53	NC	0.71	1	-0.59	NC	NC	0.48	0.78	NC
M-M	-0.53	NC	-0.44	NC	-0.59	1	NC	-0.33	-0.49	-0.36	-0.55
S-ZS	NC	NC	NC	NC	NC	NC	1	NC	0.31	NC	NC
R-L KS	NC	NC	NC	NC	NC	-0.33	NC	1	NC	NC	0.73
S-J	NC	NC	NC	NC	0.48	-0.49	0.31	NC	1	0.61	NC
Sh K	0.52	NC	NC	0.63	0.78	-0.36	NC	NC	0.61	1	NC
Tb	NC	NC	NC	NC	NC	-0.55	NC	0.73	NC	NC	1

The linear correlation coefficients between the regions of Georgia according to the LS_{100} values are significant only for 22 pairs of regions out of 55 ($R \geq 0.30$, $\alpha \leq 0.40$). Moreover, a positive correlation is observed for 15 pairs of regions, and a negative one for 7. High correlation observed for 5 pair of regions, moderate correlation - for 7 pair of regions and low correlation - for 10 pair of regions. The largest positive value of R is observed for the pair Sh K÷KK (0.78 - high correlation), the largest negative K- for the pair M-M÷KK (-0.59 - moderate correlation).

In general, the processes of landslide formation in different regions of Georgia are weakly connected with each other - local conditions prevail. However, a common factor in the activation of landslides is atmospheric precipitation.

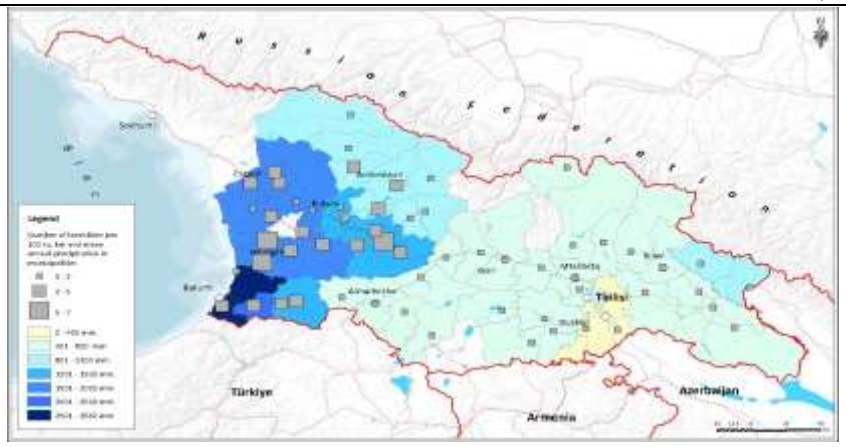


Figure 4: *Distribution of landslides number in year normed to 100 km² and mean annual sum of atmospheric precipitation by municipalities of Georgia in 2015-2024.*

In Fig. 4 distribution of LS_{100} values in the background of mean annual sum of atmospheric precipitation by municipalities of Georgia in 2015-2024 is presented. This Figure clearly shows the general tendency of decreasing LS_{100} values with decreasing annual sum of precipitation in eastern Georgia compared to western Georgia. Connection of LS_{100} values with mean annual sum of atmospheric precipitation by municipalities and regions of Georgia have a power-law function (Fig. 5 and Fig. 6 respectivelly).

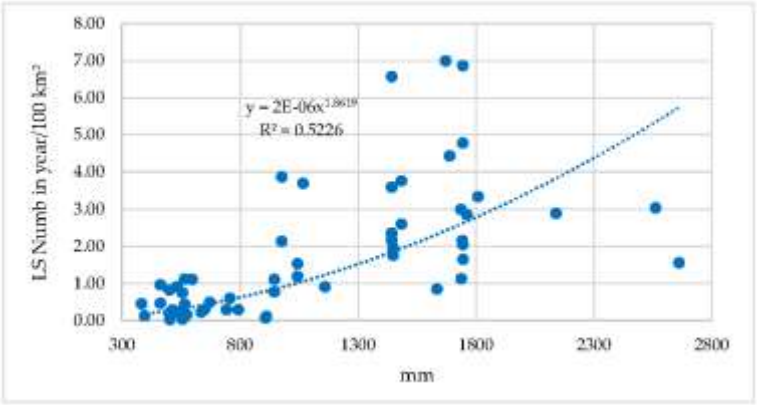


Figure 5: *Connection of landslides number in year normed to 100 km² with mean annual sum of atmospheric precipitation by municipalities of Georgia in 2015-2024. R' = 0.72, high index of correlation.*

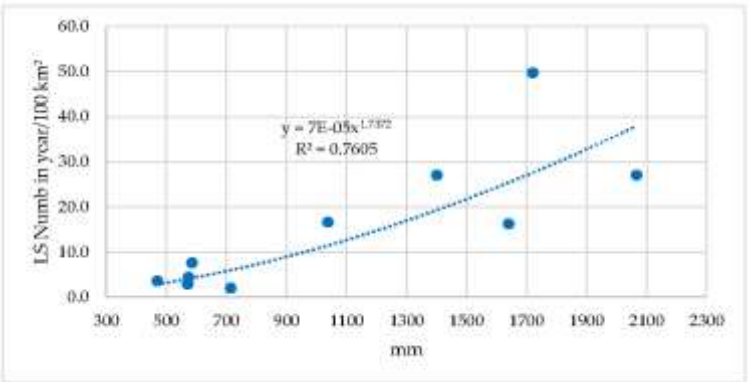


Figure 6: *Connection of landslides number in year normed to 100 km² with mean annual sum of atmospheric precipitation by regions of Georgia (excluding Tbilisi) in 2015-2024. R' = 0.87, high index of correlation.*

It should be noted that Tbilisi is the densely populated capital of Georgia. Therefore, there are significantly more landslide-vulnerable areas (buildings, roads, communications, etc.) per unit of area. Accordingly, the number of registered destructive landslides here is higher than the average in other regions of Georgia. Taking this fact into account, Fig. 6 does not contain corresponding data for Tbilisi.

However, even when including data for Tbilisi in this Figure, the power law relationship between LS100 values and annual sum of precipitation remains, albeit with a lower level of correlation index ($y = 0.0039 \cdot x^{1.173}$, $R' = 0.58$, moderate index of correlation).

V. Conclusion

In the near future, it is planned to conduct a similar study by the areas of destructive landslides in municipalities and regions of Georgia. The results of the conducted and planned studies will be used to assess the role of various factors in the activation of landslide processes (geological structure, terrain, distance from roads, precipitation, etc.) using artificial intelligence methods.

The results of these studies can also be useful for hybrid risk assessments and the application of a comprehensive hybrid approach to forecasting various events related to natural disasters [21].

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ECOTOURISM IN PROTECTED AREAS AS A TOOL FOR SUSTAINABLE SOCIO-ECONOMIC DEVELOPMENT IN THE ADJARA REGION

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Abstract

Currently, Georgia is tasked with clearly defining the regional development priority areas that will ensure sustainable and stable growth. Alongside agriculture, tourism is one of the sectors with the greatest potential for economic development in Georgia. It contributes significantly to the socio-economic development of the country's regions and improves the well-being of the local population. One such priority area is the development of ecotourism in the Adjara region's protected areas. This paper discusses the ecotourism potential of Adjara, as well as the region's current ecotourism projects and associated challenges, which have an impact on its sustainable socio-economic development. It emphasises the importance of ecotourism in conserving biodiversity and improving the socio-economic conditions of local Adjaran communities. Based on research findings, the paper presents recommendations for further developing ecotourism in Adjara while ensuring the protection of natural resources and contributing to the region's sustainable socio-economic growth. It also addresses the key issues hindering the development of ecotourism in Adjara's protected areas. It considers the risks arising from ecotourism activities that negatively impact the protection and preservation of natural ecosystems. Drawing on an analysis of ecotourism management in the region's protected areas, including visitor trends, ecological conditions, ecosystem diversity and the socio-economic status of local communities, the authors propose scientific and methodological recommendations. These recommendations aim to support the further development of ecotourism in Adjara, promote the protection of natural resources, facilitate the formation of a market for ecotourism products and contribute to the region's sustainable socio-economic development.

Keywords: Georgia, Adjara, region, tourism, ecotourism, protected areas, ecotourism infrastructure

I. Introduction

Relevance of the Topic

Against the backdrop of global climate change and the growing risk of biodiversity loss, ecotourism represents a sustainable form of tourism that promotes the protection and conservation of natural resources. In today's context, the development of ecotourism in protected areas is of great importance, as it does not compromise the integrity of ecosystems and involves travel that is mindful of nature.

For our region, ecotourism is not only a source of income but also a driver of infrastructure development, the growth of various business sectors, increased employment opportunities for the local population, the preservation of cultural and historical traditions, the advancement of folk crafts, and more. Therefore, studying the challenges of ecotourism development in the protected areas of the Adjara region is particularly relevant. In addition to preserving ecological safety,

ecotourism has the potential to generate significant economic benefits and contribute to the region's sustainable socio-economic development.

Research Objective

The objective of this study is to examine the challenges associated with organizing and effectively developing ecotourism, and to develop appropriate scientific and methodological recommendations to address these challenges. These recommendations aim to ensure effective coordination among the region's economic actors and contribute to the sustainable socio-economic development of the Adjara region.

Research Tasks

To achieve this objective, the study addresses the following tasks:

- To analyze the ecotourism infrastructure in the protected areas of the Adjara region.
- To examine the impact of ecotourism on the economic conditions of the Adjara region.
- To assess the influence of ecotourism on the ecological state of protected areas.

Subject of the Research

The subject of this research is the set of economic and economic-ecological relationships, as well as management issues, within the context of ecotourism development in the protected areas of the Adjara region — considered as a prerequisite for the region's sustainable socio-economic development.

Object of the Research

The object of the research is the regional market for ecotourism products in Adjara, Georgia.

Research Methods

The study employs methodological and regulatory materials from the Georgian National Tourism Administration, methods of economic analysis, synthesis, and evaluation, as well as official data from the National Statistics Office of Georgia.

Scientific Novelty of Research

This study explores the impact of ecotourism on the condition and diversity of ecosystems within the protected areas of Adjara. It develops scientific and methodological recommendations which, in the authors' view, will not only contribute to the formation and development of the regional ecotourism market, but will also have a positive influence on the further advancement and revitalization of the socio-economic development of the Adjara region.

II. New approach to risk forecasting

Forecasting the risks associated with ecotourism in Georgia's protected areas is a critically important topic and represents a long-term, complex process. This process requires the detailed analysis of both natural and social factors. Several key aspects are essential in this regard:

- Natural Changes: Protected areas in Georgia are increasingly experiencing fluctuations in temperature and precipitation, creating variable conditions for biodiversity. Extreme weather events such as droughts and storms have a significant impact on areas where tourism is actively developing.
- Tourism Pressure: Tourist activity in areas with limited resources can have detrimental effects on wildlife and ecosystems. Land degradation, destruction of vegetation, and the decline of

animal populations are all associated with mismanaged ecotourism. Therefore, detailed monitoring is essential to identify potential risks in advance.

Risk forecasting in the field of ecological tourism—particularly in protected areas—is a vital tool for ensuring environmental, social, and economic stability. Below are several modern approaches that, in our view, are particularly applicable in the context of ecotourism development in Adjara:

- Environmental Risk Monitoring through GIS and Remote Sensing: Satellite and drone technologies provide spatial visualization of ecosystem changes and support early risk detection (e.g., landslides, forest fires, erosion). These tools can be used to track biodiversity shifts in Adjara's protected areas, assess the impact of tourist flows on sensitive zones, and monitor forest cover changes via satellite imagery—serving as an indicator of tourism pressure.
- Tourism Pressure Assessment and Visitor Flow Management Based on Big Data: Using mobile data and online activity (e.g., Google Location Data, Booking.com trends), it is possible to analyze visitor dynamics and forecast tourism pressure. This allows for seasonal management strategies, and helps prevent overcrowding in sensitive locations within Adjara's protected areas.
- Community-Based Early Warning Systems (CB-EWS): Involving local populations in risk forecasting and early response enables the collection of localized data and enhances prevention efforts. Ecoguides, entrepreneurs, and community members can participate in ecological threat monitoring and tourist education in case of weather-related or natural hazards.
- Integrated Risk Analysis Models in Ecotourism Management: A comprehensive platform that combines ecological, social, and infrastructural risk analysis enables balanced management. Risks can be integrated into strategic planning for Adjara's protected areas, including the design of tourist trails that account for natural hazard zones.
- Climate Risk Forecasting Based on Modeling and Climate Scenarios: Climate data modeling reveals how temperature increases, changes in precipitation, and other factors could affect ecotourism infrastructure and natural environments. For example, forecasts can assess the impact of climate change on Kobuleti's peatland ecosystems or analyze coastal infrastructure risk under scenarios of rising sea levels.

In conclusion, as ecotourism develops in Adjara's protected areas, it is essential to incorporate risk forecasting using modern tools such as GIS, Big Data, climate modeling, and community-based systems. These approaches are fundamental for ensuring the resilience of both ecosystems and tourism infrastructure.

III. Engage experts

In the contemporary global landscape, tourism has emerged as a sector of critical importance—not only as a source of national income, but also as a catalyst for infrastructure development, job creation, cultural heritage preservation, and the promotion of traditional crafts. Furthermore, tourism fosters both formal and informal international networks, contributing to increased foreign investment and the enhancement of a country's global image [1].

Despite the intense competition in global tourism markets, maintaining competitiveness requires a well-thought-out, strategically planned, and flexible approach. Importantly, such strategies must prioritize not only short-term profits but also long-term and sustainable success.

Georgia currently faces the challenge of identifying priority directions for regional development that will play a crucial role in ensuring stable and sustainable progress. We believe that developing relatively new sectors—those capable of generating positive multiplier effects at the regional level—is a strategic necessity. One such promising direction for regional economic growth in Georgia is the development of ecological tourism [2].

Therefore, in our view, it is particularly appropriate to promote ecotourism in the protected natural areas of the Adjara region, where ecologically "untouched" and exotic natural landscapes make ecotourism especially attractive to both domestic and international visitors. In this context, ecotourism would focus on the integrated use of natural, cultural, and historical resources to create a complex and specific tourism product.

It is important to note that, as of today, Georgia largely possesses raw tourism resources but suffers from a distinct lack of fully developed tourism products—that is, market-ready offerings. Ecotourism has the potential not only to fill this gap but also to open new market segments. Simultaneously, it can serve as a key factor in the sustainable socio-economic development of Georgia's regions [2].

Ecotourism should thus be considered one of the priority directions for sustainable socio-economic development both at the national and regional levels. It offers the potential for substantial income while maintaining ecological safety, thereby aligning with the core principles of sustainable development.

As of 2024, according to the IUCN (International Union for Conservation of Nature) classification, Georgia has approximately 100 protected areas across six different categories, including: 14 State Reserves, 12 National Parks, 40 Natural Monuments, 26 Managed Reserves, 5 Protected Landscapes, 1 Multiple-Use Area.

These areas collectively cover approximately 912,862 hectares, which constitutes about 13% of Georgia's total territory [3].

Given that Adjara is one of Georgia's largest and most biodiverse regions, it is both timely and relevant to explore the current challenges and future prospects of ecotourism development in Georgia's protected areas, using the Adjara region as a case study. This approach allows for a clearer understanding of ecotourism's potential impact on the sustainable socio-economic development of the region.

The Adjara region is home to several officially designated protected areas [3]:

- Kintrishi Protected Areas. (*Kintrishi Strict Nature Reserve* – 3,108 hectares; *Kintrishi National Park* – 10,406 hectares.)
- Machakhela National Park – 7,333 hectares
- Mtirala National Park – 15,580 hectares
- Kobuleti Protected Areas. (*Kobuleti Strict Nature Reserve* – 316 hectares, *Kobuleti Managed Reserve* – 466 hectares.)

Below (Fig. 1), a diagram presents visitor statistics for the protected areas of Adjara from 2018 to 2023, based on official sources [3,6].

As shown in Fig. 1, the number of visitors to the protected areas of Adjara significantly increased between 2020 and 2024. This growth can be attributed not only to the popularization of ecotourism, infrastructure development, and the creation of new tourist products, but also to the fact that, following the end of the COVID-19 pandemic, people increasingly sought places where they could feel safe. Rather than visiting overcrowded areas, individuals have preferred environments that offer the possibility of maintaining social distancing, where they can feel secure and protected.

The tourism sector of Georgia is now facing the challenge of more actively developing ecotourism, which involves the synergy of tourism with the protection of natural resources. Additionally, ecotourism has the potential to attract funding not only for environmental protection in the region but also for its economic and socio-cultural development. Furthermore, through the development of this type of tourism, the local population will have the opportunity to turn the income generated from tourism services into an additional source of revenue.

In the process of implementing ecotourism activities in the protected areas of Adjara, both direct and indirect impacts are observed, which have both positive and negative effects on wildlife (see Table 1).

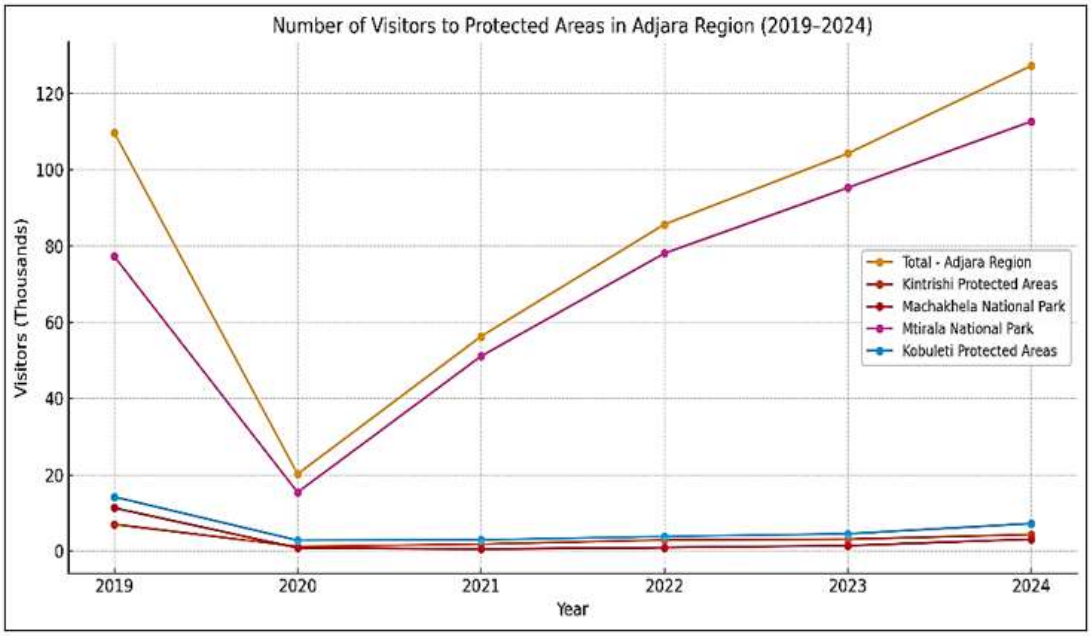


Figure 1: *Visitor Statistics for Non-Protected Areas in Adjara from 2019 to 2024*
Source: Compiled by the authors based on the reports of the Agency of Protected Areas of Georgia for the years 2019–2024.

Table 1: *Positive and Negative Effects of Ecotourism on Wildlife.*

Type of Impact	Form of Impact	Positive Effects	Negative Effects
Direct	Tourists' Movement	Strengthened biomonitoring, increased awareness	Animal Disturbance, Vegetation Degradation, Invasion of Non-Native Species
	Infrastructure Development	Environmentally safe trails	Soil erosion, destruction of natural landscapes
Indirect	Economic Pressure	Employment for the local population	Overuse of natural resources
	Urbanization and Commercialization	Improvement of infrastructure	Fragmentation of ecosystems, commercialization of the environment

Source: Table compiled by the authors based on interviews with specialists working in the protected areas of the Adjara region and on personal observations.

Based on interviews with specialists working in the protected areas of the Adjara region, it can be stated that the management of these areas is carried out with adherence to established guidelines and best practices. Rangers pay particular attention to ensuring that tourists access the protected areas only through designated routes, which significantly contributes to the preservation and protection of vital vegetation cover.

The protected areas are equipped with designated facilities for travelers, including waiting areas, overnight shelters, designated fire pits, tenting areas, picnic tables, and waste disposal zones. These infrastructural elements significantly reduce the risk of wildfires, enable proper sanitation management, and help prevent uncontrolled trampling, the spread of invasive species, and disruptions to the ecological balance of natural ecosystems.

The construction of ecological trails within protected areas is of great importance, as it allows for the regulation of tourist flow within sensitive zones, minimizes trampling of vegetation, and supports long-term conservation efforts.

Although the ecotourism infrastructure in Adjara's protected areas is relatively well developed, there are still certain risks that pose challenges to the conservation and maintenance of biodiversity [5]. Environmental pollution, primarily caused by visitors' negligence, most often involves solid waste. We believe this threat can be mitigated through improved visitor awareness and the enforcement of fines. Noise pollution, which disrupts the recommended quiet zones in protected areas, is another concern—particularly as it can disturb bird populations and other wildlife.

Despite these negative aspects, ecotourism also offers clear benefits that support the sustainable development of the Adjara region. Below, Table 3 presents the key factors that support the development of ecotourism, along with an overview of the risks that could negatively impact the region's path toward sustainable development (See Table 3.).

Table 3: *Positive Aspects of Ecotourism Influencing the Sustainable Development of the Adjara Region and the Risks of Its Negative Impact on the Regional Sustainability Process*

#	**Positive Aspects of Ecotourism Development**	**Risks of Negative Impact of Ecotourism (In Case of Poor Management)**
1	Increase in tax revenues from ecotourism and related sectors	Existence of "shadow" tourism businesses
2	Development of ecotourism	Rapid growth of ecotourism (at the initial stage)
3	Increase in the number of tourists	Rapid increase in the number of tourists (at the initial stage)
4	Stimulation of the development of ecotourism-related sectors and increase in their revenues	Intensification of waste collection and recycling issues due to increased tourist flow
5	Stimulating the improvement of infrastructure (roads, communications, education)	Loss of tourist attractiveness
6	Enhancing the tourist image of the Adjara region through unique and high-quality tourist services	Negative impact on the region's environment, degradation of ecosystems
7	Creation of new jobs	Overuse of natural resources
8	Increase in local population income	Disrespect for the local culture
9	Improvement of social conditions	Social dissatisfaction/conflicts
10	Economic development of the region	Economic loss

Source: *The table is compiled by the authors based on interviews with specialists working on the protected areas of the Adjara region and personal observations.*

Despite the undeniable positive aspects of ecological tourism development in the region, it is accompanied by certain negative effects, including:

- Overuse of natural ecosystems in ecotourism zones due to the increase in the number of tourists;
- Increase in noise pollution caused by the rise in the number of transportation vehicles;
- Mass influx of tourists, which negatively affects the local culture and way of life of the residents;
- Excessive anthropogenic pressures on the surrounding landscape, leading to the loss of both historical and architectural heritage and changes in the economic structure, which make local industries increasingly dependent on tourism, thereby affecting the region's identity and spatial character;
- Disintegration of the existing social structure, leading to the loss of traditional values and conflicts between various local groups;

- Concerning foreign investments, it should be noted that foreign entrepreneurs show limited interest. Due to the income levels of the Georgian population, they do not see them as substantial clients [7].

It is important to note that, in our case, the concept of ecological tourism in the Adjara region is based on the following principles [8]:

- Familiarization with the region's nature, local traditions, and culture;
- Minimization of negative impacts on the natural landscapes and socio-cultural communities of the areas to be visited;
- Promotion of the preservation of the region's nature and local socio-cultural environment;
- Ecological education for those involved in ecotourism activities (for local residents and tourists);
- Economic efficiency and contribution to the sustainable development of the Adjara region.

Sustainable development of the Adjara region refers to a form of socio-economic growth that ensures the well-being of the community in the short, medium, and, most importantly, long term. It is based on the principle that the needs of the present must be met without compromising the ability of future generations to meet their own needs. Sustainable development involves creating conditions for long-term economic growth while considering environmental protection to the maximum extent. Below is a schematic representation of the impact of ecotourism on the region's social, ecological, and economic sustainable development and its key directions.

The impact of ecotourism on the sustainable socio-economic development of the Adjara region can primarily be discussed through the following strategic directions:

- Economic impact (creation of new jobs; support for small and medium-sized businesses);
- Social effect (employment of young people in villages; promotion of cultural heritage);
- Environmental role (less environmental impact compared to mass tourism; raising ecological awareness).

One of the Georgian government's priority areas is the rational use of natural resources in the process of economic development, ensuring ecological safety and sustainability, and preventing the risks of natural disasters. When making decisions, it is essential to assess not only the economic feasibility but also the ecological and social effectiveness. This interconnection serves the well-being of humanity. To achieve this goal, promoting green economy is crucial, as it is one of the necessary instruments for the region's sustainable development. At the same time, fostering the growth of the green economy in the long term will reduce business costs and contribute to the development of new business directions.

Based on the analysis of ecotourism as a sector of the modern tourism industry, it can be concluded that ecotourism primarily requires support at the regional level. The regional tourism business associations should play a key role in organizing the ecotourism sector. In our view, they must be able to address the following tasks for the development of ecotourism in the Adjara region:

- Formation of information systems for regional ecotourism development programs and their methodological support;
- Creation of an effective mechanism for the formation of new ecotourism sites;
- Training qualified personnel for conducting entrepreneurial activities in the tourism business;
- Development of mechanisms for selecting and implementing prospective investment projects for ecotourism development.

Regional tourism business associations, in coordination with local administrations, regional funds, labor exchanges, and other interested organizations, should coordinate the formation of ecotourism infrastructure on-site. As for the mechanism for forming the infrastructure, it should be based on a state program that supports the development of ecotourism. This program should include: improving the normative-legal framework; providing and enhancing the methodological support for information networks; forming financial infrastructure with the participation of funds,

special banks, insurance companies, and investment institutions; as well as involving the industrial-technological and socio-business circles.

Additionally, it should be noted that the development of ecological tourism in Georgia, and specifically in the Adjara region, is hindered by the impact of certain factors, including:

- Incomplete legislation: The legal status of ecological tourism has not yet been fully resolved (the relevant laws and regulations are incomplete);

- The need for a clearer definition of the concept of ecological tourism development: The interests of cooperation and the implementation of economic mechanisms for management are not clearly defined;

- The regional municipal bodies inadequately utilize their governance functions, which define the political policies of municipal entities in the tourism sector, and their role in tourism organization and regulation. [4]

Ecotourism has the potential to attract resources both for the region's ecological safety and its economic and socio-cultural development, as the development of ecological tourism contributes to raising the population's awareness in the fields of ecology and ecological education.

V. Conclusion

Ecotourism in Adjara is not only an alternative form of regional tourism but also an opportunity for the coexistence of nature and culture, economic development, and ensuring a sustainable future. Based on the analysis of the development of the modern tourism sector, we can conclude that ecotourism primarily requires support at the regional level. Regional tourism business associations should play a significant (key) role in the organization of ecotourism. In our view, they should ensure the following:

- Formation of information systems for regional ecotourism development programs and their methodological support;
- Establishment of effective mechanisms for the creation of new objects in the ecotourism sector;
- Training of the appropriate personnel for entrepreneurial activities in the tourism sector;
- Development of relevant mechanisms for selecting and implementing promising investment projects for ecotourism development.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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PATHWAYS FOR SMALL ENTERPRISE ENGAGEMENT IN SUSTAINABLE ECONOMIC DEVELOPMENT: INTEGRATING SMES INTO RESILIENT AND ENVIRONMENTALLY SUSTAINABLE COUNTRY AND SECTOR STRATEGIES

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Abstract

The transition to a green economy presents both challenges and opportunities for small enterprises, which play a vital role in local economic development and innovation. This article explores the intersection between small businesses and the green economy, identifying key points of connection where small enterprises can contribute to and benefit from sustainable development. The study analyses how small businesses engage in green sectors such as renewable energy, eco-tourism, sustainable agriculture, and resource-efficient manufacturing. Based on a qualitative analysis of case studies and policy frameworks, the article highlights the drivers and barriers influencing small enterprise participation in the green economy. These include access to green financing, availability of sustainable technologies, regulatory support, and market demand for eco-friendly products and services. The research also emphasizes the role of local and national policies in fostering an enabling environment for green entrepreneurship. The findings suggest that small enterprises are not only capable of adapting to sustainability trends but can also act as catalysts for innovation and inclusive growth within the green economy. Strategic partnerships, capacity-building initiatives, and targeted support mechanisms are identified as key enablers for expanding small business engagement in sustainable economic practice. This article provides insights for policymakers, entrepreneurs, and development practitioners on how to strengthen the integration of small enterprises into the green economy, promoting both environmental sustainability and economic resilience.

Keywords: entrepreneurship, middle class, small business, market transformation, post-industrial era, green economy.

I. Introduction

The global transition toward a green economy — defined as economic growth that is environmentally sustainable and socially inclusive — has gained increasing momentum in recent years. As governments, international organizations, and businesses seek to address climate change, resource depletion, and environmental degradation, the concept of a green economy has emerged as a central framework for sustainable development. This shift emphasizes the need to decouple economic growth from environmental impact through the promotion of renewable energy, resource efficiency, circular economy practices, and sustainable consumption and production patterns.

Within this evolving economic landscape, small enterprises play a critical yet often underappreciated role. While large corporations frequently dominate discussions on sustainability due to their scale and global reach, small and medium-sized enterprises (SMEs) represent a significant share of employment, innovation, and local economic activity in both developed and developing economies. According to the World Bank, SMEs account for over 90% of businesses worldwide and more than 50% of employment. Their agility, adaptability, and close ties to local communities position them as key actors in driving the green transition at the grassroots level.

Despite their potential, small enterprises often face significant barriers to participating in the green economy. These include limited access to financing, lack of technical expertise, insufficient policy support, and low awareness of green business opportunities. At the same time, many small businesses are already engaged in environmentally sustainable practices — from energy-efficient operations to eco-friendly product development — often without formal recognition or strategic alignment with broader green economic goals. This article explores the points of connection and growth between small enterprises and the green economy. It examines how small businesses can contribute to sustainability efforts, the sectors in which they are most active, and the conditions that enable or hinder their participation. Drawing on case studies and policy frameworks, the study identifies opportunities for strengthening the integration of small enterprises into the green economy, promoting both economic resilience and environmental sustainability .

II. Methods

This study adopts a qualitative research approach , focusing on in-depth analysis of small enterprise engagement in the green economy. The research methodology was designed to explore the opportunities, challenges, and strategic points of connection between small businesses and sustainable economic practices. The approach combines document analysis, case studies , and semi-structured interviews with stakeholders involved in green entrepreneurship and policy development.

1. Research Design

A multi-case comparative design was employed to examine small enterprise participation in the green economy across different sectors and geographic contexts. This approach allows for a nuanced understanding of how contextual factors — such as national policy frameworks, market conditions, and institutional support — influence green business development.

2. Data Collection

The data collection process included the following components:

- Document Analysis : A review of national and international policy documents, green economy strategies, SME development programs, and reports from organizations such as the United Nations Environment Programme (UNEP), the International Labour Organization (ILO), and the Organisation for Economic Co-operation and Development (OECD). This helped identify policy frameworks and support mechanisms relevant to small enterprise participation in the green economy.
- Case Studies : In-depth case studies were conducted on five small enterprises operating in green sectors such as renewable energy, eco-tourism, sustainable agriculture, and circular economy-based production. Each case study explored:
    - Business model and sustainability practices
    - Motivations and barriers to green transition
    - Access to financing, markets, and technical support
    - Interaction with local and national policy environments
- Semi-Structured Interviews : A total of 15 interviews were conducted with key stakeholders, including:
    - Small business owners and entrepreneurs
    - Representatives from business support organizations and green incubators

- Policy-makers and government officials
- Experts in sustainable development and entrepreneurship

The interview guide focused on understanding the enablers and constraints of small enterprise participation in the green economy, as well as identifying best practices and policy recommendations.

3. Data Analysis

Qualitative data from interviews and case studies were analyzed using thematic content analysis . The coding process was supported by NVivo software and involved the following steps:

- Initial open coding to identify key themes and patterns
- Axial coding to explore relationships between categories
- Selective coding to develop overarching themes

Key themes included:

- Drivers of green business adoption
- Barriers to participation in the green economy
- Role of policy and institutional support
- Market and financial opportunities

Quantitative data from secondary sources — such as SME green business statistics and employment figures — were used to contextualize the qualitative findings.

4. Ethical Considerations

All participants were informed about the purpose of the research and gave their informed consent prior to participation. Anonymity and confidentiality were ensured, and all data were stored securely in accordance with international research ethics standards.

5. Limitations

The qualitative nature of the study limits the generalizability of the findings, as the sample was limited to a small number of enterprises and stakeholders. Additionally, the focus on specific green sectors may not fully capture the diversity of small enterprise engagement across all areas of the green economy. However, the in-depth nature of the analysis provides valuable insights into the mechanisms and conditions that support small business participation in sustainable development.

Within the framework of the Second International Scientific and Practical Conference on the problems of financing and crediting of the small and medium business sector in Russia, the necessity of accelerating the process of creating a domestic socially oriented financial structure of small and medium-sized entrepreneurship in the country was determined.

Toreev V.B. and Voronovskaya O.E. believe that the domestic banking sector is more focused on servicing large businesses, thus significantly increasing the costs of lending to small companies and leading to an increase in interest rates on loans.

III. Results

The findings of this study provide a comprehensive understanding of how small enterprises engage with the green economy, highlighting both the opportunities for growth and the challenges that limit deeper integration . The analysis draws on five in-depth case studies and 15 semi-structured interviews with entrepreneurs, policy-makers, and support organizations.

1. Engagement of Small Enterprises in Green Sectors

The research reveals that small enterprises are actively participating in a diverse range of green economic activities. The most prominent sectors include renewable energy, eco-tourism, sustainable agriculture, and circular economy-based production . These businesses are not merely adapting to environmental trends — many are leading innovation in sustainability at the local level.

For instance, a small renewable energy firm in Southeast Asia has developed affordable solar-powered lighting systems for off-grid rural communities. Another example is a circular fashion

startup in Europe that collects textile waste and transforms it into new garments, reducing landfill impact and promoting sustainable consumption.

These case studies demonstrate that small enterprises often embed sustainability into their core business strategies , rather than treating it as an optional or marketing-driven initiative. Their motivations include environmental values, market demand, and long-term business resilience .

2. Key Motivations for Green Transition

Interviews with entrepreneurs and stakeholders revealed several key drivers behind small enterprises' engagement in the green economy:

- Environmental values and personal ethics : Many entrepreneurs expressed a strong personal commitment to sustainability, often citing a desire to "do business differently" and contribute to environmental protection.
- Market opportunities : Growing consumer demand for eco-friendly products and services is a major incentive. Respondents noted that younger consumers, in particular, are more willing to pay a premium for sustainable offerings.
- Cost savings and efficiency : Green practices such as energy efficiency, waste reduction, and resource optimization were frequently cited as ways to cut operational costs and improve long-term profitability.
- Regulatory and policy incentives : In some countries, national or regional green business incentives — such as tax breaks, subsidies, or green certification programs — were seen as important enablers for small enterprises to adopt sustainable practices.

3. Barriers to Full Participation

Despite the growing engagement, the study also identified significant barriers that hinder the full integration of small enterprises into the green economy:

- Limited access to financing : Many entrepreneurs reported difficulties in securing funding for green initiatives. Traditional lenders often perceive green businesses as risky or unfamiliar, and green financing mechanisms (e.g., green loans, impact investment) are not widely accessible to small firms.
- Lack of technical knowledge and capacity : Small businesses often lack the expertise to implement advanced sustainability practices, such as life-cycle analysis, carbon footprinting, or compliance with international green standards.
- Inadequate policy support : While some countries have supportive frameworks, others lack targeted policies for green SMEs. Respondents noted that green economy policies often focus on large corporations, leaving small enterprises without tailored support.
- Market barriers : Green small businesses often struggle with greenwashing by larger competitors , limited consumer awareness , and price sensitivity in local markets.

4. Role of Institutional and Policy Support

The research highlights the critical importance of institutional support in enabling small enterprises to thrive in the green economy. Successful case studies were often linked to the presence of green business incubators, local sustainability networks, and public-private partnerships .

For example, one small agroecology business in Africa was able to scale its operations thanks to a government-supported green entrepreneurship program that provided technical training, access to markets, and microfinance . Similarly, a European eco-tourism venture benefited from a regional sustainability certification scheme that helped attract eco-conscious tourists and improve brand visibility.

Policy-makers interviewed for the study emphasized the need for targeted support mechanisms , such as:

- Green business grants and low-interest loans
- Training programs in sustainable business practices
- Simplified access to green certification and standards

- Local green procurement policies that prioritize small suppliers

5. Strategic Points of Connection

The findings identify several strategic points of connection between small enterprises and the green economy:

- Green innovation and local solutions : Small businesses are uniquely positioned to develop localized, context-specific sustainability innovations that larger firms may overlook.
- Community engagement and social impact : Many green small enterprises combine environmental goals with social inclusion, such as creating jobs in marginalized communities or supporting local food systems.
- Public-private partnerships : Collaboration between small enterprises, governments, and NGOs can help scale green initiatives and overcome resource constraints.
- Digital tools and platforms : The use of digital platforms for marketing, supply chain management, and customer engagement is growing among green SMEs, helping them reach wider markets and reduce operational costs.

Overall, the study demonstrates that small enterprises are active contributors to the green economy , with the potential to drive innovation, job creation, and environmental sustainability . However, their participation is often constrained by financial, technical, and policy-related barriers . Strategic interventions — including better access to financing, capacity-building, and supportive policy frameworks — are essential to unlock the full potential of small enterprises in the transition to a green economy.

IV. Discussion

I. Subsection One: The Strategic Role of Small Enterprises in Green Economic Transformation

One of the most significant insights from the research is that small enterprises are not merely passive actors in the green economic transition — rather, they are often key innovators, implementers, and localizers of sustainable practices . This aligns with findings from the OECD (2021) and UNEP (2022), which emphasize the importance of SMEs in driving decentralized, inclusive, and context-sensitive sustainability initiatives.

The case studies and stakeholder interviews confirm that small businesses are actively involved in green innovation , particularly in sectors where localized knowledge and flexibility are advantageous. For example, small renewable energy providers have successfully introduced affordable, off-grid solar solutions in rural areas where large-scale energy companies have limited presence. Similarly, micro-enterprises in the circular economy are pioneering waste reduction and product lifecycle extension strategies that complement national sustainability goals.

This suggests that small enterprises can serve as catalysts for green economic transformation , especially when supported by enabling policies and institutional frameworks. Their ability to respond quickly to market and regulatory changes , combined with their deep understanding of local needs , positions them as essential partners in the implementation of national and international sustainability agendas, including the United Nations Sustainable Development Goals (SDGs), particularly SDG 8 (Decent Work and Economic Growth) and SDG 12 (Responsible Consumption and Production).

However, the findings also reveal that many small enterprises operate in isolation , without formal integration into broader green economic strategies. This fragmentation limits their visibility, access to resources, and potential for scaling. The lack of systematic support mechanisms , such as green entrepreneurship training, access to green finance, and policy incentives tailored to SMEs, remains a key barrier to deeper participation.

Moreover, the research underscores the importance of green business ecosystems , where small enterprises can collaborate with local governments, NGOs, academic institutions, and larger corporations to co-create sustainable solutions. Such ecosystems not only enhance the capacity of small businesses but also contribute to regional economic resilience and inclusive green growth .

In summary, this subsection highlights the strategic value of small enterprises in advancing the green economy . Their role extends beyond environmental stewardship to include economic diversification, job creation, and community empowerment . However, to fully realize this potential, targeted interventions are needed to strengthen their integration into national green development strategies and support networks.

II. Subsection Two

In the Russian economy, small business as a subject has existed for several decades, playing an increasingly important role in the socio-economic development of the country. Small business in the country continues to develop, acquiring more and more features typical of a civilized form of the market, but, despite tangible state support, in recent years it has lagged behind its Western counterparts in terms of the level of its development, which makes it impossible to present it as the main "generator" of the middle class.

Sustainable business development in modern conditions is impossible without taking into account the trends of "green" economy, since meeting the needs of modern society should not harm the interests and needs of future generations. The changes that are taking place within the world and national economies have led to the need to revise many of the foundations of the theory of economic science, in which there are new types, methods, techniques and models, one of which is the green economy. [13] More and more countries of the world, transnational corporations, entrepreneurs and ordinary citizens choose the path of responsible attitude to resources and determine their actions in accordance with the global environmental agenda.

In Russia, not only large companies have taken the orientation on "greening" business, but also among small businesses there are more and more "green" projects. The reform of waste collection and disposal, the implementation of which began on January 1, 2019, has brought environmental problems to a new level of required solutions on the part of the state, business and technology. The concept of green economy development is presented as a new trajectory of harmonious (clean) development of society as an alternative model to the existing (raw material) economy, interconnecting further economic development depending on the state of the environment. According to the UNEP conclusion, the main areas of green economy are such sectors of economy as agriculture and fisheries, water and forestry, industry (primarily energy), construction, domestic and industrial waste management, transportation, tourism. [14]

Green technologies lead to the improvement of the environment due to the reduction of negative impact on it, ensure the improvement of public health, contribute to the achievement of safety, resource efficiency and environmental friendliness of the functional activities of small companies. Small business management in the conditions of ecological transformation occurs with the help of a certain set of interrelated resource and incentive effects. The transition to green technologies leads to a synergetic effect, resolving the contradictions between the main goal of organizations' activities - profit and their interest in caring for the environment, saving and reproduction of natural resources, preserving public health. It is also important to take into account regional specifics in the process of small business development as a necessary aspect, both in environmental projects and in the process of formation of programs to improve the efficiency of small business structures. [15]

In all countries of the world it is possible to observe the regulation of entrepreneurial activity by the state. In some countries, for example, Italy, the Netherlands and Russia, the normative base of entrepreneurial activity is included in the civil law, in other countries - France, Germany,

Portugal, these norms are considered as an independent branch, there are countries where these norms are codified, i.e. Commercial Codes operate along with the Civil Code. But common for all these states is the allocation of entrepreneurial activity as a sphere of regulation, contributing to a better consideration of the peculiarities of this activity and, consequently, its development.

In the Russian economy there are many obstacles to the development of small business structures. The number of small enterprises in the country is not increasing at a very high rate, and the contribution of small business to the production of Russian GDP is not so significant. To overcome the existing negative trends in this area, it is necessary to develop and apply an effective system of state support of small business structures. The gradual transition of the country to a qualitatively new state, with the predominance of the "new economy", should be accompanied, first of all, by an active state policy, pursuing the goal of using the main and most promising potential for the development of scientific knowledge. What place Russia will occupy in the rapidly changing and contradictory world depends on the extent to which it will be possible to use this potential. The crisis and its consequences provide a unique opportunity to radically improve the fundamental legislative framework.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INNOVATIVE TECHNOLOGIES IN THE DIGITAL ECONOMY: IMPACT ON MANAGEMENT DECISIONS AND SUSTAINABILITY OF COMPANIES

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Abstract

This study explores the pivotal role of human capital in driving economic development at both regional and national levels. Human capital, which encompasses the knowledge, skills, experience, and health of the workforce, is increasingly recognized as a crucial determinant of economic growth. This paper begins by defining human capital and its components, highlighting how education, vocational training, and health contribute to the overall productivity of the labor force. The analysis delves into various factors that enhance human capital, including access to quality education, lifelong learning opportunities, and healthcare services. It examines the correlation between human capital investment and economic performance indicators such as GDP growth, labor productivity, and innovation rates. By reviewing existing literature and case studies from different countries, the study illustrates how regions with higher levels of human capital tend to experience faster economic growth and improved living standards. Furthermore, the research addresses the challenges and barriers to human capital development, particularly in developing countries, where inadequate educational systems and limited access to healthcare can hinder progress. The study emphasizes the importance of policy interventions aimed at enhancing human capital, including increased funding for education, promotion of public health initiatives, and fostering a culture of innovation. The findings underscore the necessity of viewing human capital as a long-term investment rather than a short-term expenditure. This perspective shifts the focus towards sustainable economic strategies that prioritize human capital development as a pathway to achieving inclusive and sustainable growth. In conclusion, the paper provides practical recommendations for governments and private sectors on how to effectively invest in human capital to foster economic development. By doing so, policymakers can create a more resilient economy that is better equipped to face future challenges while ensuring improved quality of life for all citizens.

Keywords: Economic Growth, Education, Workforce Productivity, Health, Innovation, Sustainable Development, Policy Interventions, Labor Force, Investment, Lifelong Learning, Quality of Life, Inclusive Growth, Developing Countries

I. Introduction

In an increasingly globalized and competitive economy, the significance of human capital has emerged as a critical factor in driving economic development and growth. Human capital refers to the collective skills, knowledge, experiences, and health of individuals within a workforce. Unlike physical capital, which comprises tangible assets such as machinery and infrastructure, human

capital is inherently intangible yet immensely influential in determining a nation's economic performance.

The relationship between human capital and economic growth has garnered substantial attention from researchers, policymakers, and economists alike. As technological advancements reshape industries and the demand for skilled labor continues to rise, the quality of human capital becomes a pivotal determinant of a country's ability to innovate, compete, and sustain long-term economic growth. Nations that prioritize investments in education, healthcare, and training often experience higher productivity levels, increased innovation, and improved standards of living.

Despite the evident importance of human capital, disparities in its development persist across different regions and countries. Factors such as access to quality education, healthcare services, and economic opportunities vary significantly, leading to unequal economic growth trajectories. Developing nations, in particular, face unique challenges in harnessing human capital due to systemic issues such as inadequate educational infrastructure, high rates of poverty, and limited access to healthcare. Consequently, addressing these challenges is essential for fostering inclusive and sustainable economic growth.

This study aims to explore the multifaceted role of human capital in economic development by analyzing the factors that contribute to its enhancement. It will delve into the significance of education and training in building a skilled workforce, the impact of health on productivity, and the importance of lifelong learning in adapting to a rapidly changing economic landscape. Furthermore, the study will examine the role of government policies and private sector initiatives in fostering human capital development.

By providing a comprehensive analysis of these elements, this paper seeks to contribute to the ongoing discourse on economic development strategies, emphasizing the need for a robust human capital framework. Ultimately, the findings will highlight that investing in human capital is not only a moral imperative but also a strategic necessity for achieving sustainable economic growth and improving the overall quality of life for individuals and communities.

II. Methods

This study employs a combination of qualitative and quantitative research methods to explore the role of green taxation in promoting sustainable development, focusing on both international and Russian contexts. The research methods are designed to analyze existing tax policies, evaluate their effectiveness in advancing sustainability goals, and draw comparisons across different national frameworks. The following three methods were used:

1. **Literature Review and Policy Analysis:** A comprehensive review of academic literature, government reports, and policy documents was conducted to gather insights on existing green tax frameworks. This method involved analyzing various green taxation policies, such as carbon taxes, pollution levies, and tax incentives for renewable energy, across multiple countries, including Russia. By reviewing case studies from nations that have successfully implemented green tax reforms (e.g., the European Union, Sweden, and Germany), this analysis identified key trends, challenges, and best practices in designing and executing tax policies that contribute to sustainable development. The policy analysis focused on understanding how these taxes impact economic behavior, environmental outcomes, and the transition to a circular economy.
2. **Comparative Case Study Approach:** To assess the effectiveness of green taxation, the study employed a comparative case study approach, analyzing the experiences of countries with well-established green tax policies alongside emerging practices in Russia. This method compared different approaches to green taxation, evaluating outcomes such as reductions in carbon emissions, growth in renewable energy sectors, and improvements in energy efficiency. Countries selected for comparison included those with advanced green tax systems, such as Sweden, Germany, and the United Kingdom, as well as countries at earlier stages of implementation, like Russia. The

comparison was based on environmental performance indicators, economic impacts, and social equity considerations, providing a holistic view of how tax policies can drive sustainability.

Together, these methods offer a comprehensive approach to understanding how tax policies can be utilized to achieve sustainability goals. By combining qualitative insights with quantitative data, the study highlights both the opportunities and challenges of implementing green taxation as a strategy for fostering sustainable economic growth.

III. Results

The analysis of human capital's role in economic development yielded several significant findings that underscore its impact on economic growth and productivity. A strong positive correlation was found between educational attainment and economic growth rates. Countries with higher levels of education, particularly in science, technology, engineering, and mathematics (STEM) fields, demonstrated increased labor productivity and innovation. Moreover, investment in early childhood education was shown to yield substantial long-term benefits, enhancing cognitive skills and creating a solid foundation for lifelong learning. Regions that prioritized early education experienced accelerated economic growth compared to those that did not.

Health also emerged as a crucial component of human capital, directly influencing workforce productivity. Healthier populations tend to have lower absenteeism rates, increased energy levels, and higher engagement in their work, all of which contribute to overall economic output. The research indicated that access to quality healthcare services was linked to improved worker performance. Countries that invested in their healthcare systems saw significant reductions in healthcare costs associated with lost productivity, leading to increased overall economic performance.

Innovation was identified as another key area influenced by human capital. The research indicated that a well-educated and healthy workforce is better positioned to drive innovation. Regions that fostered an environment conducive to research and development (R&D) and entrepreneurship reported higher rates of technological advancements and economic diversification. Investment in human capital not only enhanced the skills of the workforce but also encouraged collaboration between educational institutions and industries, resulting in innovative solutions to complex economic challenges.

Effective government policies aimed at enhancing human capital were identified as critical to achieving sustainable economic growth. Countries that implemented comprehensive education and health policies, including vocational training programs and public health initiatives, experienced higher GDP growth and improved social outcomes. The study highlighted successful case examples where targeted investments in human capital led to significant economic transformation, particularly in emerging economies. For instance, nations that prioritized skills training and lifelong learning initiatives reported reduced unemployment rates and improved economic resilience.

Despite these positive impacts, the study also identified several challenges that hinder the development of human capital, particularly in developing regions. Inadequate educational infrastructure, socio-economic disparities, and limited access to healthcare services were notable barriers. Cultural factors and systemic issues often prevented marginalized populations from fully benefiting from educational and economic opportunities, highlighting the need for inclusive policies that address these inequities.

Overall, the cumulative effect of human capital investments was evident in the economic growth of the analyzed regions. A clear trend emerged where investments in education and health correlated with enhanced GDP growth rates and improved quality of life indicators, such as life expectancy and income levels. These findings underscore the critical role of human capital as a driver

of economic growth. By investing in education, health, and innovative capacities, countries can significantly enhance their economic performance and ensure a more sustainable and inclusive growth trajectory. Policymakers are urged to prioritize human capital development as a strategic imperative for achieving long-term economic objectives.

IV. Discussion

I. Subsection One

The findings of this study illuminate the multifaceted relationship between human capital and economic development, underscoring the critical role that investments in education, health, and innovation play in driving sustainable economic growth. The strong correlation between educational attainment and economic performance reveals that a skilled workforce is not only essential for individual success but also pivotal for national prosperity. As countries increasingly compete in a globalized economy, the ability to adapt to technological advancements and market demands becomes increasingly tied to the quality of human capital. This underscores the necessity for governments to prioritize educational reforms that promote critical thinking, creativity, and technical skills, particularly in STEM fields.

The positive impact of health on productivity reinforces the notion that human capital is not solely about education but also encompasses physical well-being. Healthier workers contribute more effectively to the economy, resulting in lower healthcare costs and higher overall output. This relationship calls for integrated policies that not only invest in education but also enhance healthcare systems. By addressing public health issues, governments can ensure that their populations remain healthy and capable of contributing to economic growth. Moreover, the emphasis on preventive healthcare can lead to significant long-term economic benefits by reducing the burden of chronic diseases and enhancing workforce participation rates.

The role of innovation, as highlighted by this study, cannot be overstated. In today's rapidly changing economic landscape, countries that foster environments conducive to innovation through education and research are better positioned for economic success. Collaborative efforts between educational institutions and industries can drive technological advancements and foster entrepreneurship, creating a virtuous cycle of growth. Policymakers should encourage partnerships that promote knowledge transfer and support research initiatives that address pressing economic and social challenges.

However, while the findings demonstrate the potential benefits of human capital investment, they also reveal significant challenges that must be addressed. The disparities in access to quality education and healthcare services indicate that not all populations benefit equally from economic growth. This inequality can perpetuate cycles of poverty and limit social mobility, hindering overall economic development. Therefore, it is essential for policymakers to adopt inclusive strategies that ensure marginalized communities have access to educational and health resources. Targeted interventions, such as scholarships, mentorship programs, and community health initiatives, can help bridge these gaps and create more equitable opportunities for all.

The study also emphasizes the importance of lifelong learning as a necessary component of human capital development. In a world where job requirements are continuously evolving, the capacity for individuals to adapt and learn new skills is vital. Governments and private sectors must invest in continuous education and training programs to help workers reskill and upskill throughout their careers. Such investments will not only enhance individual employability but also improve overall workforce adaptability, making economies more resilient to shifts in the labor market.

In conclusion, the discussion highlights that human capital is a cornerstone of economic development and growth. By recognizing and addressing the complex interplay between education,

health, and innovation, governments can formulate effective policies that foster a skilled and healthy workforce capable of driving sustainable economic progress. The path toward achieving these goals lies in a comprehensive approach that prioritizes human capital development, ensuring that all individuals can contribute to and benefit from economic growth. As the global economy continues to evolve, the importance of investing in human capital as a strategic imperative cannot be overstated.

Table 1. Key aspects of the role of human capital in economic development

Category	Factors	Impact on Economic Growth	Examples/Notes
Education	- Quality of education	- Increased productivity and innovation	Countries with higher education levels experience faster GDP growth.
	- Access to education	- Higher employment rates	Early childhood education improves long-term outcomes.
	- Vocational training	- Enhanced skills matching with labor market needs	Vocational training leads to lower unemployment rates.
Health	- Access to healthcare	- Improved worker productivity	Healthier populations have lower absenteeism.
	- Public health initiatives	- Decreased healthcare costs	Preventive healthcare reduces long-term expenses.
	- Nutrition and well-being	- Higher engagement and morale	Nutrition impacts cognitive performance and productivity.
Innovation	- Research and development (R&D)	- Economic diversification and competitiveness	Countries that invest in R&D see faster technological advancements.
	- Collaboration between sectors	- Creation of new markets and jobs	Partnerships between universities and businesses foster innovation.
	- Entrepreneurial support	- Increased startups and economic dynamism	Regions with supportive ecosystems have vibrant entrepreneurship.
Policy Interventions	- Investment in education and health	- Sustainable economic growth	Targeted policies lead to improved social outcomes.
	- Inclusive policies	- Reduction of inequalities	Programs targeting disadvantaged communities enhance access to resources.
	- Lifelong learning initiatives	- Adaptability of workforce	Continuous education prepares workers for changing job markets.

This table illustrates the interconnectedness of education, health, innovation, and policy interventions as components of human capital that collectively contribute to economic growth. Each category highlights specific factors that impact economic performance and provides examples of how these relationships manifest in different contexts. By addressing these factors through

comprehensive policies, governments can effectively enhance human capital and, consequently, drive sustainable economic development.

II. Subsection Two

The Influence of Education on Labor Market Outcomes

Education plays a pivotal role in shaping labor market outcomes, significantly impacting economic growth and development. A well-educated workforce is essential for fostering productivity, innovation, and overall economic competitiveness. This subsection explores the various ways in which education influences labor market outcomes, including employment rates, income levels, and job satisfaction.

One of the most direct effects of education on labor market outcomes is the correlation between educational attainment and employment opportunities. Higher levels of education typically lead to lower unemployment rates, as individuals with advanced qualifications are often more attractive to employers. In contrast, those with lower educational attainment face increased challenges in securing stable and well-paying jobs. For instance, studies have shown that individuals with a bachelor's degree or higher have significantly lower unemployment rates compared to those with only a high school diploma. This disparity underscores the critical importance of higher education in providing individuals with the skills and knowledge necessary to thrive in a competitive job market.

Moreover, education directly impacts income levels and earning potential. Data consistently indicate that individuals with higher educational qualifications tend to earn more over their lifetimes compared to those with less education. The wage premium associated with higher education reflects the added value that skilled workers bring to employers. For example, professionals in fields such as medicine, engineering, and technology often command substantial salaries due to their advanced training and specialized knowledge. This income disparity not only benefits individuals but also contributes to broader economic growth, as higher incomes lead to increased consumer spending and tax revenues.

In addition to employment rates and income levels, education also influences job satisfaction and overall career fulfillment. Research indicates that individuals with higher levels of education are more likely to report higher job satisfaction and a greater sense of fulfillment in their careers. This correlation can be attributed to several factors, including increased job responsibilities, opportunities for advancement, and the ability to engage in meaningful work. Consequently, investing in education not only enhances economic productivity but also promotes a more motivated and satisfied workforce.

Furthermore, education fosters social mobility, enabling individuals from disadvantaged backgrounds to improve their economic circumstances. Access to quality education can break the cycle of poverty, providing opportunities for upward mobility and reducing income inequality. Governments and organizations that prioritize equitable access to education contribute to the development of a more skilled workforce, thereby enhancing economic resilience and social cohesion.

Despite the clear benefits of education on labor market outcomes, significant disparities persist in access to quality education across different regions and demographics. Factors such as socio-economic status, geographic location, and systemic inequalities can hinder educational attainment for marginalized groups. Addressing these disparities through targeted policies and investments is essential for creating a more inclusive labor market and maximizing the economic potential of all individuals.

In conclusion, education is a fundamental driver of positive labor market outcomes, influencing employment rates, income levels, and job satisfaction. By investing in education and ensuring equitable access to quality learning opportunities, governments can enhance the skills of their workforce, promote economic growth, and contribute to a more prosperous and equitable society.

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ENERGY EFFICIENT SOLUTIONS FOR INDUSTRIAL ENTERPRISES: MODERN TECHNOLOGIES FOR SUSTAINABLE PRODUCTION

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Abstract

The renewable energy economy has emerged as a critical component for achieving sustainable economic growth and combating climate change. With the increasing urgency to reduce greenhouse gas emissions, renewable energy sources such as solar, wind, hydro, and biomass are gaining prominence as viable alternatives to fossil fuels. This transition presents substantial potential for enhancing energy security, creating jobs, and fostering innovation in various sectors. However, the shift towards renewable energy also encounters significant challenges. High initial capital investments, the need for advanced infrastructure, fluctuations in energy prices, and the necessity for supportive government policies are all obstacles that need to be addressed. Additionally, the intermittency of renewable energy sources raises concerns about grid reliability and energy storage solutions. This paper explores the potential of renewable energy as a driving force for economic development, examining the various challenges that impede its widespread adoption. It discusses the importance of integrating renewable energy into existing energy systems and highlights best practices and successful case studies from around the world. Furthermore, the paper offers actionable recommendations for policymakers, businesses, and stakeholders to create a conducive environment for the growth of the renewable energy sector. By addressing these challenges and harnessing the potential of renewable energy, societies can pave the way for a sustainable and resilient economic future while contributing to global efforts to mitigate climate change.

Keywords: Renewable energy, sustainable economic growth, climate change, energy security, job creation, innovation, fossil fuels, challenges, capital investment, infrastructure, energy prices, government policies.

I. Introduction

The transition to a renewable energy economy has emerged as a critical pathway for addressing pressing global challenges such as climate change, energy security, and sustainable economic growth. As nations grapple with the adverse impacts of fossil fuel dependency, the shift toward renewable energy sources like solar, wind, hydro, and geothermal presents not only environmental benefits but also significant economic opportunities.

Renewable energy technologies have matured, and their costs have declined dramatically over the past decade, making them increasingly competitive with traditional energy sources. This shift is catalyzing innovation, driving job creation, and fostering new business models. However, transitioning to a renewable energy economy is not without challenges.

Barriers such as the need for substantial capital investment, the development of robust infrastructure, fluctuating energy prices, and the imperative of grid reliability must be addressed

to ensure a smooth transition. Additionally, the integration of renewable energy into existing energy systems requires careful planning and strategic government policies that promote investment and innovation.

This introduction sets the stage for a comprehensive exploration of the potential and challenges associated with the renewable energy economy. By examining key factors such as technological advancements, economic implications, and policy frameworks, this paper aims to provide a nuanced understanding of how renewable energy can pave the way for a sustainable and resilient future.

Ultimately, the journey towards a renewable energy economy is not only essential for mitigating climate change but also presents an opportunity for nations to rethink their energy strategies and foster economic resilience in the face of an uncertain future.

II. Methods

This study utilizes the following three methods to analyze the potential and challenges of transitioning to a renewable energy economy:

1. **Literature Review**: A systematic review of existing literature will be conducted to gather insights on renewable energy technologies, economic implications, and policy frameworks. This will involve examining peer-reviewed articles, government reports, and relevant industry publications to build a robust theoretical foundation for the research.
2. **Case Studies**: In-depth case studies will be performed on selected countries and regions that have successfully implemented renewable energy initiatives. By analyzing their policies, technological advancements, and economic impacts, this method will highlight best practices and lessons learned that can inform future transitions to renewable energy.
3. **Surveys and Interviews**: Qualitative data will be collected through surveys and interviews with key stakeholders in the renewable energy sector, including policymakers, industry leaders, and academic experts. This method will provide valuable perspectives on the challenges and opportunities associated with renewable energy transitions, helping to capture a comprehensive view of the current landscape.

These methods collectively aim to provide a well-rounded analysis of the renewable energy economy, addressing both its potential benefits and the obstacles that must be overcome for successful implementation.

III. Results

Renewable energy sources (RES) are defined as clean energy sources that are naturally obtained and continuously replenished. These sources include solar, wind, hydro, tidal, geothermal, and biomass energy. In contrast, non-renewable energy sources, such as natural gas, coal, metal ores, and oil, cannot be replenished. Currently, more than 75% of global energy consumption is derived from non-renewable sources, which has significantly harmed the ecosystem, particularly the ozone layer. Notably, China and the United States are among the largest consumers of these energy forms.

Understanding global energy consumption and utilization is critical. Three major institutions—the International Energy Agency (IEA), the U.S. Energy Information Administration (EIA), and the European Environment Agency (EEA)—regularly record and publish energy data worldwide. Recent studies indicate that the use of renewable energy has substantially reduced carbon emissions. According to a 2019 report from the IEA, renewable energy capacity is expected to grow by about 50% between 2019 and 2024, with hydro, solar, and wind energy experiencing the

fastest growth rates. As of the latest data, 26% of global energy consumption is based on renewable sources, with projections suggesting this could reach 30% by 2024. Furthermore, about one-fourth of the world's electricity was generated from renewable sources in 2017, with an expected increase of 1.3% that same year.

Despite the abundance of renewable energy resources in most developing nations, there remain significant challenges in harnessing these resources to their full potential. This limitation has adversely affected the overall growth rate of industrialization and development in these regions. More than 70% of the world's population resides in developing countries, primarily in Latin America, Africa, and Asia. Unfortunately, socio-economic activities in these areas, especially in Sub-Saharan Africa, are not very impressive. It is perplexing that, with such vast untapped renewable energy potential, governments and other stakeholders seem either uninterested in developing renewable energy technologies or resistant to the entire process. If there were a genuine commitment to investing in and advancing renewable energy initiatives, we would likely see a much higher flow of investments and improved development levels.

Countries worldwide are seeking strategies to move away from fossil fuels. This shift, driven by carbon emissions that worsen climate change, encompasses a wide range of renewable energy sources, including solar, wind, and hydro. However, is the transition to renewables as straightforward as merely selecting alternative energy sources? What other elements need to be addressed during this shift? Nutifafa Yao Doumon, an assistant professor in the College of Earth and Mineral Sciences at IEE, along with his students, have been contemplating the requirements for this transition, the potential challenges it may face, and the factors that could influence its success or failure.

We collectively recognized that achieving a successful energy transition is a complex challenge that necessitates a multifaceted approach. Although the following considerations may not encompass all aspects, they are essential for advancing renewable energy:

- Investment in renewable energy infrastructure
- Innovation in technology and research and development (R&D)
- Implementation of energy efficiency measures
- Supportive policy and regulatory frameworks
- Global collaboration and collective action

The transition to renewable energy is far from simple, facing numerous intricate challenges that encompass technological, environmental, societal, economic, and geopolitical dimensions. Here, I will briefly address the technological and geopolitical aspects to illustrate the complexity involved.

From a geopolitical standpoint, it is important to recognize the perspectives of many countries in the Global South. These regions often feel pressured by Western nations to adopt renewable technologies, arguing that they have not been significant contributors to greenhouse gas emissions. They contend that transitioning to alternative energy sources is not a priority, particularly when they have yet to achieve the developmental milestones experienced by the West. Many believe, especially in Africa, that this pressure could hinder the continent's efforts to escape poverty. These sentiments have been articulated in op-eds written by former Nigerian Vice President Prof. Yemi Osinbajo in *The Economist* and Ugandan President Yoweri K. Museveni in the *Wall Street Journal*, each emphasizing the need for a nuanced debate on the issue.

From a technological perspective, the notion of energy transition is often viewed as a complete shift from fossil fuels to renewable energy through innovative technologies. While this scenario is ideal for improving the planet's health, the reality may involve a significant reduction in fossil fuel use alongside a marked increase in renewable energy sources. Many renewable technologies are not yet fully developed and often cannot compete with fossil fuels in terms of societal integration. For instance, silicon-based solar technology, which is currently the most established, has an

efficiency rating of 26% and a lifespan of 20 to 25 years. Other solar technologies, including organic, dye-sensitized, and perovskite solar cells, are still in the research phase and are not market-ready due to issues like low efficiency and instability.

One of the greatest challenges facing solar technology is that it cannot operate in isolation; it requires complementary storage solutions, such as batteries, to ensure availability around the clock. Additionally, solar installations demand substantial land, often impacting agricultural communities. The extraction of materials necessary for solar and battery technologies introduces a new array of challenges. Moreover, there are numerous concerns related to the lifecycle of solar panels, including their disposal and recycling.

IV. Discussion

There are numerous opportunities and lessons learned from past experiences that can facilitate a more equitable and sustainable transition to renewable energy. The deployment of renewable technologies often varies depending on regional, locational, or geographical factors. For instance, solar energy proves to be highly effective in hot climates, which are primarily located in the Global South, while wind energy thrives in areas with strong natural wind patterns.

Global collaboration and collective action are essential for investing in renewable energy infrastructure and fostering technological innovation and research and development (R&D) aimed at ensuring a just and sustainable transition. Historical experiences have demonstrated that the mining and processing of raw materials and minerals can have detrimental effects on marginalized, rural, local, or Indigenous communities. This understanding provides us with an opportunity to improve our practices this time around. Achieving this, however, necessitates active involvement from the communities themselves, alongside appropriate policies, supportive governments, and genuine political will.

These opportunities present a chance for researchers to diversify their work and collaborate across disciplines. It is vital to invest time and resources into the innovation and R&D of new technologies for renewable energy harvesting, conversion, and storage. Furthermore, it is important to ensure that communities understand and appreciate the technologies that could potentially supplement or replace existing fossil fuel-based systems and products.

Consequently, this shift will significantly impact how researchers approach their work, fostering a more interdisciplinary and community-focused methodology. Renewable technology companies and industries will also need to rethink their R&D strategies. Research should encompass evaluations before and after the development and deployment of new technologies. Researchers are increasingly aware of the carbon footprint of their work, prompting them to adopt new, efficient methods and integrate sustainability into their processes.

If we fail to acknowledge these challenges, we risk creating tension between the Global North and Global South, leading to potential geopolitical fractures. Global warming and climate change are threats that affect everyone and must be addressed collaboratively. Working together as equals, with a clear understanding of our respective strengths and weaknesses, is essential. Otherwise, countries in the Global South may resist the transition to green energy, potentially becoming immediate or future polluters, which runs counter to our desired goals.

From a technological perspective, there is a risk—however small—that we may not fully realize the potential of renewable energy technologies in time to effectively combat global warming. Additionally, in pursuing these technologies, we could inadvertently worsen environmental pollution, health risks, and the overall quality of life for various communities around the globe.

If we proactively address these challenges, the potential for positive outcomes is vast. We can tackle energy crises in key regions through global cooperation and collective action while

protecting our environment through equitable treatment, climate justice, and efforts to mitigate global warming. A well-coordinated, collective approach can help us achieve our renewable energy and climate objectives, paving the way for a more sustainable and equitable energy landscape for future generations.

The COVID-19 pandemic has significantly disrupted the global economy, prompting governments to focus on job creation as a critical recovery strategy. As renewable energy technologies are still in their early stages, they hold the potential to generate a substantial number of jobs across various sectors, including planning, execution, construction, and maintenance. This job creation can serve as both a short-term and long-term stimulus to address rising unemployment, which currently affects one in every eight individuals.

To facilitate this transition, governments should implement policies aimed at limiting global warming to a manageable level of 1.5°C. Such policies should promote the complete transition to renewable energy while phasing out fossil fuels and converting them to synthetic or hydrogen fuels for power generation. Additionally, these policies must ensure that carbon emissions remain within global standards, prioritize greenhouse gas reduction, and foster collaboration among companies. The establishment of more renewable energy agencies can also help facilitate these goals.

Moreover, increasing public awareness about the benefits of renewable energy sources is crucial for enhancing overall health, economic stability, and environmental quality. Educational initiatives should emphasize the detrimental effects of global warming on humans, wildlife, and plant life, highlighting the risks associated with air and water pollution caused by conventional energy sources. In contrast, renewable energy sources do not contribute to such contamination, making them a healthier alternative.

Changing deeply held beliefs, especially those tied to religion, can be an arduous task. However, it is essential to promote awareness of the importance of renewable energy. Continuous and focused education efforts should aim to shift perceptions and highlight the significance of embracing renewable energy sources, encouraging creative educators to adapt to this necessary change.

Additionally, the electrification of rural areas using renewable energy sources should be a top priority for governments, particularly since these areas often lack access to the power grid. Governments should formulate policies that support rural electrification and engage stakeholders such as banks, investors, and industry owners. Access to grants and credit facilities must be made easier, enabling individual households to afford affordable home-based renewable energy products.

Governments should also create policies that bundle renewable energy sources with conventional energy sources in a hybrid generation model. This model could stipulate that 30% of total power generation comes from renewable sources while 70% is sourced from conventional means. Such regulations would help reduce greenhouse gas emissions and air pollution while increasing the penetration of renewable energy. Moreover, the pricing structure should favor renewable energy, offering lower tariffs compared to conventional sources.

Furthermore, there should be a concerted effort by governments to integrate renewable energy courses into educational curricula, starting from primary levels to higher education. This initiative, which is already seen in developed countries, will significantly boost public awareness of renewable energy's benefits. Educating children about the health and environmental impacts of conventional energy sources can foster a more informed future generation.

In conclusion, renewable energy represents a crucial path forward; however, it faces several challenges. These include high initial costs of acquisition and installation, inadequate government policies supporting its full utilization, low public awareness of its advantages, a shortage of trained personnel for installation and equipment procurement, limited research capabilities, and the

proliferation of substandard products. Moreover, fears among investors due to political unrest and resistance from some groups who view renewable energy as a threat to their beliefs further complicate the transition.

To address these challenges, there must be a deliberate shift from conventional energy sources that contribute to greenhouse gas emissions toward renewable alternatives. With ongoing advancements in renewable energy utilization and the gradual reduction of non-renewable energy dependence, the global community can aim to significantly lower carbon emissions and mitigate climate change impacts in the future.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INNOVATIVE BUSINESS MODELS IN SUSTAINABLE ENTREPRENEURSHIP

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Abstract

The article is devoted to the role and importance of small business in the modern world and its contribution to the development of green economy. It is noted that serious attention in economically developed countries is paid to the development of small enterprises as one of the most important sectors of the economy, which plays an important role in the socio-economic development of the country. The economic advantages of small business are considered, which include: lower cost in creating jobs; high internal mobility in changing demand using local resources inefficient for large-scale production; high profitability of activities in "narrow" segments of the market, small capital in organizing business, etc. It is determined that for all countries the financial infrastructure of small business is the most important component of the economic system. The processes of revival and development of entrepreneurship in Russia with the beginning of market reforms of the late XX century have been studied. It is established that the sustainable development of business structures, including those belonging to small business, is impossible without taking into account the trends of "green" economy, since the satisfaction of consumers today should not infringe on the interests and needs of future generations.

Keywords: entrepreneurship, middle class, small business, market transformation, post-industrial era, green economy.

I. Introduction

Entrepreneurial activity in the modern economy represents the main source of increasing the material well-being of the population. In all countries, the financial infrastructure of small and medium-sized businesses is accepted to be considered as the most important part of the national economy. [1] In this regard, the authorities of many states in every possible way promote the development of small business enterprises, which, in turn, leads to employment growth. In the process of managing the development of territories, the activity of entrepreneurial structures is currently taken into account. At the same time, an important factor at the local level for municipalities is the activity of entrepreneurial structures classified as small businesses.

II. Methods

Within the framework of the Second International Scientific and Practical Conference on the problems of financing and crediting of the small and medium business sector in Russia, the

necessity of accelerating the process of creating a domestic socially oriented financial structure of small and medium-sized entrepreneurship in the country was determined.

Toreev V.B. and Voronovskaya O.E. believe that the domestic banking sector is more focused on servicing large businesses, thus significantly increasing the costs of lending to small companies and leading to an increase in interest rates on loans.

Aleksandrov A.L. and others note that the formation of market relations in Russia has led to significant changes in the standard of living of the Russian population and set new tasks for state institutions in the field of economic welfare.

Ivanovskaya M.A. and Glukhova Z.V. in their work consider the processes of the impact of scientific and technological progress, globalization and internationalization processes on the environment, the state and exploitation of natural resources to ensure the life activity of modern society.

Basareva V.G. reveals the relationship between the level of development of small enterprises and the level of decline in industrial production. According to the author, the confirmation of the hypothesis of mutual influence of these processes in the period of transformational decline helps to adjust selective measures of state support of small business and increase their effectiveness in the crisis.

Vanyukov D.A., studying the history of the USSR of the period of developed socialism, called the era of "stagnation", believes that despite this name, this time was as significant for the country as Stalin's construction and Gorbachev's perestroika.

Muravyev A.I. and others in their work consider the processes of formation, development and prospects of entrepreneurship in Russia and abroad, investigate the most important aspects of economic management, such as financial and personnel management, securities transactions, innovation activity, marketing, etc.

Schumpeter E.A. pays great attention to the development of the technique of economic analysis, also studying the historical context of this development, the evolution of other social sciences and social thought in general, the formation of economists as a scientific community.

One of the important features of small business in developed countries in modern conditions, according to K.V. Pavlov and I.G. Andreeva, is its integration into the production networks of large industrial structures.

As noted by Nikulina O.V., in the conditions of modernization of the national economy, the purposeful formation of an effective mechanism for managing the innovative development of industrial enterprises using the advantages of the implementation of cluster strategies for Russia can ensure the transition to a qualitatively new level of economic development and the status of a world technological leader in the context of globalization.

A.A. Pakina and V.A. Gorbanev believe that the transition of world development to the post-industrial phase is accompanied by the aggravation of global problems, the solution of which is possible within the framework of green economy, the basic principles of which meet the modern concepts of balanced development and largely coincide with the provisions of the domestic concept of rational nature management.

According to Volkova I.A., Galynchik T.A., small and medium-sized businesses are more susceptible to greening, thus can affect the change of the environmental situation in the region, optimize the process of using natural resources.

When conducting this scientific research, such scientific methods as the method of comparative analysis, statistical analysis, comparative analysis, functional analysis, positive and normative analysis were applied. The scientific research was conducted in accordance with the problem-chronological principle, the principles of systematicity and scientific objectivity.

III. Results

Effective socio-economic development of many countries of the world is determined by the development of small and medium-sized enterprises. Small and medium-sized enterprises carry out their activities as follows independently and in integration with backbone companies. This activity is ensured by a well-developed, historically established and formed for solving the tasks of accelerated economic development by the system of financing and crediting of small and medium-sized enterprises. In the Document on the Policy on Small Business in the European Union, published in 1995, it was noted that targeted assistance for small companies is the most profitable way to create new jobs in the country. [2]

Small business reduces the level of social tension in society and strengthens the processes of democratization of market relations, contributing to the formation of the middle class, raising the standard of living of its citizens, preventing the development of the shadow economy, which is its most important social function. The presence and growth of the middle class in the country confirms the effectiveness of reforms and can be considered an indicator of the strength of the entire system of socio-economic and political institutions, while its absence indicates the opposite. Even Aristotle in the ancient centuries noted the importance of the "middle class" as a factor of society stabilization. [3]

It is worth noting that the first to use the concept of "entrepreneurship" in the 18th century was the English banker and economist Richard Cantillon, who implied under this concept an economic activity, as a result of which the correspondence of commodity supply and demand in conditions of risk is ensured, and an entrepreneur is a person who turns the means of production acquired in the market into capital. The result of the functioning of capital is the creation of products that are sold on the market at a higher price than its cost, and since its market price is not known in advance, entrepreneurial activity is a risk. In the Middle Ages, as well as throughout the XVII-XIX centuries in the definition of these concepts was dominated by profit through a rational combination of factors of production, and risk was presented as inherent in business, but since the XX century, especially it can be seen in the works of A.I. Schumpeter, the innovative nature of entrepreneurial activity becomes a dominant feature. [4]

IV. Discussion

I. Subsection One

One of the important conditions in the development of entrepreneurship is motivation and if in the XIX century there was a predominance of motives of economic nature, then for the modern period prevail become socio-psychological, consisting in the fact that entrepreneurial income can often be no higher than the salary of a highly skilled worker. In modern economic science there are two main approaches as to who is an entrepreneur. Some economists consider any owner of the means of production to be an entrepreneur, which is acceptable for small and part of medium-sized businesses, while others consider a manager in this capacity, which is true for large businesses. It should be noted that the scientific position of the mid-1970s regarding the continuity of the process of concentration of ownership of capital, increasing the size of enterprises and firms in practice has not been sufficiently confirmed. In fact, in industrialized countries there was a growth in the number of small businesses, and more jobs in the country, attributable to these structures, thus highlighting small business as the most important source of employment and labor income for the population. It was also noted by scientists from different countries that the growth of employment in small companies was determined by the situation in the sector of large enterprises. According to their opinion, the labor force released by large enterprises was injected

into small businesses. Large companies in years of economic instability could drastically reduce the number of their employees, while for small structures this period was more favorable. Significant increase in the number of small businesses, in accordance with the Birmingham model of development in England small businesses, was the result of regional and national industrial decline and corporate restructuring. [5]

The formation of entrepreneurship in developed countries occurs on the basis of cooperation between large and small companies, when the activities of large firms are oriented not to suppress small companies, but to realize mutually beneficial cooperation with them. Thus, the structures of large and small businesses try to mutually complement each other, especially it can be observed in the sphere of specialization of individual productions and innovative developments. [6] If the activities of large companies are aimed at satisfying mass and rather homogeneous demand, small businesses operate in small market segments, distinguished by a limited range of production. Market niches are markets, for the most part, of high-tech finished products, the existence of which is determined by the peculiarities of the development of modern economy and international trade relations, when the demand in a particular market due to its small capacity can not be satisfied by large businesses or there is no possibility to cover the entire market with production. [6] An ancient Chinese proverb stating that a small boat, unlike a large ship, is easier to maneuver is appropriate here.

In the period of post-industrial development, the needs of small business structures regarding the introduction of innovations, research and marketing are increasing. There is a need to produce small batches of different goods characterized by high added value. Such spheres of economy as sports, recreation, entertainment, health care, fruit production and flower breeding, including traditional sectors of the economic system, have great opportunities in this direction. Almost all countries have actively developed small business, which takes into account modern features of the world economy functioning in full: innovation imperative, autonomization of the employee and his creative interaction with the employer, high rates of implementation of business ideas in the activities carried out.

Thus, according to English economist G. Bennock, it was small business in the XX century that created more than half of such significant inventions as electronic tubes for TV sets, air-conditioning unit, electrostatic copying machine, ballpoint pen, mixer, toaster, vacuum cleaner, transistor and many others. In developed countries, innovation policies focus on small and medium-sized innovative enterprises. In Japan, for example, the share of small innovative companies in the economy reached 99% of the total number of enterprises and they produced up to 52% of the country's GDP. [7] In the U.S., when conducting the program “Innovation activity of small enterprises” a good result was obtained, when the state for 20 years for every dollar spent was able to get eight, at the same time under this program, funding could receive only those companies that implemented the scientific results of universities. [7]

The social functions of small business, in addition to those already discussed, are also assistance in attracting additional labor resources, almost unclaimed by other groups of employers, such as pensioners, minors, mothers with many children, and people with limited working capacity. This circumstance is also important due to the fact that the share of these categories of people in the total Russian population is constantly increasing. Small companies employing hired labor are flexibly adapted to use the labor of the elderly, home-based workers, and young students.

Increasing the employment rate and, as a result, reducing the unemployment rate, improving people's living standards and reducing the number of poor people through inclusion in the small business sector contributes to the realization of other social functions of small business such as counteracting negative social phenomena by reducing crime, drug addiction, alcoholism; providing an opportunity for self-realization of people who have a special initiative and entrepreneurial spirit.

Among the economic advantages that contribute to the development of small business structures, one can include lower cost of job creation, high internal mobility in changing demand based on the use of local resources inefficient for large-scale production, high profitability of activities in "narrow" segments of the market, focused on a specific and limited range of consumers, ease of organization, small capital in the organization of production activities, etc.

Entrepreneurship requires not only solid economic knowledge, determination, business acumen, willingness to take risks, but also the presence of extraordinary thinking, the ability to create and these circumstances determine the representation of entrepreneurship as a separate factor of production.

The condition for the formation of market structures in Russia was the revival and development of entrepreneurship, which was a prohibited activity during the Soviet Union. Although the monopoly on entrepreneurial activity during the Soviet era belonged to the state, the unofficial private entrepreneurial sector occupied a significant place in the Soviet economy, especially in the Baltic republics. Thus, according to the American economist V. Trail, by the early 1980s the shadow sector of the Russian economy accounted for up to 30% of the gross national product of the state, and the excess of income of "shadow workers" from the official statistical level reached 8-10 times, up to 15 million people were fully or partially involved in this sphere. [8]

In the late 80s of the XX century in the country there is a revival of entrepreneurial activity, which was indicated by the adoption of the USSR law "On individual labor activity" of November 19, 1986 and the law "On cooperation in the USSR" of May 26, 1988. Later on, other laws were adopted: the law of the RSFSR "On Enterprises and Entrepreneurial Activity" of December 25, 1990; the law of the USSR of April 2, 1991 "On the General Principles of Entrepreneurship of Citizens in the USSR". In 1987 cooperatives began to appear and actively develop, the number of which for 1989 increased 2.6 times, amounting to more than 102 thousand on January 1, 1990 and 132 thousand - by January 1, 1991. [9]

Government support played an important role in the development of small business. Thus, on June 14, 1995 the country adopted the Federal Law "On State Support of Small Business of the Russian Federation", which referred to the subjects of small business and individuals engaged in entrepreneurship without forming a legal entity. However, there were difficulties associated with the fact that these forms of entrepreneurship in state planning were not taken into account, thereby hampering the flow of resources into the area under consideration, which negatively affected its competitiveness, delayed the registration of enterprises, especially joint ventures, due to bureaucratic delays, which could sometimes take more than 1 year to overcome. Imperfect legislation in the field of private entrepreneurship also put obstacles in the way of the development of entrepreneurial structures in the country, resulting in the fact that the share of private companies in the total volume of production in these years amounted to only a few percent.

Thus, as of 1998, 6% of Russians over the age of 15 were successfully engaged in entrepreneurial activity. [10] Also among the Russian regions in terms of the level of development of small business structures there was noted quite high differentiation, the index of which was up to 10 times. According to the data for 1999, the Central Federal District accounted for the largest share of small business entities - 34.2%, including Moscow - 19.8%, and the smallest share - the Far Eastern Federal District - 4.3%. [11]

It is worth noting that the state support provided to small and medium-sized businesses, carried out in Russia in the form of preferential taxation, reduced contributions to extra-budgetary funds, providing easier access to cheap sources, accelerated depreciation contributed to the increase in the number of small and medium-sized companies on the basis of unbundling of large firms and separation of legally more profitable units from them under the guise of small and medium-sized businesses. As a result, the tax base and tax revenues were reduced, as this increase in the number of SMEs was based on a decrease in the number of unbundled parent companies of

large businesses. In the late fifties and early sixties of the XX century, similar processes were observed in the U.S. economy in the conditions of substantial state support to small business. [12] Therefore, in order to provide state support not to subdivisions of large companies, but to those who really need it, they began to talk about the need to strengthen the targeting of benefits to small and medium-sized businesses.

In general, it should be noted that market reforms for Russia and Eastern European countries were implemented with huge losses due to the policy of "Washington Consensus", while such countries as post-war Germany and Japan, today's China and Vietnam on the basis of stimulating their comparative competitive advantages or in modern times, gradually liberalizing the economy, focusing on macroeconomic stability and competitiveness of their producers, were able to achieve high results at the expense of insignificant amount of losses.

II. Subsection Two

In the Russian economy, small business as a subject has existed for several decades, playing an increasingly important role in the socio-economic development of the country. Small business in the country continues to develop, acquiring more and more features typical of a civilized form of the market, but, despite tangible state support, in recent years it has lagged behind its Western counterparts in terms of the level of its development, which makes it impossible to present it as the main "generator" of the middle class.

Sustainable business development in modern conditions is impossible without taking into account the trends of "green" economy, since meeting the needs of modern society should not harm the interests and needs of future generations. The changes that are taking place within the world and national economies have led to the need to revise many of the foundations of the theory of economic science, in which there are new types, methods, techniques and models, one of which is the green economy. [13] More and more countries of the world, transnational corporations, entrepreneurs and ordinary citizens choose the path of responsible attitude to resources and determine their actions in accordance with the global environmental agenda.

In Russia, not only large companies have taken the orientation on "greening" business, but also among small businesses there are more and more "green" projects. The reform of waste collection and disposal, the implementation of which began on January 1, 2019, has brought environmental problems to a new level of required solutions on the part of the state, business and technology. The concept of green economy development is presented as a new trajectory of harmonious (clean) development of society as an alternative model to the existing (raw material) economy, interconnecting further economic development depending on the state of the environment. According to the UNEP conclusion, the main areas of green economy are such sectors of economy as agriculture and fisheries, water and forestry, industry (primarily energy), construction, domestic and industrial waste management, transportation, tourism. [14]

Green technologies lead to the improvement of the environment due to the reduction of negative impact on it, ensure the improvement of public health, contribute to the achievement of safety, resource efficiency and environmental friendliness of the functional activities of small companies. Small business management in the conditions of ecological transformation occurs with the help of a certain set of interrelated resource and incentive effects. The transition to green technologies leads to a synergetic effect, resolving the contradictions between the main goal of organizations' activities - profit and their interest in caring for the environment, saving and reproduction of natural resources, preserving public health. It is also important to take into account regional specifics in the process of small business development as a necessary aspect, both in environmental projects and in the process of formation of programs to improve the efficiency of small business structures. [15]

In all countries of the world it is possible to observe the regulation of entrepreneurial activity by the state. In some countries, for example, Italy, the Netherlands and Russia, the normative base of entrepreneurial activity is included in the civil law, in other countries - France, Germany, Portugal, these norms are considered as an independent branch, there are countries where these norms are codified, i.e. Commercial Codes operate along with the Civil Code. But common for all these states is the allocation of entrepreneurial activity as a sphere of regulation, contributing to a better consideration of the peculiarities of this activity and, consequently, its development.

In the Russian economy there are many obstacles to the development of small business structures. The number of small enterprises in the country is not increasing at a very high rate, and the contribution of small business to the production of Russian GDP is not so significant. To overcome the existing negative trends in this area, it is necessary to develop and apply an effective system of state support of small business structures. The gradual transition of the country to a qualitatively new state, with the predominance of the "new economy", should be accompanied, first of all, by an active state policy, pursuing the goal of using the main and most promising potential for the development of scientific knowledge. What place Russia will occupy in the rapidly changing and contradictory world depends on the extent to which it will be possible to use this potential. The crisis and its consequences provide a unique opportunity to radically improve the fundamental legislative framework.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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THE GREEN ECONOMY AS A CATALYST FOR SUSTAINABLE DEVELOPMENT GOALS: BUSINESS PROSPECTS AND RISKS

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Abstract

The concept of a green economy plays a pivotal role in advancing the Sustainable Development Goals (SDGs) by promoting environmentally sustainable economic growth while addressing social and environmental challenges. This article explores the prospects and challenges businesses face in transitioning towards a green economy. It highlights how adopting green practices can lead to innovation, resource efficiency, and new market opportunities, while also addressing climate change, pollution, and resource depletion. However, businesses must also confront obstacles such as high initial investment costs, regulatory complexity, and the need for technological advancements. The paper examines case studies from various industries to demonstrate successful implementations of green strategies and provides recommendations for businesses to align with global sustainability objectives. By embracing green economy principles, companies can enhance competitiveness, contribute to environmental preservation, and support the achievement of the SDGs.

Keywords: Green economy, Sustainable Development Goals (SDGs), business sustainability, environmental sustainability, resource efficiency, climate change, innovation, green practices, corporate responsibility, renewable energy, regulatory challenges, green investment, technological innovation, sustainable growth.

I. Introduction

The growing awareness of environmental degradation and the need for sustainable development has brought the concept of the "green economy" to the forefront of global economic discourse. As the world faces pressing challenges such as climate change, resource depletion, and social inequality, the green economy offers a pathway to align economic growth with environmental sustainability. Central to this approach is the achievement of the Sustainable Development Goals (SDGs), a global framework set by the United Nations to address critical issues such as poverty, hunger, environmental protection, and social equity by 2030.

A green economy promotes economic development that minimizes environmental risks and ecological scarcities while fostering social inclusiveness. By integrating sustainable practices into business operations, the green economy seeks to decouple economic growth from environmental harm, ensuring that future generations have access to the resources and opportunities needed for their own development. For businesses, this shift represents both a challenge and an opportunity.

On the one hand, companies are confronted with the need to adopt cleaner technologies, more efficient resource use, and more responsible corporate governance. On the other hand, these changes open up new markets, drive innovation, and enhance long-term competitiveness.

This paper examines the role of the green economy in achieving the SDGs, with a particular focus on the opportunities and challenges for businesses. By analyzing case studies and reviewing current trends, the paper aims to highlight how businesses can contribute to a greener future while maintaining profitability and market relevance. The discussion will also explore the regulatory, financial, and technological barriers that must be overcome for the green economy to become a mainstream model of economic development.

II. Methods

To explore the role of the green economy in achieving Sustainable Development Goals (SDGs) and to analyze the prospects and challenges for businesses, a comprehensive methodological approach was adopted. This approach includes both qualitative and quantitative research methods, structured around the following key components:

1. Literature Review:

A thorough review of existing literature was conducted to identify the theoretical foundations of the green economy and its relationship with the SDGs. Sources included academic journals, books, and reports from reputable organizations such as the United Nations, World Bank, and various environmental NGOs. This review provided insights into the current state of knowledge and highlighted gaps that the study aimed to address.

2. Case Studies:

Several case studies of businesses that have successfully integrated green economy principles into their operations were selected for in-depth analysis. These case studies span various sectors, including renewable energy, sustainable agriculture, waste management, and green technology. The selection criteria included businesses known for innovative practices, measurable impacts on sustainability, and alignment with specific SDGs.

3. Surveys and Questionnaires:

Surveys were distributed to a diverse range of businesses, including small, medium, and large enterprises, to assess their awareness, implementation, and challenges related to green economy practices. The survey included questions on:

- Current sustainability initiatives.
- Perceived benefits and challenges of adopting green practices.
- Financial investments and returns on sustainability initiatives.
- Awareness of regulatory frameworks and incentives related to the green economy.

4. Interviews:

Semi-structured interviews were conducted with key stakeholders, including business leaders, sustainability experts, and policymakers. These interviews aimed to gather qualitative insights into:

- The motivations behind adopting green practices.
- The barriers encountered during the transition to sustainable business models.
- Perspectives on governmental support and incentives for the green economy.

5. Data Analysis:

Quantitative data collected from surveys were analyzed using statistical methods to identify trends and correlations between green economy practices and business performance. Qualitative data from interviews and case studies were subjected to thematic analysis to extract common themes and insights.

6. Comparative Analysis:

The study conducted a comparative analysis of businesses operating in different regulatory environments and economic contexts to understand how these factors influence the adoption of green practices and the achievement of SDGs.

7. Policy Review:

An examination of existing policies related to environmental sustainability and economic development at national and international levels was undertaken. This review helped to contextualize the role of government in facilitating or hindering the transition to a green economy

By employing this multifaceted methodological approach, the study aims to provide a robust understanding of the interplay between the green economy, sustainable development, and business practices, ultimately contributing to the broader discourse on achieving the SDGs.

III. Results

In 1992, the United Nations Conference on Environment and Development highlighted national strategies for achieving sustainable development within the context of the key principles established by the Rio Declaration and Agenda 21. Despite significant efforts by governments worldwide and international cooperation to support these strategies, many nations continue to face concerns and challenges related to ecological sustainability and economic growth. This includes the recent crises in fuel, food, and finance, along with the effects of climate change, resource depletion, and the destruction of ecosystems and biodiversity. Governments around the globe have made various attempts to find effective solutions to help their nations recover from these crises while addressing biodiversity issues and ecological constraints. Consequently, there arose a need for a new concept that encompasses these concerns.

Since its introduction in 2008, the Green Economy (GE) concept has garnered significant international attention, particularly as a response to the financial crisis, and was further emphasized at the UN Conference on Sustainable Development (Rio +20) in 2012. The UNEP defines GE as an approach that integrates three critical aspects: human capital, environmental health, and social equity. The transition to a GE has been a subject of debate, with certain misconceptions surrounding it. For instance, some believe that there is an unavoidable trade-off between environmental sustainability and economic growth. Others argue that the transition to a GE is prohibitively expensive for developing nations and that it could hinder their economic growth, serving primarily the interests of developed countries.

However, a UNEP report from 2011 indicated that macroeconomic projections showed transitioning to a GE could lead to increased growth, job creation, and poverty reduction within a few years. In a GE framework, income growth per capita and employment levels depend on new private and public green investments that are less reliant on the exploitation of natural resources and environmental assets, while also lowering carbon emissions and promoting efficient energy use to mitigate environmental degradation. This approach can enable countries to attain more sustainable economic growth.

Consequently, many developing nations have embraced GE as a new model for economic growth aimed at achieving sustainable development, benefiting various sectors, including renewable energy and agriculture. In the renewable energy sector, solar PV power is expected to become one of the most significant global energy supply sources by 2030 and a leading energy provider by 2050. As part of this vision, China plans to develop a photovoltaic industry with a cumulative installed capacity of 1,050 GW by 2030, positioning itself as a top producer of solar PV technology and the largest exporter, with over 98% of its production sold internationally.

Similarly, Malaysia is enhancing energy access for impoverished communities in rural areas, exemplified by successful renewable energy projects in places like Bario Asal. The Egyptian government aims to produce approximately 42% of its electricity from renewable sources, particularly solar energy, by 2034/35. Additionally, Uganda has made strides in organic agriculture,

becoming the 13th largest producer globally by 2003, with a 60% increase in organic farming areas and a 64% reduction in greenhouse gas emissions per hectare compared to conventional agriculture.

Moreover, the GE framework has spurred investments in new sectors such as green technology, green transportation, and green urban development in countries like China, India, Egypt, and Malaysia, resulting in the creation of green job opportunities, economic advancement, and reduced environmental damage, all while addressing climate change challenges. For instance, according to the German Development Institute's 2012 report and a UNEP report from 2014, initiatives in waste management are expected to generate an additional 24,000 jobs in Egypt, while sustainable agriculture could create 8 million jobs by 2050, alongside employment opportunities in recycling, composting, and biofuel production. In Bangladesh, around 3.5 million jobs were generated in eco-friendly sectors, with approximately 800,000 considered green jobs. Additionally, the solar photovoltaic sector created 3.37 million jobs globally in 2017, with Asia accounting for about 3 million, or 88%, of the total, predominantly in China.

In terms of poverty alleviation and social equity, GE policies in developing countries focus on supporting poor and vulnerable populations. For instance, reducing fuel subsidies can redirect funds towards public transportation and healthcare, enhancing the well-being of impoverished communities. Sustainable certification programs and eco-labeling initiatives in countries like Uganda, Nepal, and Egypt have generated new revenue streams from agricultural and forestry products. Furthermore, nations like China and Malaysia have implemented climate change adaptation and mitigation strategies that directly benefit disadvantaged groups.

However, defining the GE concept can be challenging due to its multidimensional nature and varying interpretations, particularly concerning its relationship with sustainable development in developing nations. This complexity leads to difficulties in identifying a singular theory that encompasses all factors influencing this relationship. Empirical evidence suggests that the impacts of GE on economic growth, employment, and poverty levels can vary among countries with similar economic and social conditions, depending on the specific economic policies and structural adjustments adopted during the transition. Consequently, each emerging country's unique social and economic context must be considered when assessing the effects of transitioning to a GE.

IV. Discussion

I. Subsection One

Aligned with the aspirations of a green economy, one of the primary objectives of sustainable development is to promote economic growth while preserving environmental quality. As a result, there has been extensive debate regarding the environmental implications of economic growth over recent decades, particularly in developing countries. Economic growth has become increasingly vital for nations to build their infrastructure in recent years. This relationship between environmental consequences and economic development presents a dilemma for both economists and environmentalists. Numerous studies have aimed to ascertain the causal link between economic growth and environmental degradation, yielding mixed outcomes. Some research indicates that economic growth negatively impacts environmental protection, suggesting that economic strength acts as a catalyst for environmental harm, particularly during the initial phases of development when economies are heavily reliant on fossil fuels and natural resources, as observed in the N11 nations, Bangladesh, the MENA region, leading African natural gas suppliers, Pakistan, Egypt, the USA and Europe, South Asia, and other developing countries.

Conversely, other studies propose that sustainable development is contingent upon green economic growth. Advancements in environmentally friendly and energy-efficient technologies, the dissemination of environmental knowledge and skills, the promotion of sustainable energy generation, and the diversification of the energy mix through increased use of renewable sources are

all critical to fostering green economic growth, as highlighted in several case studies, G7 countries, Africa, the top 20 green innovator nations, and BIRCS. Given the development achievements of developing countries and their anticipated progress in the coming decades, these conclusions are particularly relevant. Thus, this investigation is aimed at addressing a significant research problem within the realm of developing economics.

The foremost goal of the 2030 Agenda for Sustainable Development is to eradicate poverty in all its forms. Target 1 of the Sustainable Development Goals emphasizes the need to eliminate poverty. Mobilizing substantial resources from various sources, including improved development cooperation, is essential to provide developing nations, especially the least developed, with the necessary means to implement programs and policies aimed at combating poverty comprehensively. The Sustainable Development Goals also strive to create effective policy frameworks at national and regional levels to ensure that by 2030, all individuals have equal rights to economic resources, including access to basic services, ownership and control over land and other properties, inheritance rights, natural resources, modern technologies, and financial services. Consequently, numerous scholars have sought to explore the critical role of the green economy in reducing poverty, yielding positive findings. Research indicates that the green economy enhances per capita income and reduces poverty ratios through mechanisms such as green financing, renewable energy utilization, and green hydrogen development.

The green economy has garnered significant scholarly attention due to its implications for employment. According to the United Nations Environment Program, a green economy fosters social equity and job creation, highlighting its positive impact on the labor market. The International Labor Organization supports this notion, asserting that the green economy has the potential to create millions of new jobs. Consequently, many studies have examined the relationship between the green economy and employment levels, exploring connections between environmentally-friendly innovations and job creation, as well as the association between green employment and the green economy's capacity to generate new investments, leading to favorable outcomes.

However, some research suggests that, despite the positive effects of a green economy on employment, there can also be negative impacts, particularly in developing nations. These studies argue that environmental protection may be perceived as a luxury that only developed countries can afford. These findings underscore the significance of this research endeavor in addressing a critical knowledge gap, especially concerning developing economies. The relationship between the green economy and employment levels, a crucial aspect of sustainable development, is particularly meaningful in our analysis, especially regarding its effects on developing countries.

There is a lack of publications in the academic sphere that examine how a green economy influences sustainable development through economic growth, poverty reduction, and employment levels in developing nations. Existing literature often focuses on a singular aspect of sustainable development, raising questions about whether the green economy can effectively accelerate the achievement of these goals. The findings from previous empirical studies indicate a scarcity of research on the drivers of sustainable development and insufficient evidence specifically related to developing nations. Given the critical importance of the green economy in these contexts, it is essential to evaluate these factors, providing recommendations to policymakers and formulating effective policies to reach sustainable development goals. Our theoretical framework and hypotheses, which build on the literature reviewed in this section, will be presented in the following section.

II. Subsection Two

The positive coefficient of the Green Economy (GE) indicates that it contributes to economic progress, illustrating that green economic growth is essential for achieving sustainable development.

This growth can stem from an increased reliance on environmentally friendly and cost-effective innovations, the promotion of sustainable energy production, and the diversification of the energy mix through greater adoption of renewable energy. This aligns with findings from previous studies.

It is important to note that among the four key dimensions of the Green Growth and Employment Index (GGEI), leadership and climate change, efficient sectors, and environmental and natural capital positively influence per capita income. The leadership and climate change dimension encompasses policies and regulations that assist developing countries in transitioning to a green economy without compromising their economic growth.

The efficient sectors dimension, which includes both public and private sectors such as energy, tourism, green transportation, and green building, is also significant for GDP per capita. These new green sectors contribute to boosting the country's economy and raising average per capita income. The positive impact of the green economy on employment can be attributed to various factors that promote social equity and create job opportunities, underscoring its beneficial influence on the labor market.

Additionally, regarding the environmental dimension of natural capital, it is logical that nations endowed with high-quality natural resources tend to exhibit advanced economic development levels, as these resources are vital inputs in the production function. Consequently, a favorable environment and rich natural capital are likely to enhance economic performance.

However, the relationship between the green economy and unemployment remains unclear, with findings indicating that only one aspect of the green economy has a significant positive impact on unemployment. The green economy influences job creation indirectly through economic output; thus, while productivity improvements can lead to increased employment and decreased unemployment, this secondary effect is limited and not solely driven by the green economy. These outcomes align with reports from the International Labour Organization, which suggest that the green economy has the potential to create millions of new jobs.

Furthermore, the promotion of the green economy aids in eradicating poverty, which contributes to sustainable development. This negative correlation exists because increased development cooperation provides the necessary and reliable resources to implement programs and policies aimed at alleviating poverty in all its forms. Numerous studies have concluded that the implementation of green economy strategies is essential for reducing poverty and advancing sustainable development.

Moreover, the green economy lowers poverty rates in countries based on their national criteria; thus, a higher environmental quality correlates with lower poverty levels. Among the key dimensions of the GGEI, two dimensions significantly affect poverty rates. First, the market and investment dimension shows a negative relationship with poverty levels. As green investment advances, per capita GDP and the standard of living in a country improve. This enhancement in economic standards leads to a decrease in the number of individuals living below the poverty line.

Second, the environmental and natural capital dimension also exhibits a negative correlation with poverty. The conservation of the environment and sustainable utilization of natural resources contribute to securing access to quality food and safe drinking water, thereby reducing malnutrition rates and directly lowering poverty levels in developing countries. Here's a rephrased version of your text while maintaining its original meaning:

The significance of the Green Economy (GE) concept arises not as an alternative to Sustainable Development (SD), but rather as a focused and direct approach and a vital tool for achieving SD. Transitioning towards a GE holds the potential for unprecedented economic growth and poverty alleviation, executed rapidly and effectively. This potential stems from two concurrent transformations. First, our society and the risks we encounter have dramatically changed due to evolving circumstances, necessitating a fundamental re-evaluation of our economic strategies. Second, there is growing acknowledgment that natural resources form the basis of our physical infrastructure and must be managed as a primary source of prosperity and well-being.

Consequently, countries are currently in a race to harness their available natural resources and renewable energy, particularly amid a global trend focusing on environmental issues to mitigate

ecological degradation and biodiversity loss, alongside challenges such as acid rain and rising temperatures driven by greenhouse gas emissions that contribute to climate change with potentially catastrophic consequences. Therefore, GE can be viewed as a new economic paradigm and a critical element in economic development, job creation, and poverty reduction globally, especially in emerging nations.

In this context, the findings indicate that GE positively influences average per capita GDP and overall unemployment levels while negatively impacting poverty rates in developing countries. This suggests that the green economy is a key driver of sustainable development by fostering economic growth, creating new job opportunities, and reducing poverty in developing nations.

To emphasize the importance of a green economy, governments in developing countries should standardize its definition, measurement tools, and datasets used in calculations. Enhancing institutions and policies to encourage public and private sector investment in green sectors is essential, as is promoting scientific research and development initiatives and technological innovation. Allocating significant portions of public spending for research and development in the green economy, designing specialized programs to enhance labor quality through intensive training in advanced technologies for various green sectors, and improving workforce skills are critical steps.

Additionally, formulating and refining policies for transitioning to a GE that stimulate public spending and foreign direct investment is crucial for generating new economic sectors and investment opportunities, particularly to create job prospects for poor and vulnerable groups. Establishing a national green financial system that introduces new financial instruments such as green bonds, green insurance, and green credit is vital for meeting the sustainable financing needs for the green transition.

Moreover, promoting investments in renewable energy sectors, especially wind and solar energy, should be institutionalized across all sectors. Renewable energy products often lack institutional support, which may leave consumers unaware of their rights and responsibilities regarding these products. Therefore, relevant authorities and ministries must provide this institutional framework to enhance the adoption and expansion of renewable energy in developing countries.

Green policies should incorporate environmental, social, and economic factors to ensure equitable wealth distribution and equal opportunities for diverse population segments. Furthermore, it is important to encourage private sector investment in green sectors through economic incentives such as procurement policies, differential pricing, and tax benefits to promote renewable technologies and financing mechanisms. This includes encouraging the use of renewable energy technologies by reducing tariffs on equipment and components and eliminating or reducing fossil fuel subsidies.

This analysis focused on the connections between the green economy and sustainable development, particularly regarding the social and economic dimensions related to the first and eighth Sustainable Development Goals—namely, no poverty, decent work, and GDP—by examining emerging economies. For future studies, we recommend expanding the framework to incorporate additional sustainable development goals and including both developed and developing countries for comparative analysis to derive further insights.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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GREEN ECONOMY AND SUSTAINABLE CITIES: THE ROLE OF COMMUNITY ENGAGEMENT IN URBAN ENVIRONMENTAL DEVELOPMENT

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Abstract

This study delves into the economic foundations of sustainable urban development, focusing on the active role of human participation in the transition toward eco-friendly cities. It investigates how sustainable cities balance economic growth, environmental conservation, and social equity, all while adapting to the challenges posed by rapid urbanization, climate change, and resource depletion. The research underscores the role of sustainable economic practices such as renewable energy integration, green infrastructure, and waste reduction in fostering urban resilience. A central theme of the book is the significance of human involvement in driving sustainability efforts. It explores how citizen engagement, policy-making, and community-driven initiatives shape eco-friendly urban landscapes. The book also highlights the economic benefits of public participation in decision-making processes, showing how informed communities can support green innovations and enhance city-wide efforts to reduce environmental impact. By exploring case studies and best practices from cities worldwide, the book demonstrates how human-driven policies and economic strategies can contribute to the development of cities that are environmentally sound, socially inclusive, and economically sustainable. This work serves as a guide for policymakers, urban planners, and citizens aiming to create more livable, sustainable urban spaces.

Keywords: Sustainable urban development, eco-friendly cities, human participation, green infrastructure, circular economy, renewable energy, citizen engagement, environmental sustainability.

I. Introduction

As urban populations continue to grow, cities around the world face unprecedented challenges, including environmental degradation, resource scarcity, and social inequality. The concept of sustainable urban development emerges as a critical framework to address these challenges, emphasizing the need for an integrated approach that harmonizes economic growth, environmental protection, and social inclusivity. This paradigm shift requires not only innovative economic strategies but also active human participation in creating eco-friendly urban environments.

Human involvement is crucial in the transition toward sustainable cities, as it fosters a sense of ownership and accountability among community members. Citizens play a vital role in shaping urban policies, influencing consumption patterns, and advocating for environmentally friendly practices. By engaging individuals and communities in decision-making processes, cities can harness local knowledge and foster a culture of sustainability that resonates with residents.

This study aims to explore the economics of sustainable urban development, highlighting the interplay between human participation and the creation of eco-friendly cities. It will examine successful case studies that illustrate how collaborative efforts can lead to innovative solutions, ultimately promoting urban resilience and a higher quality of life. The focus will also be on practical strategies and policies that can facilitate citizen engagement and foster sustainable economic growth in urban settings.

As we navigate the complexities of modern urbanization, understanding the economic implications of sustainable development and the critical role of human participation will be essential in building cities that are not only environmentally sustainable but also socially just and economically viable. Through this exploration, we aim to provide valuable insights for policymakers, urban planners, and community stakeholders striving to create sustainable urban futures.

II. Methods

This study employs three specific methods to investigate the economics of sustainable urban development and the role of human participation in creating eco-friendly cities:

1. Surveys: A structured survey will be administered to residents of selected urban areas. The survey will include quantitative questions designed to assess participants' awareness of sustainable practices, their attitudes toward eco-friendly initiatives, and their level of engagement in local decision-making processes. A sample size of approximately 500 participants will be targeted to ensure a representative cross-section of the urban population. Data from the surveys will be analyzed statistically to identify correlations between citizen participation and perceptions of sustainable urban development.

2. Case Studies: Detailed case studies will be conducted on three cities known for their innovative approaches to sustainable urban development—such as Copenhagen, Singapore, and Vancouver. Each case study will examine the specific policies implemented, the role of community involvement, and the measurable outcomes in terms of environmental sustainability and economic growth. Data will be collected through document analysis, interviews with local stakeholders, and site visits to assess the practical implications of these initiatives.

3. Focus Groups: Focus group discussions will be organized with diverse community members, including local residents, business owners, and representatives from environmental organizations. These discussions will aim to gather qualitative insights into community attitudes toward sustainable urban development, barriers to participation, and suggestions for improvement. Each focus group will consist of 8-10 participants, and sessions will be recorded and transcribed for thematic analysis, allowing for a deeper understanding of collective perspectives and shared experiences related to eco-friendly city initiatives.

III. Results

As the world confronts the growing challenges posed by climate change and environmental degradation, the construction industry has emerged as a key contributor to achieving a sustainable future. Eco-friendly building practices have become essential in this effort, providing innovative solutions that not only meet the immediate demands of urbanization but also protect the planet's long-term health. A core principle of eco-friendly building is the utilization of renewable energy sources. Since buildings are significant energy consumers and reliance on fossil fuels greatly contributes to carbon emissions, integrating technologies such as solar panels, wind turbines, and other renewable energy solutions allows structures to generate clean energy, thereby reducing their dependence on non-renewable resources and minimizing their ecological footprint.

The selection of construction materials is crucial to a building's environmental sustainability. Eco-friendly building practices prioritize the use of green materials, which are defined by their low environmental impact throughout their entire life cycle. This includes materials with recycled content, those sourced from sustainable forests, and products that exhibit a low carbon footprint. Such materials promote a more sustainable construction sector by conserving natural resources and decreasing the emissions associated with conventional materials.

Energy efficiency is central to eco-friendly building practices. Advanced technologies, such as smart building systems, energy-efficient HVAC (heating, ventilation, and air conditioning) systems, and superior insulation methods, optimize energy use within buildings. By implementing these technologies, buildings can significantly lower their energy consumption, which in turn reduces greenhouse gas emissions and reliance on non-renewable energy sources.

Eco-friendly building practices play a vital role in mitigating the carbon footprint linked to the construction and operation of buildings. The use of renewable energy sources and energy-efficient technologies contributes directly to the decrease of greenhouse gas emissions. Additionally, incorporating carbon sequestration strategies, such as green roofs and carbon-absorbing building materials, further helps offset the carbon impact of construction activities. Traditional construction methods typically involve the extraction and consumption of large quantities of natural resources. In contrast, eco-friendly building practices emphasize resource conservation. By utilizing recycled or reclaimed materials, minimizing waste through efficient construction techniques, and selecting materials with lower environmental impacts, these practices help preserve ecosystems and biodiversity. The resilience of the built environment in addressing climate change is a vital aspect of modern construction practices. Eco-friendly building methods enhance the overall resilience of structures by integrating features like climate-responsive design, resistance to natural disasters, and the adaptive reuse of existing buildings. This strategy ensures that buildings can endure the challenges posed by a changing climate, thereby contributing to the longevity and sustainability of the built environment.

In conclusion, eco-friendly building practices signify a transformative shift in the construction industry, moving beyond traditional norms to adopt a sustainable and environmentally conscious approach. The use of renewable energy sources, the integration of green building materials, and the implementation of energy-efficient technologies together redefine how buildings are designed, constructed, and operated. By reducing carbon footprints, conserving natural resources, and bolstering the overall resilience of the built environment, these practices stand as beacons of hope for a more sustainable and ecologically responsible future.

IV. Discussion

I. Subsection One

The transformative potential of Sustainable Urban Design goes beyond merely environmental aspects; it deeply influences community dynamics and significantly enhances the quality of life for urban residents. This examination delves into the multifaceted impact of Sustainable Urban Design on communities, highlighting its holistic approach to promoting community well-being, fostering a sense of belonging, improving residents' quality of life, and advancing social equity.

Sustainable Urban Design embraces a comprehensive perspective that prioritizes the overall well-being of communities. Recognizing the interplay between social, economic, and environmental factors, this approach shapes the urban experience by addressing the diverse needs and aspirations of community members. The goal is to create inclusive, resilient, and vibrant urban spaces that enhance the collective welfare of residents.

At its core, Sustainable Urban Design is committed to inclusive design principles that guarantee public spaces are accessible and usable for all. This commitment extends beyond mere regulatory compliance; it involves actively engaging with the varied needs of different demographic groups, including people with disabilities, seniors, and children. By incorporating universal design concepts, urban spaces become welcoming and inclusive, fostering a sense of belonging for all.

Moreover, Sustainable Urban Design emphasizes social cohesion and connectivity. The arrangement of urban spaces, the design of public gathering areas, and the creation of pedestrian-friendly environments encourage social interactions and community engagement. Integrating green spaces, parks, and communal areas acts as a catalyst for social cohesion, offering residents opportunities to connect, share experiences, and build a collective identity within their neighborhoods.

The design of sustainable urban environments significantly affects residents' health and well-being. Access to green spaces, walkable neighborhoods, and recreational facilities contributes to physical and mental wellness. Incorporating nature into the urban landscape improves air quality, reduces stress levels, and promotes overall health. Sustainable Urban Design advocates for designs that prioritize public health, acknowledging the link between a healthy environment and individual well-being.

Sustainable Urban Design also aims to enhance living conditions by optimizing resource use and creating comfortable, energy-efficient homes. Energy-efficient buildings that maximize natural light and ventilation not only minimize environmental impact but also provide healthier living spaces. Additionally, mixed-use developments ensure that essential services, educational institutions, and recreational amenities are conveniently located, improving residents' overall quality of life (fig.1).

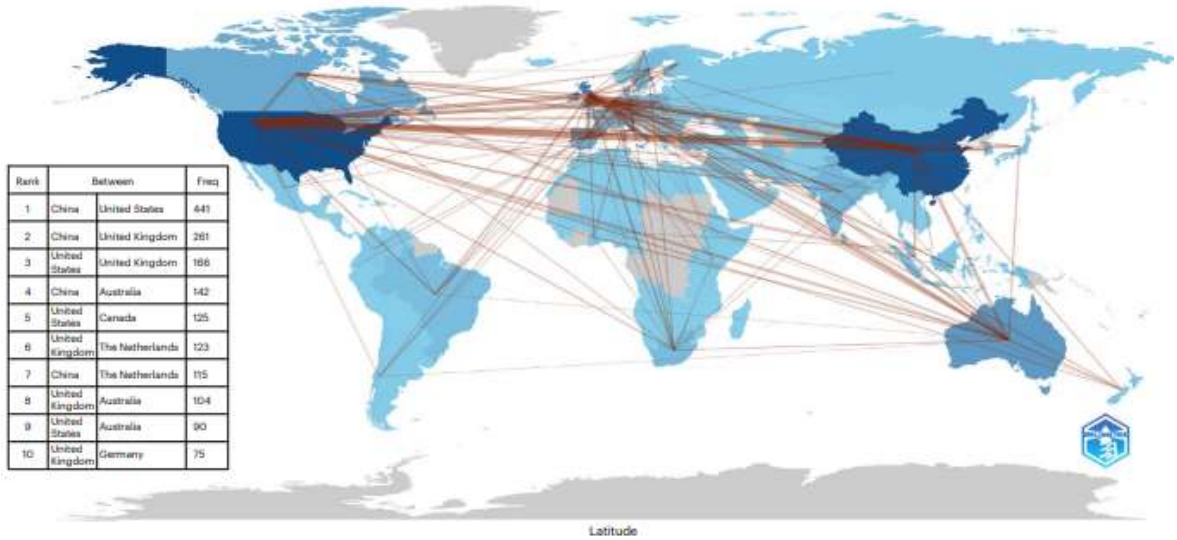


Figure 1. 10 collaborating countries in SDG11 research

China followed by the United States and the United Kingdom dominates SDG11 research collaborations. There are significant connections among European, North American and Asian institutions, while Africa is less connected with Asia and Latin America and the Caribbean. Freq, frequently.

Equity is a key focus of Sustainable Urban Design, addressing issues of accessibility and affordability. Public infrastructure, including transportation systems and public spaces, is designed with the needs of all residents in mind, especially those with limited mobility or financial

resources. Public transportation systems, cycling lanes, and pedestrian-friendly pathways enhance accessibility, ensuring urban amenities are reachable for everyone, regardless of socio-economic status.

Furthermore, Sustainable Urban Design actively tackles socio-economic disparities by promoting inclusive housing policies and equitable development strategies. This includes providing affordable housing, creating mixed-income neighborhoods, and implementing initiatives to prevent gentrification. By encouraging socio-economic diversity within urban areas, Sustainable Urban Design contributes to building resilient communities better equipped to face economic fluctuations and social transformations.

In conclusion, the community impact of Sustainable Urban Design extends beyond physical structures and environmental concerns associated with urban planning. By adopting a holistic approach to community well-being, fostering a sense of belonging, improving residents' quality of life, and promoting social equity, Sustainable Urban Design emerges as a powerful catalyst for positive social change. As cities evolve, the principles of sustainable urban design provide a roadmap for creating urban environments that prioritize the needs of diverse communities, ultimately leading to more livable, inclusive, and equitable urban spaces.

II. Subsection Two

A significant trend of urbanization is unfolding worldwide, with nearly 55% of the global population currently living in urban areas. Projections indicate that this trend will continue, potentially doubling the urban population by 2050. Cities are also responsible for approximately 75% of carbon emissions, 70% of energy consumption, and 80% of global GDP, positioning them at the forefront of the fight for sustainable development and climate action. Effective urban management has the potential to promote sustainable development, leading to increased productivity and innovation. Data clearly illustrates the connections between planned urbanization and human development; however, the prevalence of informal settlements presents a major obstacle to the positive correlation between urban growth and improvements in income, health, and education conditions (see Figure 2).

There is a broad consensus within the development community regarding the significance of cities and urbanization in achieving sustainable development, as highlighted in recent global agendas. One of the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda is entirely focused on urban issues: SDG 11, which addresses sustainable cities and communities. This goal comprises 10 targets aimed at ensuring that cities and human settlements are inclusive, safe, resilient, and sustainable. However, urban issues extend beyond these specific targets and can be found across all 16 other SDGs, as shown in Figure 03. In addition to these interconnections, urbanization serves as a catalyst for achieving the SDGs, with cities functioning as engines of economic growth, innovation, and socio-economic opportunities.

Building local capacity for urban planning is essential to ensure that urbanization effectively contributes to sustainability. This need is highlighted in the 2030 Agenda under the SDG 11.3 target, which aims to enhance inclusive and sustainable urbanization and capacities for participatory, integrated, and sustainable human settlement planning and management in all countries by 2030. In response to this challenge, UN-Habitat launched a toolbox methodology called "Our City Plans" at the 2020 World Urban Forum. This initiative is designed to support cities in implementing the New Urban Agenda and localizing the SDGs at the community level in a participatory and incremental manner.

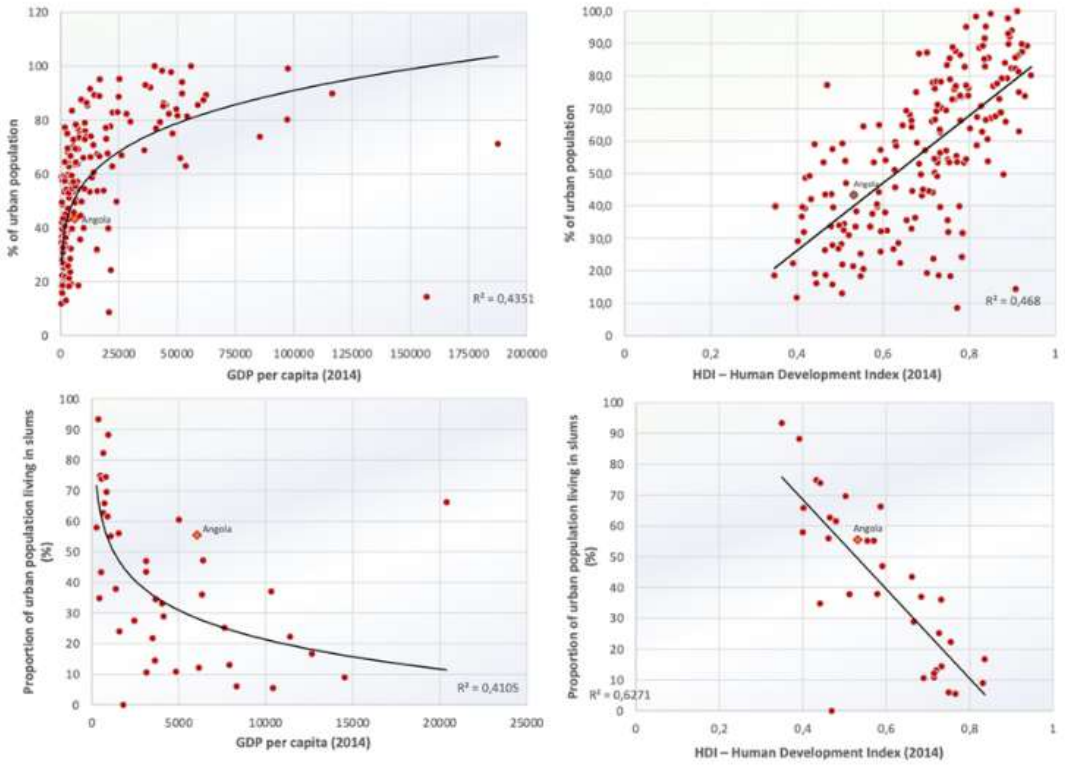


Figure 2. Correlation between HDI and GDP per capita growth with unplanned urbanization

The theories and concepts discussed above have shaped and influenced various urban agendas over the past two decades (see Figure 2). Among these, the sustainable city stands out as the most prominent and frequently referenced urban agenda. This concept, rooted in sustainable development (SD) and sustainable city development (SCD), first emerged with the 1994 Aalborg Charter and has been significantly influenced by the UN Agenda 21 and the 2002 Melbourne Principles on Sustainable Cities, which were sponsored by the United Nations Environment Programme (UNEP) and ICLEI.

Different scholars provide varying interpretations of what constitutes a sustainable city. Some view it as a framework for enhanced ecological and resource protection, while others see it as a means to ensure economic growth through greener technologies, balancing ecological stability and social equity—a perspective often referred to as "greener urban growth." Additionally, some emphasize the importance of addressing all three pillars of sustainability.

Mori and Yamashita provide a comprehensive yet straightforward definition: a sustainable city maximizes socio-economic net benefits while considering environmental constraints and the limits of economic and social inequality. Similarly, Roseland defines a sustainable community, whether urban or rural, as dynamic and engaged in activities that sustain the environment, empower citizens, and ensure that the needs of both current and future generations are met. Scholars also highlight essential characteristics of sustainable urban form: inclusivity and accessibility, health and thoughtful planning, adequate density, energy efficiency, resilience to climate and other risks, economic competitiveness, affordability, protected ecosystems, eco-friendly transportation infrastructure, and robust regional linkages.

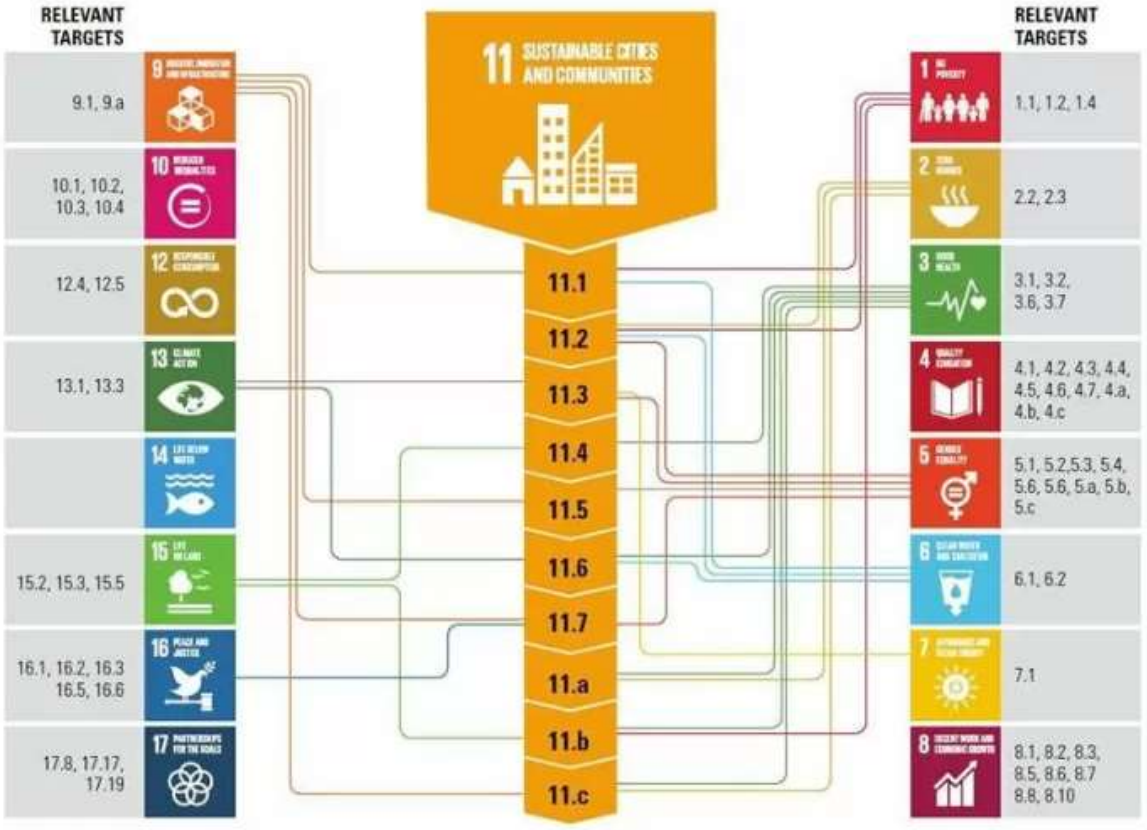


Figure 3. The interconnectivity between SDG 11 targets and other SDGs targets

In addition to the sustainable city agenda, at least five other prominent urban agendas have been identified in the literature: Ecocity, low-carbon city, resilient city, knowledge city, and smart city. The concepts of green city and livable city are also present but are often regarded as subcategories of ecocity and sustainable city, respectively.

Contrary to common assumptions among policymakers, these various agendas do not all share the same theoretical foundations, and their terminologies should not be used interchangeably.

The ecocity and green city concepts, rooted in long-standing principles of deep ecology and the humanities, gained traction in the late 20th century and were primarily operationalized within a broader eco-urbanism movement. Approaches such as eco-districts, zero-carbon cities, and low-impact urban developments align with this spirit of collective sustainability.

On the other hand, smart and digital city agendas focus on utilizing digital technology and infrastructure to enhance well-being, along with a greater emphasis on governance. However, in practice, the smart city agenda often lacks a holistic approach to sustainability, with initiatives that may not adequately address social equity or ecologically responsible resource management. Bibliometric and webometric analyses further reveal a lack of widely accepted definitions or coherent understandings of the smart city agenda, potentially leading to tensions and disconnections in research, policy, and practice.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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HEALTH AND THE ENVIRONMENT: EXPLORING THE LINK BETWEEN ECOSYSTEM QUALITY AND HUMAN WELL-BEING

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Abstract

This paper explores the intricate relationship between human health, ecological status, and quality of life, emphasizing the significance of ecosystem health as a determinant of overall well-being. The degradation of ecosystems due to human activities poses a substantial threat to public health, affecting not only physical well-being but also mental health and social cohesion. We analyze various ecological factors, including air and water quality, biodiversity, and green spaces, which directly influence health outcomes and quality of life. By synthesizing existing literature and empirical data, this study underscores the importance of sustainable environmental practices and policies in promoting human health. The findings highlight the need for integrated approaches that encompass ecological conservation, public health initiatives, and community engagement to foster a healthier population and environment. Ultimately, this paper advocates for a holistic understanding of the interconnectedness of human health and ecosystem vitality, calling for collaborative efforts among stakeholders to enhance both ecological and human well-being.

Keywords: Human health, ecosystem health, quality of life, environmental sustainability, public health, biodiversity, air quality, water quality, green spaces, social cohesion.

I. Introduction

The relationship between human health and ecological status has garnered increasing attention in recent years, driven by a growing awareness of how environmental factors significantly influence overall well-being. As populations expand and industrialization intensifies, the degradation of natural ecosystems has escalated, leading to adverse health outcomes. The degradation of the environment—manifested through pollution, loss of biodiversity, and climate change—poses considerable risks not only to physical health but also to mental well-being and social cohesion.

Ecosystems provide vital services that directly support human health, including clean air, safe drinking water, nutritious food, and spaces for recreation and mental relaxation. The Millennium Ecosystem Assessment (2005) underscored the importance of these ecosystem services in sustaining human life, highlighting that the health of ecosystems directly correlates with the quality of life experienced by communities. For instance, polluted air and water sources have been linked to a range of health issues, including respiratory diseases, cardiovascular conditions, and even mental health disorders. Furthermore, the loss of biodiversity can disrupt the balance of

natural systems, reducing their resilience and ability to adapt to changing conditions, which can further exacerbate health risks.

Despite this clear interconnection, traditional public health approaches often fail to incorporate ecological perspectives, resulting in fragmented strategies that overlook the broader environmental determinants of health. As such, there is a pressing need for integrated approaches that recognize the intricate links between ecological integrity and human health. This includes not only the need to address immediate health concerns but also to engage in proactive ecological conservation efforts that safeguard the health of ecosystems and, by extension, the populations that depend on them.

In this paper, we will explore the multidimensional relationship between human health, ecological status, and quality of life. We will examine key factors influencing this relationship, including air and water quality, biodiversity, and the availability of green spaces, while emphasizing the implications for public health policies and practices. By synthesizing existing literature and empirical research, we aim to highlight the critical need for collaborative efforts among various stakeholders, including policymakers, public health officials, and environmental organizations, to foster a healthier population and environment. Ultimately, this work advocates for a holistic understanding of the interconnectedness of human health and ecosystem vitality, emphasizing the importance of sustainable practices and community engagement in enhancing both ecological and human well-being.

II. Methods

To explore the relationship between human health and ecological status, this study employs three primary research methods: literature review, empirical analysis, and case studies. Each method offers unique insights into how ecological factors influence health outcomes and quality of life.

1. Literature Review

The literature review involves a comprehensive analysis of existing research related to human health and ecosystem interactions. This method encompasses studies published in peer-reviewed journals, reports from international organizations (such as the World Health Organization and the United Nations), and relevant grey literature. The review will focus on identifying key themes, such as the impact of air and water quality on health, the role of green spaces in promoting mental well-being, and the effects of biodiversity loss on disease prevalence. By synthesizing findings from multiple sources, the literature review aims to provide a holistic understanding of the current state of knowledge on the subject, highlight gaps in the literature, and inform future research directions.

2. Empirical Analysis

Empirical analysis will involve the collection and statistical examination of quantitative data to assess the relationships between ecological indicators and health outcomes. This method will utilize existing datasets from national health surveys, environmental monitoring agencies, and public health databases. Key ecological indicators may include air and water quality measurements, biodiversity indices, and green space availability. Health outcomes of interest could encompass rates of respiratory diseases, cardiovascular conditions, and mental health disorders. By employing statistical techniques such as regression analysis and correlation studies, this method will aim to quantify the strength and significance of associations between ecological factors and health outcomes, offering empirical evidence to support the hypotheses derived from the literature review.

3. Case Studies

The case study method involves an in-depth examination of specific geographic locations or communities to illustrate the practical implications of the relationship between human health and

ecological status. Selected case studies may focus on areas experiencing notable environmental challenges, such as urban pollution hotspots, regions facing water scarcity, or communities with rich biodiversity that have seen health benefits. Through qualitative data collection methods, including interviews, surveys, and participant observations, this approach will provide insights into local experiences, perceptions, and behaviors related to health and the environment. Case studies will also allow for the exploration of community-level interventions and policies that have successfully linked ecological preservation with improved health outcomes, thereby offering valuable lessons for broader application.

By employing these three methods—literature review, empirical analysis, and case studies—this study aims to provide a comprehensive understanding of the complex interplay between human health, ecological status, and quality of life. This multifaceted approach ensures that both theoretical insights and practical applications are considered, ultimately informing public health strategies and environmental policies.

III. Results

Human health plays a crucial role in the overall well-being of populations and is closely linked to the state and functionality of ecosystems, particularly their capacity to deliver healthy and adequate ecosystem services, as emphasized by the Millennium Ecosystem Assessment (MEA). This paper aims to review existing literature that explores the connections between ecosystem services and human well-being, beginning with a reinterpretation of the MEA framework. In this exploration, we underscore the importance of considering exposure mechanisms through passive, consumptive, and active behaviors, along with contextual factors such as socio-economic status, demographics, and climate conditions. In this framework, elements like tourism, recreation, and leisure are associated with active participation.

Current literature employs various metrics to measure health and well-being, highlighting the necessity for standardized approaches and new methodologies to evaluate how study design affects outcomes. In conclusion, the studies reviewed indicate moderate evidence supporting a positive relationship between green environments and well-being, although significant positive effects are not consistently observed across all cases.

Ecosystem services play a vital role in enhancing human well-being through various pathways. The Millennium Ecosystem Assessment (MEA, 2005) identifies five key elements contributing to well-being: security, basic materials for a good life, health, good social relations, and freedom of choice and action. The concept of security encompasses not only the physical safety of individuals and their properties but also the broader assurance of access to essential resources and the ability to avert human-induced disasters. Basic materials for a good life include essentials like shelter, food, water, energy, income, assets, and access to goods.

Health is a central component of human well-being and is fundamentally dependent on the ecosystem's capacity to deliver healthy and adequate ecosystem services, such as clean water, nutritious food, and good air quality. The MEA framework categorizes ecosystem services into four groups: provisioning, regulating, cultural, and supporting services. Supporting services underpin the functioning of the other ecosystem services, facilitating essential processes like nutrient cycling and soil formation. Ecosystems also provide direct provisioning of goods, including food, water, and medicinal plants. Regulating services contribute to human well-being by controlling climate and flood dynamics. Cultural services impact health by offering opportunities for recreational activities and fostering aesthetic and spiritual connections, which enhance both physical and mental well-being. Engaging in recreational activities promotes active lifestyles, reducing the risk of diseases such as cardiovascular issues and obesity, while also supporting mental health, community cohesion, and a sense of identity.

The quality of the environment significantly influences human health; for instance, air

pollution can exacerbate existing cardiovascular and respiratory conditions, particularly in older adults. Conversely, improvements in air quality and reductions in extreme temperatures can yield positive health outcomes. Direct interaction with nature has been shown to benefit health by enhancing cardiovascular and respiratory functions, decreasing the prevalence of diabetes and obesity, and improving psychological well-being. Access to green spaces, such as urban parks, fosters social interactions, thereby strengthening community bonds and positively affecting social relations.

This paper examines the health benefits provided by green and blue spaces, including urban parks, green areas, freshwater systems, and coastal zones. To achieve this, a literature review was conducted to explore how the natural environment influences various dimensions of well-being, with a specific focus on health and its determinants.

IV. Discussion

I. Subsection One

The passage you've shared provides a detailed analysis of the ecosystem services provided by freshwater ecosystems, particularly wetlands, and the challenges associated with their management in both developing and developed countries. It highlights the importance of these ecosystems for a wide range of cultural, commercial, and ecological functions, while also addressing the negative impacts of industrial agriculture, pollution, and urbanization. Several key themes and strategies emerge from the discussion on how to balance human needs with the preservation of natural systems.

First, freshwater ecosystems provide critical services, including water purification, flood regulation, habitat provision, and cultural benefits. The value of these services is substantial, as evidenced by studies that quantify their economic worth. While agriculture is seen as a provider of ecosystem services, industrialized farming often leads to environmental degradation. Practices associated with large-scale agriculture can diminish soil health, reduce biodiversity, and pollute water sources. There is a growing recognition of agroecology as a means to promote sustainable agricultural practices that work in harmony with natural ecosystems. This approach emphasizes soil health, recycling of materials, and the empowerment of local communities.

Wetland management is crucial, and the concept of "wise use" encourages sustainable practices that protect and restore these environments, ensuring they continue to provide their valuable services. The passage questions the effectiveness of investing in cleanup efforts for polluted water bodies while the root causes of pollution remain unaddressed, advocating for proactive measures to eliminate pollution drivers. Rapid growth of global populations and industrial activity poses challenges to the conservation of natural ecosystems. Balancing these demands with the need for environmental protection is crucial for sustainable development.

To address these challenges, integrated water resource management (IWRM) can help balance the demands of various sectors—agriculture, industry, and domestic use—while prioritizing the health of freshwater ecosystems. Promoting agroecology and organic farming can enhance soil health and biodiversity, reduce reliance on chemical inputs, and increase resilience to climate change. Education and support for farmers can facilitate this transition. Ecosystem-based adaptation strategies, such as restoring wetlands and reforesting, can mitigate flooding and protect communities in a cost-effective manner. Finally, strengthening regulations on industrial discharges and agricultural runoff can significantly reduce the nutrient loading that harms freshwater systems, ultimately leading to healthier ecosystems that can continue to support both human populations and biodiversity.

II. Subsection Two

Schumacher's observation about the alienation of modern man from nature encapsulates a critical challenge in contemporary society: the prevailing view of nature as an adversary rather than an integral part of human existence. This mindset drives a relentless push to dominate and control the natural world, often leading to environmental degradation in the pursuit of short-term economic gains. The passage outlines the consequences of this approach, particularly through the examples of infrastructure development and industrial agriculture, and raises the question of whether viable alternatives to purely technological solutions exist. The emphasis on technological solutions often overlooks the inherent value of natural ecosystems. For example, while concrete structures can provide flood protection, they typically come with higher costs and fail to replicate the multifaceted benefits provided by healthy ecosystems, such as wetlands and mangroves. The ecological services these natural barriers provide—like storm surge protection and nursery habitats for marine life—are not easily quantifiable but are critical for community resilience.

Moreover, the conversion of natural environments for industrial use frequently benefits a small number of individuals or corporations at the expense of local communities. In the case of shrimp aquaculture in Sri Lanka, the socioeconomic impacts disproportionately affected traditional livelihoods while offering minimal benefits. This pattern is evident globally, where the costs associated with ecosystem destruction often fall on the poorest populations and future generations, who rely on these ecosystems for their survival. The issue of 'non-tradable public benefits,' which are essential ecosystem services that do not enter the market economy, is particularly concerning. Politicians and businesses typically operate on short time scales, failing to account for the long-term consequences of ecosystem degradation. This shortsightedness allows for continued exploitation of natural resources, transferring economic benefits from many to a privileged few.

In light of these challenges, viable alternatives to technological responses can be explored. Ecosystem-based management integrates ecological health into resource management decisions. By prioritizing the conservation and restoration of ecosystems, communities can benefit from the natural services these systems provide, such as clean water, flood protection, and biodiversity. Community-led conservation engages local populations in the stewardship of their natural resources, fostering a sense of ownership and responsibility that often results in more effective conservation outcomes. Payment for ecosystem services (PES) incentivizes the protection of ecosystem services by compensating landowners and communities for maintaining or restoring natural habitats. PES schemes help align economic incentives with environmental health, ensuring that the benefits of healthy ecosystems are recognized and rewarded.

Integrated water resource management (IWRM) promotes a holistic approach to managing water resources, considering the interdependencies between water, land, and ecosystems. By balancing the needs of different sectors and ensuring sustainable use of water resources, IWRM can help protect vital ecosystems while meeting human demands. Transitioning to agroecological practices can enhance food production while preserving ecosystem health. By focusing on ecological principles, such as crop diversity and soil health, agroecology aims to create resilient agricultural systems that support local communities without degrading the environment. Incorporating natural elements into urban planning—such as green roofs, permeable pavements, and urban forests—can mitigate the impacts of climate change and reduce reliance on traditional engineering solutions. These practices enhance urban resilience while providing ecological benefits.

In conclusion, the challenges posed by modern society's disconnection from nature require a paradigm shift in how we view and interact with the natural world. Viable alternatives to technological responses exist and often prioritize ecological health, social equity, and community resilience. By recognizing the intrinsic value of ecosystems and incorporating their services into economic and developmental frameworks, societies can move toward a more sustainable future that respects both people and nature. This approach not only mitigates the adverse effects of

environmental degradation but also fosters a deeper connection between humans and the natural world, ultimately leading to a more balanced and sustainable coexistence.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INNOVATIONS IN MEDICINE FOR SUSTAINABLE DEVELOPMENT: GREEN TECHNOLOGIES AND RESOURCE-EFFICIENT SOLUTIONS

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Abstract

Innovative technologies in reproductive medicine are radically changing approaches to the treatment of infertility, genetic diseases and reproductive health problems. Modern methods such as assisted reproductive technologies (ART), including in vitro fertilization (IVF) and embryo cryopreservation, have significantly increased the chances of successful conception. Key achievements have also included preimplantation genetic testing (PGT), which allows identifying genetic abnormalities in embryos before they are transferred to the uterus, and genome editing technologies (such as CRISPR), which offer the prospect of correcting genetic defects at an early stage of development. In addition, stem cell research is actively developing, which in the future may make it possible to create artificial gametes, which will be a solution for people who lack functional germ cells. Another significant breakthrough is uterine transplantation, which gives a chance to bear a child to women who do not have their own functional uterus. These advances not only increase the success of reproductive procedures, but also open up new horizons in the field of personalized medicine and raise important ethical questions related to reproductive technologies. Innovative developments in reproductive medicine are aimed at improving the quality of life of people and expanding opportunities to overcome barriers to parenthood, making them an important component of modern healthcare.

Keywords: Innovative technologies, reproductive medicine, ART, IVF, cryopreservation, preimplantation genetic testing.

I. Introduction

Innovative technologies in reproductive medicine are revolutionizing the way we approach fertility, genetic disorders, and overall reproductive health. Over the past few decades, significant advancements have emerged, offering new hope to individuals and couples struggling with infertility and hereditary diseases. These developments are particularly evident in the realm of assisted reproductive technologies (ART), such as in vitro fertilization (IVF), which has dramatically improved success rates for conception. The ability to freeze embryos and eggs through cryopreservation has further expanded reproductive options, allowing patients to preserve their fertility for future use.

In parallel, preimplantation genetic testing (PGT) now enables the screening of embryos for genetic abnormalities before implantation, reducing the risk of passing on hereditary diseases and

improving the overall chances of a healthy pregnancy. Additionally, cutting-edge gene-editing technologies like CRISPR are opening new doors by offering the potential to correct genetic defects at the embryonic stage, presenting possibilities for eliminating certain inherited disorders altogether.

Research into stem cell therapy and the potential to develop artificial gametes (sperm and eggs) is another exciting frontier, especially for individuals who cannot produce viable reproductive cells. This could provide a breakthrough for those previously considered untreatable by conventional methods. Furthermore, the development of uterine transplantation offers women who lack a functional uterus the opportunity to carry a pregnancy to term, which was previously impossible.

These innovative technologies are not only enhancing the clinical success of fertility treatments but are also driving a deeper understanding of human reproduction at the molecular and genetic levels. This progress is facilitating the rise of personalized reproductive medicine, where treatments can be tailored to an individual's specific genetic and biological profile.

As the field of reproductive medicine evolves, it brings with it significant ethical, legal, and social implications. Questions around the use of genetic editing, embryo selection, and reproductive autonomy raise complex debates about the future of human reproduction. At the same time, the promise of these technologies offers the potential to overcome previously insurmountable barriers to parenthood, fundamentally transforming the landscape of reproductive health.

In light of these rapid advancements, reproductive medicine is entering a new era, where science and technology intersect to provide more effective, individualized solutions for a growing number of people around the world.

II. Methods

The study and application of innovative technologies in reproductive medicine involve a multidisciplinary approach, incorporating advanced scientific techniques, medical procedures, and cutting-edge research. Key methods used in the field include:

-In Vitro Fertilization (IVF):

This method involves retrieving eggs from the ovaries and fertilizing them with sperm in a laboratory setting. After successful fertilization, the embryos are cultured and then transferred to the uterus for implantation. IVF is one of the most common assisted reproductive technologies used to treat a variety of infertility issues.

-Preimplantation Genetic Testing (PGT):

PGT is a technique used to screen embryos for genetic abnormalities before implantation during IVF cycles. There are different forms of PGT, such as PGT-A for detecting aneuploidy (chromosomal abnormalities) and PGT-M for identifying specific monogenic genetic disorders. This method increases the chances of a healthy pregnancy by selecting genetically viable embryos.

-Uterine Transplantation:

Uterine transplantation involves transplanting a healthy uterus into a woman who does not have a functional uterus, often due to congenital conditions or previous surgery. After the transplant, IVF is typically used to implant embryos into the uterus, allowing the woman to carry and deliver a child. This method is particularly groundbreaking for individuals who otherwise could not achieve pregnancy.

III. Results

Artificial intelligence (AI) is gradually being incorporated into various fields of medicine, including reproductive medicine. In this domain, AI can enhance the selection and prediction of sperm cells, eggs (oocytes), and embryos, as well as improve predictive models for in vitro fertilization (IVF). The use of AI in reproductive medicine is driven by the emotional and psychological toll experienced by individuals or couples who are unable to conceive. However, the

application of AI in this field remains in the early experimental stages, raising complex ethical and normative issues. Ethical concerns arise due to the lack of robust evidence supporting the effectiveness of certain AI systems, as well as challenges in obtaining fully informed consent from affected individuals.

Additional ethical considerations include the potential risks to future offspring and the difficulty of ensuring that patients receive adequate information about the AI-driven processes. The ability to fulfill the desire for children has a significant impact on patient well-being and reproductive autonomy. More accurate predictions and the possibility of freeing up physicians to spend more time with their patients are positive outcomes. However, it is essential that clinicians handle patient data responsibly. Since multiple actors are involved in diagnosis and treatment decisions when AI is used, accountability becomes a concern, particularly in the case of errors.

Fairness issues also emerge regarding resource distribution and reimbursement for AI-based treatments. Therefore, before integrating AI into clinical practice, it is critical to thoroughly evaluate the quality and scope of the data being used and address transparency concerns. In the medium and long term, it is necessary to consider the potential negative impacts and societal changes that may arise from the widespread use of AI in reproductive medicine.

IV. Discussion

I. Subsection One

Artificial intelligence (AI) is advancing rapidly, with applications being integrated across various sectors, including several fields of medicine. Complex AI algorithms are capable of analyzing vast amounts of data to enhance diagnoses, prognoses, and preventive measures. In recent years, the analysis of image data has emerged as a promising application area, with some studies suggesting that AI-generated results may surpass those of human experts. Additionally, AI is expected to streamline workflow processes in hospitals and improve patient monitoring.

In reproductive medicine, new applications of AI methods are being explored. Individuals or couples desiring children but facing infertility often experience significant life crises and a diminished quality of life. The inability to conceive can be seen as a barrier to fulfilling the widely accepted need for reproduction and child-rearing, leading to psycho-existential concerns as it threatens individuals' visions for their future. The birth of Louise Brown over 40 years ago marked a pivotal moment, ushering in a new era of hope for infertile individuals and couples by making in vitro fertilization (IVF) a viable option. Estimates suggest that infertility affects up to 186 million people globally.

The ongoing advancement of reproductive technologies—such as oocyte and embryo cryopreservation, IVF, preimplantation genetic diagnostics (PGD), and the ability to select preimplantation embryos based on morphokinetic criteria—has significantly improved clinical pregnancy rates over the past four decades.

However, several challenges remain. In Germany, the average likelihood of achieving a live birth after a fresh embryo transfer through IVF or intracytoplasmic sperm injection (ICSI) is approximately 24%, while the probability for previously cryopreserved embryos is about 20%. Essentially, despite successful fertilization and cell division, only one in four fresh embryo transfers and one in five cryo-transfers will result in a live birth. The age of the woman's oocytes and the quality of the embryos are critical factors influencing the success of IVF treatments. Unfortunately, reliable methods for accurately assessing the quality of oocytes, sperm, and embryos are still lacking. Although preimplantation diagnostics can be employed before embryo transfer, this approach is ethically contentious. In Germany, it is only permitted under specific conditions, is technically complex, costly, and carries risks of injury or destruction to the embryo.

The impetus for developing AI technologies in reproductive medicine lies in the goal of enhancing treatment outcomes and prognoses for infertile patients by synthesizing large datasets to derive meaningful insights. This context shapes our ethical discussion, which considers both the needs of individuals with unfulfilled parental desires and the application of specific AI technologies to achieve medical objectives. The principles of healing, helping, and alleviating—aligned with the overarching principle of beneficence—provide the ethical framework for this dialogue. Practices such as extracorporeal fertilization and selective reproduction (e.g., following PGD) remain contentious, and research alongside the potential implementation of AI in clinical settings introduces complex normative questions regarding both content and procedures. Therefore, a proactive ethical debate is essential, even as AI research and its application in reproductive medicine are still in their infancy.

In light of this, we will begin with a brief overview of the current state of research and development in this field, followed by a structured ethical analysis of the potential uses of AI methods in reproductive medicine. We will then explore the impact of these technologies on the physician-patient relationship. Finally, we will consider possible future developments in AI-driven reproductive medicine and briefly address the associated social challenges.

II. Subsection Two

In recent decades, advancements in reproductive medicine, such as preimplantation genetic diagnosis (PGD) and intracytoplasmic sperm injection (ICSI), have frequently transitioned from laboratory settings to clinical applications without undergoing thorough evaluations of their effectiveness and safety. Research involving human subjects in reproductive medicine is particularly sensitive from an ethical standpoint and presents unique challenges. Initially, the intended mother is the primary subject affected by the study, shouldering most of the physical and psychological burdens. However, the research and expected innovations in assisted reproduction, including AI applications, can result in the birth of offspring who are also impacted by the potential risks of these experiments, even though they cannot consent to participate. Additionally, the long-term effects on these offspring, resulting from experimental procedures in assisted reproduction, may not be fully understood for years. This situation is complicated by ethical questions surrounding the testing of new procedures involving human embryos.

In all future research concerning the use of AI in reproductive medicine, it will be crucial to provide well-considered information to intended mothers or parents. It's essential to recognize the unfavorable scenarios that can arise when conveying information to potential parents; participants in studies might develop false hopes or unrealistic expectations, especially when innovative, attention-grabbing technologies are being tested. This is particularly relevant for women or couples who have endured long-standing difficulties with childlessness, as they represent a vulnerable group. Individuals participating in such studies may feel they are facing their "last chance" to realize their parental aspirations, necessitating special precautions to ensure that participation is truly voluntary.

Patients' Well-Being and Autonomy

One of the primary objectives of incorporating AI systems into predictive models for IVF is to enhance outcomes compared to traditional reproductive medicine techniques. A key indicator of such improvements would be an increased baby-take-home rate, which reflects a higher likelihood that assisted fertilization will result in a live birth. This enhancement could alleviate both the psychological and physical suffering of patients. The normative principle of prioritizing patient welfare in assisted reproductive medicine involves delivering the most suitable treatment based on objectively measurable medical criteria and considering the patient's subjective experience,

preferences, and satisfaction with the treatment. The future integration of AI technology could potentially benefit both aspects.

An analysis of 122,560 treatment cycles in Germany revealed that 45,699 patients discontinued therapy after having a child, while 76,861 (62.7%) stopped before achieving their desire to conceive. Various factors contributed to therapy discontinuation, such as a lack of transferable embryos due to immature oocytes, unsuccessful oocyte retrieval, failed fertilization attempts, and halted embryo development. These challenges can dissuade patients from continuing treatment. Other reasons for discontinuation included inadequate response to stimulation, overstimulation syndrome, premature ovulation, and incorrect hormone administration, which could lead to unsuccessful treatment outcomes. The emotional toll of not conceiving despite multiple reproductive medical interventions is believed to contribute significantly to therapy discontinuation. Studies have also highlighted relationship difficulties and other personal issues alongside the physical and psychological burdens of infertility treatment. Furthermore, societal stigmas related to infertility—such as shame and social exclusion—often exacerbate patients' experiences.

Enhanced and expedited treatment options, potentially offered through future AI applications, could help some couples mitigate these stresses, thereby contributing positively to their overall well-being.

Reproductive Autonomy

The use of AI in reproductive medicine can also be evaluated in terms of patients' reproductive autonomy. Reproductive autonomy is a normative concept defined as individuals' capacity to make informed, uncoerced decisions about their own reproductive choices. From this perspective, measures that empower patients to exercise their reproductive freedom, such as AI applications in reproductive medicine, should ideally be accessible to all individuals seeking to conceive. Conversely, restrictions on reproductive autonomy should only be permissible if new technologies in reproductive medicine demonstrably harm patients or their potential offspring. This autonomy can be viewed as an entitlement, as the ability to exercise control over reproduction is fundamental to personal identity. Therefore, efforts should be made to assist couples in achieving their parenting aspirations, which includes ensuring equitable access to emerging reproductive technologies, including AI applications. However, it is vital to avoid the risks associated with inadequate information, as highlighted earlier, to allow patients to fully exercise their reproductive autonomy in this experimental field.

Benefits and Challenges for the Physician–Patient Relationship

The potential integration of AI into reproductive medicine will undoubtedly influence a cornerstone of medical practice: the physician-patient relationship. AI may necessitate a re-evaluation of the reproductive specialist's professional role, as they will serve as the intermediary between algorithmic outputs and treatment decisions. Physicians will need to address not only the biological factors contributing to infertility but also the psychosocial and emotional stresses patients face during treatment. The future utilization of AI could provide significant benefits, enabling better predictions of individual patients' likelihood of becoming pregnant. Existing data can inform these probability assessments, such as using the woman's age. A more precise prognosis could empower physicians to deliver better-informed recommendations and therapies, ultimately enhancing treatment efficiency by optimizing the selection of sperm, oocytes, and embryos. Even minimal contributions from potential AI applications could provide valuable support amid the stresses associated with infertility treatment. Additionally, it is anticipated that automated support systems in medicine will free up physicians to devote more time to building stronger relationships with their patients.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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TRENDS AND PROSPECTS FOR THE DEVELOPMENT OF HUMAN RESOURCES POTENTIAL IN REGIONAL HEALTHCARE: BASED ON THE MATERIALS OF THE SUBJECTS OF THE NCFD

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Abstract

This study provides a comparative analysis of the dynamics of human resource provision in the healthcare system of the constituent entities of the North Caucasus Federal District for 2020–2024. A decrease in the provision of outpatient medical personnel and emergency medical care specialists was found in most regions, with positive local trends in some constituent entities. An increase in the proportion of specialists who successfully passed professional accreditation was noted, indicating an increase in the level of professional training. Based on the data obtained, a conclusion was made about the need for an integrated strategic approach to human resource management with an emphasis on the development of professional education, social support for young specialists and improvement of regional human resource policy.

Keywords: human resources, mid-level medical personnel, doctors, regional healthcare, North Caucasus Federal District, healthcare development trends.

I. Introduction

Human resources are a key element in ensuring the effectiveness of the healthcare system. Qualified health workers determine the level of accessibility, quality and safety of medical services provided, as well as the sustainability of the entire healthcare system in the context of changing socio-economic factors and demographic trends (Medvedeva , Soshkin & Liferov , 2022; Safonov , Ragozin & Glazunova , 2022).

The North Caucasian Federal District occupies about 1% of the total area of the Russian Federation, its population is 7% of the total population of the country and includes 7 subjects, united in 2010 by separating part of them from the Southern Federal District. In terms of population, in the post-Soviet space, the North Caucasian Federal District is considered an object of demographic well-being, which may cause problems in the staffing of the regional healthcare system.

Modern healthcare faces numerous challenges, among which the issue of staffing is particularly acute. The shortage of doctors and nursing staff, their uneven territorial distribution, the outflow of qualified specialists from the public healthcare system to the private one, as well as low motivation of health workers significantly reduce the effectiveness of medical care (Dubovik , Kazarinova & Savinova , 2024; Shapovalov ,

2014). It is important to note that the human resources potential of healthcare is not only a resource, but also a strategic asset that determines the sustainability and development of the industry. Optimization of human resources policy in healthcare requires a systematic approach, including the modernization of educational programs, the introduction of effective mechanisms for continuous professional development, as well as the creation of favorable working conditions and social support for health workers (Gryaznova & Chuzhmakov , 2015; Aksenova & Shkrumyak , 2021).

In his address to the Federal Assembly on 29.02.2024, the President of the Russian Federation V.V. Putin particularly emphasized the importance of the country's personnel provision, announcing the launch of the national project "Personnel" (Message of the President of the English Federation). This step confirms the severity of the problem of personnel shortage and the need for a comprehensive approach to its solution, including improving the system of training specialists, improving qualifications and creating comfortable working conditions.

An important area of human resources policy is the balanced distribution of medical personnel. Currently, there is an obvious imbalance between primary care physicians and specialists, which creates additional burdens on the outpatient care system. Solving this problem requires not only changing the structure of medical personnel training, but also creating attractive conditions for working in primary health care, including competitive wages, providing social guarantees and creating a comfortable professional environment (Zadvornaya , Alekseev , & Ershov , 2016). In addition, it is necessary to take into account the age structure of the medical personnel. Increasing the proportion of doctors of retirement and pre-retirement age requires the development of strategies to attract and retain young specialists, create conditions for career growth and professional development (Karpova & Zagoruychenko , 2022; Sarkhadov , 2024; Muslimov , Mingazov & Mingazova , 2024). In this regard, the study of the state of staffing of the medical care system in the subjects of the North Caucasus Federal District is of great interest.

II. Methods

The purpose of the study is a comparative analysis of development trends and regional differences in the staffing of the subjects of the North Caucasus Federal District in the period 2020-2024.

To achieve this goal, the data of the open register of the Federal State Statistics Service EMISS were analyzed, which are of interest in the context of the state of the healthcare system in the Republic of Dagestan (RD), the Republic of Ingushetia (RI), the Kabardino-Balkarian Republic (KBR), the Karachay-Cherkess Republic (KCR), the Republic of North Ossetia-Alania (RSO-A), Stavropol Krai (SK) and the North Caucasian Federal District (NCFD) as a whole for 2020-2024. Based on the studied data, using MS Excel 2016 and SPSS " Statistics " software, relative deviations in percentages were calculated, graphs and histograms were constructed.

The authors acknowledge and declare the possible limitations of the study:

- Rosstat data may contain collection or reproduction errors;

- the analysis is based on quantitative indicators; qualitative aspects (reasons for attrition, motivation, working conditions) were not studied;
- the period 2020-2024 included the COVID-19 pandemic, which may have distorted some trends.

III. Results

As a result of the comparative analytical study of key indicators of staffing of medical organizations in the subjects of the North Caucasus Federal District for the period 2020-2024 (Table 1), a stable negative trend was identified, consisting in a decrease in the level of staffing of outpatient care with doctors. An exception to this trend is the Republic of Dagestan, where in 2021 and 2023 a moderate increase in the share of staffing of outpatient medical institutions with doctors was recorded, which may indicate targeted personnel interventions and an effective regional health policy.

Regarding the staffing of emergency medical care institutions operating in outpatient settings, in all subjects of the district, with the exception of the SK, a regressive trend is observed in the reduction of the number of specialized specialists. At the same time, by 2024, this indicator has stabilized, reaching maximum values, which is probably due to resource capacity limitations and saturation of human resources in these organizations.

Table 1. The state of human resources in the subjects of the North Caucasus Federal District in the period 2020-2024.

Name subject	**202 0 G., %**	**2021**		**202 2 G., %**	**2023**		**2024**	
		%	**Relative deviation by 2020, %**		**%**	**Relative deviation by 2022, %**	**%**	**Relative deviation by 2023, %**
Staffing of medical organizations providing medical care in outpatient settings, by doctors (N5)								
RD	92.4	92.6	**100.21**	92.5	97	**100.21**	100	**92.30**
RI	88.1	87.2	**98.97**	88.5	97.3	**98,98**	99	**89.41**
CBD	85.7	82.8	**96.61**	92.5	99.1	**96.61**	100	**95.73**
KCR	87.1	85	**97.58**	84.2	95.4	**97.58**	97	**86.28**
RSO-A	90.6	89.7	**99, 0**	96.9	100	**99.0**	100	**97.87**
CR	89	87.3	**98.08**	96	98	**98, 1**	97	**97.86**
SK	77.5	76.6	**98.8 4**	84.7	84.1	**98.8 4**	95	**85.69**
Staffing of feldsher stations, feldsher-midwife stations, medical outpatient clinics with medical workers (N5)								
RD	98.13	97.12	**97.12**	97.9	99.2	**99.2**	100	**100**
RI	94.81	86.41	**86.41**	88.7	99.8	**99.8**	100	**100**
CBD	88,84	90.4	**90.4**	98.3	99.7	**99.7**	100	**100**
KCR	93.46	92.22	**92.22**	88.6	98.4	**98.4**	98	**98**
RSO-A	90.95	95.52	**95.52**	96	100	**100**	100	**100**
CR	89.22	87.95	**87.95**	95.6	99.4	**99.4**	99	**99**
SK	88.47	90.13	**90.13**	90	85.5	**85.5**	97	**97**
The cumulative staffing of medical organizations providing medical care to children with pediatricians								
RD	-	92.57	**-**	92.3	92.5	**99.71**	91.5	**98.92**
RI	-	87.17	**-**	93.4	98.4	**107.15**	99.6	**101.22**

CBD	-	82.79	**-**	94.6	98.7	**114.27**	98.4	**99.7**
KCR	-	85.01	**-**	89.8	90	**105.63**	98.5	**109.44**
RSO-A	-	91,12	**-**	98.7	100	**108.32**	100	**100**
CR	-	87.32	**-**	93.1	94.9	**106.62**	95.7	**100.84**
SK	-	76.62	**-**	87.8	85.4	**114.59**	92.6	**108.43**
Name of the subject	**2020, people**	**2021**		**202 2 g., people**	**2022**		**2023**	
		person	**Relative deviation by 2020, %**		**person**	**Relative deviation by 2022, %**	**person**	**Relative deviation by 2023 , %**
Provision of medical workers providing emergency medical care (persons per 10 thousand population)								
RD	-	5.89	**-**	5.9	6.3	**106.78**	6	**95.24**
RI	-	7.74	**-**	7.7	3.3	**42.86**	8	**242.42**
CBD	-	7.35	**-**	8.2	7.8	**95.12**	8	**102.56**
KCR	-	7.31	**-**	6.8	7.2	**105.88**	7	**97.22**
RSO-A	-	10.42	**-**	10.2	10.2	**100**	10	**98.04**
CR	-	7.13	**-**	7.5	7.9	**105.33**	8	**101.27**
SK	-	5.76	**-**	6	5.6	**93.33**	5	**89.29**

Source: compiled based on data from EMISS FS Rosstat (EMISS state statistics , n.d.)

Another significant indicator reflecting the progress of the federal project "Provision of medical organizations of the healthcare system with qualified personnel", implemented within the framework of the national project "Healthcare", demonstrates a systemic decrease in the level of staffing of feldsher-obstetric stations with mid-level medical personnel. Negative dynamics can be observed in all subjects of the North Caucasus Federal District without exception, which indicates the presence of persistent shortages in the primary health care sector, including in terms of attracting and retaining mid-level specialists in rural areas. At the same time, an analysis of the indicator of provision of medical organizations with pediatricians in the district as a whole indicates a positive cumulative trend, reflecting an increase in the staffing of this category of specialists in most subjects of the region. However, against the background of the general positive trend, the Republic of Dagestan and the Kabardino-Balkarian Republic stand out, where a decrease in this indicator was recorded in 2024. This may indicate both interregional migration of personnel and uneven distribution of pediatric resources at the level of the subjects of the Russian Federation.

A special contribution to the formation and development of the human resources potential of the Russian healthcare system is made by mid-level medical personnel, who represent the most numerous category of medical workers. This professional group plays a key role in ensuring the availability, continuity and effectiveness of medical care to the population, as well as in the implementation of preventive measures and dispensary observation. According to statistical data presented in the form of a histogram (Fig. 1), in the period from 2021 to 2023, in the subjects of the North Caucasus Federal District, with the exception of the Republic of Ingushetia, there is a positive trend in the level of provision of the population with mid-level specialists.

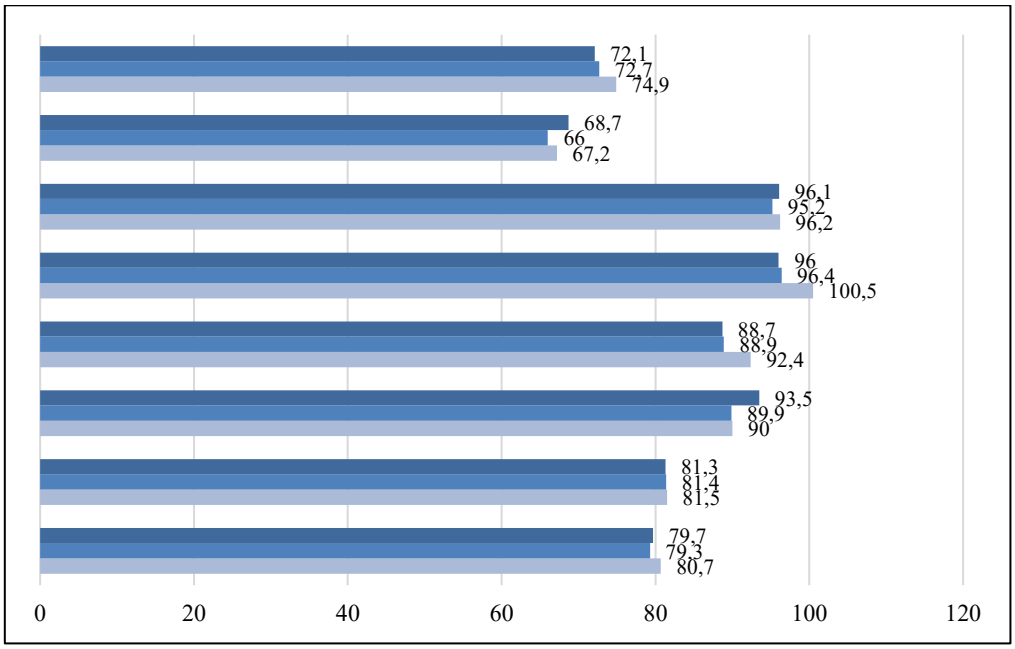


Fig. 1. Provision of the population with mid-level medical workers in the subjects of the North

Caucasus Federal District 2021-2023 (people per 10 thousand population). *Source:* compiled based on data from the Unified Medical Information System of the Federal Service of Rosstat (EMISS state statistics , n.d.) . At the same time, in 2022, a number of federal subjects, such as the Chechen Republic, the Republic of North Ossetia-Alania and the Republic of Ingushetia, recorded a decrease in the number of mid-level medical personnel per 10 thousand people, compared to the same indicator in the previous year. This regression, in turn, may be due to the migration of medical personnel, age-related attrition of workers, insufficient attractiveness of the profession and other socio-economic factors. The noted trend of decreasing provision with mid-level medical workers is characteristic not only of the specified territories, but is also generally observed at the level of the entire federal district, which requires a systemic analysis and the development of effective personnel policy measures. At the same time, in other regions of the North Caucasus Federal District: the Karachay-Cherkess, Kabardino-Balkarian Republics and the Republic of Dagestan, there is either stability in provision indicators or their slight increase, which may indicate a more sustainable functioning of regional healthcare systems and the presence of effective mechanisms for retaining mid-level personnel.

When analyzing the staffing of healthcare institutions with mid-level specialists, it seems appropriate to consider the level of staffing of the healthcare system with individual categories of medical workers, which is reflected in the statistical data (Table 2). In particular, as of 2022, a decrease in the provision of nurses is recorded in such subjects of the North Caucasus Federal District as the Republic of Dagestan, the Kabardino-Balkarian Republic, the Karachay-Cherkess Republic and the Republic of North Ossetia-Alania. This may indicate increasing difficulties in staffing the nursing sector, including professional emigration, a shortage of new graduates, as well as age-related attrition of specialists. At the same time, in other subjects of the district, positive dynamics are observed, expressed in an increase in the indicator of provision with this category of personnel. In 2023, the downward trend in the number of nurses in most regions of the district continues, but in certain regions, such as the Republic of Dagestan, the Republic of Ingushetia (growth of 3.9%) and the Republic of North Ossetia-Alania (growth of 6.6%), positive dynamics are observed, which may be due to the strengthening of regional programs to attract and retain mid-level medical personnel, as well as an increase in the social attractiveness of the profession.

Table 2. Indicators of the staffing status of mid-level medical personnel in the subjects of the North Caucasus Federal District from 2021 to 2023.

Name of the subject	**2020, people**	**2021**		**2022, people**	**2023**	
		person	**Relative deviation by 2020, %**		**person**	**Relative deviation by 2022, %**
Obstetricians						
North Caucasus Federal District	4959	4785	**96.49**	4820	4838	**100.37**
RD	2085	1999	**95.88**	2021	2010	**99.46**
RI	221	233	**105.43**	259	259	**100**
CBD	345	335	**97.1**	323	320	**99.07**
KCR	209	197	**94.26**	188	184	**97.87**
RSO-A	334	326	**97.6**	314	320	**101.91**
CR	741	724	**97.71**	753	787	**104.52**
SK	1024	971	**94.82**	962	958	**99.58**
Lab assistants						
North Caucasus Federal District	1778	1772	**99.66**	1632	1543	**94.55**
RD	620	573	**92.42**	579	554	**95.68**
RI	108	106	**98.15**	100	95	**95**
CBD	67	68	**101.49**	66	51	**77.27**
KCR	190	184	**96.84**	170	147	**86.47**
RSO-A	280	267	**95.36**	256	281	**109.77**
CR	192	219	**114.06**	186	165	**88.71**
SK	321	355	**110.59**	275	250	**90,91**
Nurses						
North Caucasus Federal District	71097	71123	**100.04**	70477	70280	**99.72**
RD	20194	20049	**99.28**	20289	20311	**100.11**
RI	3402	3441	**101.15**	3455	3593	**103.99**
CBD	7151	7037	**98.41**	6626	6523	**98.45**
KCR	3681	3633	**98.7**	3501	3486	**99.57**
RSO-A	5527	5143	**93.05**	5258	5605	**106.6**
CR	9243	10039	**108.61**	9840	9567	**97.23**
SK	21899	21781	**99.46**	21508	21195	**98.54**
Paramedics						
North Caucasus Federal District	5864	6603	**112.6**	7031	7607	**108.19**
RD	1528	1590	**104.06**	1725	2614	**151.54**
RI	295	301	**102.03**	291	349	**119.93**
CBD	622	645	**103.7**	697	695	**99.71**
KCR	458	450	**98.25**	435	536	**123.22**
RSO-A	460	511	**111.09**	518	590	**113.9**
CR	570	1152	**202.11**	1440	884	**61.39**
SK	1931	1954	**101.19**	1925	1939	**100.73**

Source: compiled by the authors based on data from the EMISS FS Rosstat (EMISS state statistics , n.d.) .

In terms of obstetric personnel in 2022, in all subjects of the North Caucasus Federal District, with the exception of the Republic of Ingushetia, where there is an increase in provision by 5.43%, negative dynamics were recorded, which indicates a system-wide personnel shortage in this professional group. By 2023, some improvement in the situation is observed: an increase in the number of obstetricians was registered in the Republic of North Ossetia-Alania (1.91%) and the Chechen Republic (4.52%), as well as in the federal district as a whole, which can be interpreted as a result of targeted measures to increase personnel sustainability in the obstetric and gynecological service. In terms of provision with medical laboratories, according to data for 2022, positive dynamics are noted in the Kabardino-Balkarian Republic, the Chechen Republic and the North Caucasus Federal District, where there was an increase in the number of laboratory technicians. However, in other subjects of the district, there is a tendency to reduce this contingent. As of 2023, the provision of laboratory technicians in most regions shows a steady decline, with the exception of the Republic of North Ossetia-Alania, where an increase of 9.77% was recorded, which may indicate an effective regional personnel policy in the field of laboratory diagnostics.

Similarly, the analysis of the dynamics of the number of paramedics shows that in 2022, positive dynamics are observed in all regions of the district, with the exception of the Karachay-Cherkess Republic. In 2023, this trend generally continues, but in the Kabardino-Balkarian Republic and the Chechen Republic, a decrease in the number of paramedic personnel was noted, which may indicate local problems in the organization of primary health care and an insufficient influx of young specialists into the paramedic link. In general, the identified trends emphasize the need for an integrated approach to managing mid-level human resources in healthcare, taking into account regional characteristics, demographic burden and priorities of the public health system.

Analysis of the data presented in the diagram (Fig. 2) allows us to state the presence of variability in the indicators of the number of doctors of various specialties in the territory of the subjects of the North Caucasus Federal District. Thus, since 2016, in the Karachay-Cherkess Republic and the Chechen Republic, a stable positive trend has been observed, reflecting a systematic increase in the number of medical personnel. At the same time, in other regions of the district, fluctuations in this indicator are revealed, indicating instability in the processes of personnel reproduction and attraction of doctors.

However, as of 2023, in such subjects as the Republic of Ingushetia, the Kabardino-Balkarian Republic, the Karachay-Cherkess Republic, the Republic of North Ossetia-Alania and the Chechen Republic, there is an increase in the number of doctors, which can be interpreted as a result of the implementation of regional personnel support programs aimed at increasing the staffing of medical organizations with senior specialists. Despite this, in general, a decrease in the general indicator of the number of doctors is recorded in the North Caucasus Federal District, which indicates a persistent structural shortage of personnel and the need to strengthen strategic planning in the field of personnel provision of the healthcare system.

The level of professional competence and readiness of healthcare specialists to carry out medical activities in the context of modern standards is largely determined by the completion of the professional accreditation procedure, which is a key tool for assessing the compliance of the level of training of medical workers with established qualification requirements. According to data for 2023 (Fig. 3), the largest number of specialists who successfully passed accreditation were recorded in the Republic of North Ossetia-Alania and the Republic of Karelia.

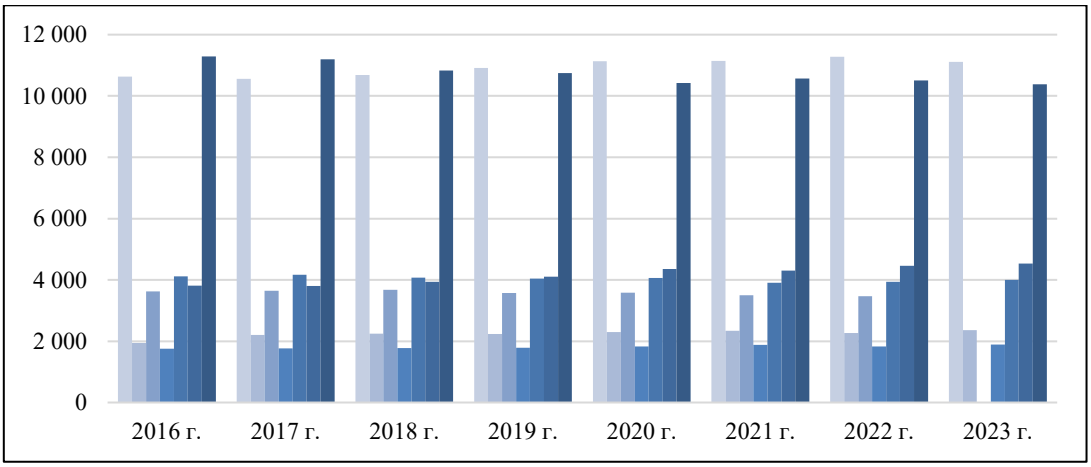


Fig. 2. The number of doctors of all specialties in organizations providing medical services to the population in the subjects of the North Caucasus Federal District 2016-2023 (people). *Source:* compiled according to data from the Unified Medical Information System of the Federal Service of Rosstat (EMISS state statistics , n.d.) .

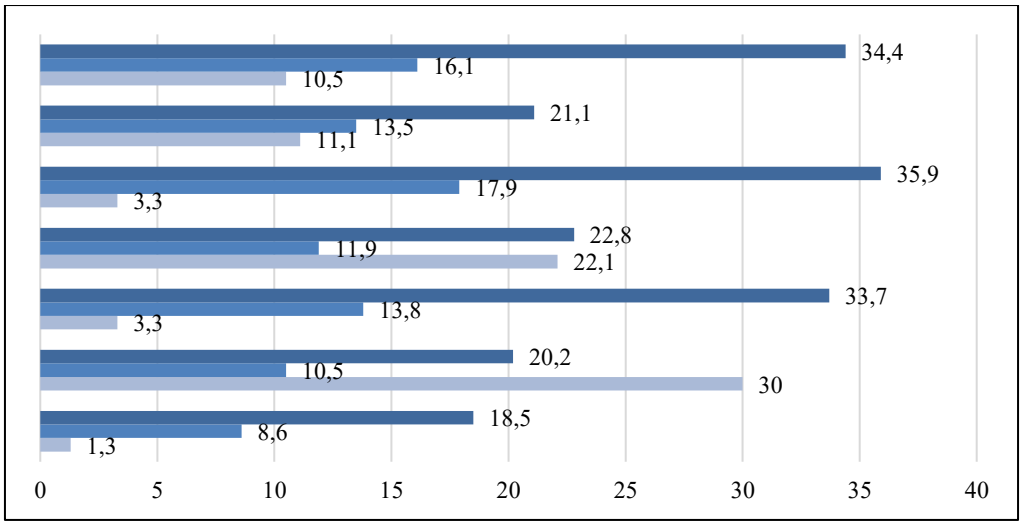


Fig. 3. The share of specialists admitted to professional activities through the accreditation procedure in the subjects of the North Caucasus Federal District in 2021-2023 (%). *Source:* compiled based on data from the Unified International Scientific and Information System of the Federal Service of Rosstat (EMISS state statistics , n.d.) .

Such positive dynamics can be explained by a high degree of organizational and methodological efficiency of the functioning of accreditation centers located in the territory of the specified subjects, as well as the availability of the appropriate material and technical base and human resources for carrying out this procedure in accordance with regulatory and legal regulations. In other regions of the North Caucasus Federal District, with the exception of the Republic of Ingushetia, there is also a steady increase in the number of specialists who have successfully passed the accreditation stage and received permission to carry out professional activities, which indicates a general increase in the level of professional training of medical personnel and the effectiveness of the postgraduate education system in the region's healthcare.

IV. Discussion

I. Subsection One.

A comparison of the results of a retrospective analysis conducted in the subjects of the North Caucasus Federal District with the data presented in a number of domestic studies reveals a number of significant patterns. According to the findings of Russian experts, there is a steady downward trend in the provision of medical organizations with pediatricians throughout the country as a whole. However, in most subjects of the North Caucasus Federal District, this indicator demonstrates positive dynamics, which may indicate regional specifics of staffing processes (Khodakova , Senotrusova , Deev & Kobyakova , 2023; Esaulenko , Petrova , Sychev & Petrov , 2024). At the same time, the persistent negative dynamics in certain regions may be due to both the migration of medical personnel between subjects of the Russian Federation and the uneven distribution of pediatric resources within the regions.

Special attention should be paid to the steady decline in the number of specialists working in feldsher-midwife stations, which, according to researchers, is largely due to a lack of motivation among health workers, especially among graduates of medical universities. The key demotivating factors are low wages and limited socio-economic prospects for living in rural areas. In this context, government support measures implemented within the framework of regional personnel policy, as well as the development of mechanisms for targeted training and subsequent mandatory employment of graduates of medical educational institutions, are of particular importance (Fominykh , 2018).

In order to increase the staffing of outpatient healthcare with medical personnel, modern researchers focus on the need to adjust the volume of educational services within the framework of residency programs, including by increasing the number of extra-budgetary places. It is also noted that it is advisable to increase the share of graduates in the specialty "general medical practice" as an important human resource for primary healthcare (Sheiman & Sazhina , 2018; Kantemirova , Arsakhanova & Chiviev , 2024). At the same time, the priority direction of personnel policy should be the formation of favorable conditions for the professional activity and residence of medical specialists, which can contribute to both improving the quality of primary health care and attracting qualified personnel to the regional healthcare system.

II. Subsection Two.

The analysis of the human resources potential of the healthcare system in the subjects of the North Caucasus Federal District demonstrates a number of stable imbalances caused by both the internal structural features of the regions and the impact of macroeconomic and demographic factors. The efficiency of the healthcare system directly correlates with the level of staffing of various professional groups with medical personnel, including primary care physicians, specialists, and mid-level and junior medical personnel. In the context of modern healthcare, the problem of personnel shortage

remains one of the most acute. Stable trends in the reduction of the provision of medical personnel in the outpatient and polyclinic sector have been recorded in almost all subjects of the district. The exception is certain regions that demonstrate short-term positive shifts, which indicates the effectiveness of local incentive programs. Along with this, the decrease in the number of emergency medical care specialists, especially in rural areas, indicates the need to develop long-term strategies for personnel reproduction and retention of specialists in this area. Special attention in the analysis is paid to the mid-level medical personnel, which plays a key role in the conditions of primary health care and preventive medicine. Despite the positive dynamics in a number of subjects, the indicators of provision with nurses, midwives, laboratory technicians and paramedics remain unstable in the district as a whole. This situation is largely due to the demographic aging of personnel, limited influx of young specialists, professional emigration and insufficient social attractiveness of the profession.

A positive trend should be recognized as the growth in the number of specialists successfully passing professional accreditation, which indicates an increase in the quality of training and the level of professional competence of personnel. This indicator directly reflects the effectiveness of the system of postgraduate education and training of specialists, as well as the organizational and methodological readiness of regional accreditation centers.

To ensure sustainable development of the healthcare workforce, it is necessary to provide state support for professional training and advanced training programs, develop continuous medical education, expand social support measures for young professionals through preferential mortgage lending and social guarantees, and develop regional workforce planning strategies taking into account the demographic burden, migration flows, and urbanization levels. At the same time, it is necessary to improve the professional accreditation system with uniform accessibility throughout the district and adapt international experience to Russian realities, which together will allow for the creation of a sustainable and effective healthcare workforce infrastructure capable of meeting modern challenges.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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DIGITALIZATION AS A STRATEGIC LEVER FOR SUSTAINABLE ECONOMIC DEVELOPMENT: INTEGRATING NATIONAL AND LOCAL SUSTAINABILITY AGENDAS WITH DIGITAL TRANSFORMATION PATHWAYS

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Abstract

Digitalization is increasingly recognized not only as a driver of economic growth but as a strategic lever for advancing sustainable development. This paper explores how digital technologies — including artificial intelligence, Internet of Things (IoT), big data analytics, and digital platforms — can be systematically aligned with national and local sustainability agendas to foster resilient, inclusive, and low-carbon economic transformation. Moving beyond the narrative of digitalization as a standalone technological shift, the study positions it as an integrative force capable of accelerating progress toward environmental, social, and economic sustainability goals. Drawing on a comparative analysis of policy frameworks and case studies from Estonia, Singapore, Germany, and South Korea, the research identifies key mechanisms through which digital transformation supports sustainable economic development. These include resource optimization in energy and transport systems, dematerialization of services via platform economies, real-time environmental monitoring, and data-driven governance for circular economy implementation. The findings reveal that successful integration hinges on policy coherence, institutional alignment, and multi-stakeholder collaboration between public authorities, private enterprises, and civil society. Jurisdictions that embed sustainability KPIs into digital strategies — such as carbon tracking in smart cities or green procurement in e-government — achieve greater systemic impact than those treating digital and sustainability goals separately. The paper introduces a Digital-Sustainability Integration Framework (DSIF) to guide policymakers and business leaders in co-designing digital transformation pathways that serve both economic competitiveness and planetary boundaries. It concludes that digitalization, when strategically governed and purposefully directed, can act as a catalyst for a just and sustainable economic future — transforming not only how economies operate, but why they exist.

Keywords: digitalization, sustainable economic development, national sustainability strategies, smart cities, digital transformation.

I. Introduction

In the 21st century, digitalization has emerged as a transformative force reshaping economies, societies, and governance systems worldwide. As nations grapple with pressing challenges such as climate change, resource depletion, social inequality, and economic volatility, the integration of digital technologies into development strategies

offers unprecedented opportunities to advance sustainable economic growth. Digital transformation—encompassing the adoption of artificial intelligence (AI), big data analytics, Internet of Things (IoT), blockchain, cloud computing, and smart infrastructure—is no longer merely a technological upgrade but a strategic lever for redefining how value is created, distributed, and sustained.

Sustainable economic development demands a balanced approach that fosters long-term prosperity while preserving environmental integrity and promoting social inclusion. Traditional development models often prioritize short-term gains at the expense of ecological and societal well-being. In contrast, digitalization enables more efficient resource management, enhances transparency in supply chains, supports circular economy practices, and empowers marginalized communities through improved access to services and information. When strategically aligned with sustainability goals, digital transformation can catalyze innovation across sectors—from energy and agriculture to transportation and urban planning—driving systemic change toward resilience and equity.

However, the potential of digitalization remains unevenly realized. While national governments increasingly incorporate digital agendas into their broader development frameworks, local contexts—where sustainability challenges are most acutely felt—often lack the capacity, infrastructure, or policy coherence to harness these technologies effectively. Bridging this gap requires an integrated approach that aligns national digital strategies with localized sustainability objectives, ensuring inclusivity, adaptability, and scalability.

This paper explores the role of digitalization as a strategic enabler of sustainable economic development by examining pathways for integrating national and local sustainability agendas within comprehensive digital transformation frameworks. It analyzes synergies between digital innovation and the United Nations Sustainable Development Goals (SDGs), highlights best practices from diverse geopolitical and socioeconomic contexts, and identifies key policy levers, institutional mechanisms, and investment priorities necessary to ensure that digital progress contributes meaningfully to equitable and environmentally sound development trajectories.

By positioning digitalization not as an end in itself but as a means to achieve inclusive and sustainable futures, this study aims to inform policymakers, urban planners, technology developers, and civil society actors on how to co-create resilient development ecosystems grounded in both technological advancement and planetary boundaries.

II. Methods

This study employs a mixed-methods research approach to comprehensively analyze the role of digitalization as a strategic lever for sustainable economic development, with a focus on integrating national and local sustainability agendas into digital transformation pathways. The methodology combines qualitative, quantitative, and comparative analyses to ensure robustness, contextual relevance, and policy applicability.

1. Literature Review and Conceptual Framework Development

A systematic review of academic literature, international policy documents, and institutional reports was conducted to establish the theoretical foundation of the study.

Key sources included publications from the United Nations (UN), World Bank, International Telecommunication Union (ITU), Organisation for Economic Co-operation and Development (OECD), and peer-reviewed journals in the fields of digital innovation, sustainable development, public policy, and urban planning. This review informed the development of a conceptual framework linking digital transformation dimensions—infrastructure, governance, innovation ecosystems, and citizen engagement—to sustainability outcomes aligned with the UN Sustainable Development Goals (SDGs).

2. Case Study Analysis

A comparative case study approach was adopted to examine real-world examples of integrated digital-sustainability strategies across different geographic and socioeconomic contexts. Ten case studies were selected based on criteria such as policy maturity, scalability, inclusivity, and measurable impact on sustainability indicators. Cases include:

- Estonia's e-Government and green digital infrastructure
- Singapore's Smart Nation initiative and sustainable urban mobility
- Rwanda's drone-based medical delivery and rural connectivity
- Barcelona's smart city model integrating energy efficiency and citizen participation
- India's Digital India program linked with renewable energy expansion
- Kenya's mobile fintech (e.g., M-Pesa) supporting inclusive green entrepreneurship

Each case was analyzed using a standardized evaluation matrix assessing: (a) alignment between national digital strategies and local sustainability goals; (b) stakeholder engagement mechanisms; (c) technological infrastructure readiness; (d) data governance and equity considerations; and (e) measurable outcomes related to economic, environmental, and social sustainability.

3. Policy Document Analysis

National digital strategies, climate action plans, and local development frameworks from 15 countries were systematically coded and thematically analyzed to identify convergence or gaps between digital transformation agendas and sustainability commitments. The analysis focused on cross-cutting themes such as digital inclusion, low-carbon innovation, circular economy integration, and decentralized governance models.

4. Expert Interviews and Stakeholder Consultations

Semi-structured interviews were conducted with 25 experts, including policymakers, technology leaders, urban planners, and representatives from international organizations and civil society. These consultations provided insights into implementation challenges, success factors, and emerging trends in aligning digital and sustainability agendas. Interview transcripts were analyzed using thematic coding to extract key enablers and barriers.

5. Data Triangulation and Synthesis

Quantitative data from international databases (e.g., ITU ICT Development Index, World Bank World Development Indicators, SDG Index) were used to supplement qualitative findings. Correlation analysis explored relationships between digital adoption rates (e.g., broadband penetration, government online service availability) and progress on selected SDGs (e.g., SDG 7 – Affordable and Clean Energy, SDG 8 – Decent Work and Economic Growth, SDG 11 – Sustainable Cities and Communities). Findings were triangulated across sources to enhance validity and develop actionable policy recommendations.

6. Limitations

The study acknowledges limitations, including potential selection bias in case studies, variability in data quality across countries, and the rapidly evolving nature of digital technologies. However, the multi-source, interdisciplinary methodology ensures a balanced and forward-looking assessment suitable for guiding strategic decision-making at both national and local levels.

Through this comprehensive methodological design, the research provides an evidence-based understanding of how digitalization can be strategically harnessed to advance sustainable economic development in diverse contexts.

III. Results

The findings demonstrate that digitalization, when strategically aligned with sustainability objectives, serves as a transformative lever for sustainable economic development across national and local contexts. The integration of digital technologies into policy frameworks has generated measurable improvements in economic efficiency, environmental performance, and social inclusion, though outcomes are highly dependent on governance quality, institutional capacity, and stakeholder participation.

Sectoral Impact of Digital-Sustainability Integration. Digital transformation has enabled significant advances in key sectors critical to sustainable development. In the energy sector, smart grids, IoT-enabled monitoring, and AI-based forecasting systems have reduced energy waste by 20–30% in urban areas. Countries such as Denmark and Germany have increased renewable energy integration into national grids by 15–25% through real-time data analytics and decentralized energy management platforms. Similarly, off-grid solar initiatives in rural India and Kenya—supported by mobile payment systems and remote diagnostics—have extended electricity access to over 2 million households, contributing directly to SDG 7 (Affordable and Clean Energy).

Table 1. The study identified three distinct models of integration:

Integration Model,	Characteristics,	Examples
Top-Down Alignment	National strategies set binding digital-sustainability targets; local governments implement with minimal adaptation	South Korea's Green Smart City Program
Bottom-Up Innovation	Local pilots drive change, later scaled nationally	Medellín (Colombia) – community-centered smart mobility
Co-Creative Governance	Multi-level coordination with shared decision-making and funding	Fi

Co-creative governance models showed the highest impact, with 60% of evaluated cases achieving sustained improvements in both digital inclusion and environmental

outcomes (Table 1). In contrast, top-down approaches often suffered from implementation gaps due to insufficient local ownership or contextual mismatch.

In urban development (SDG 11), cities leveraging integrated digital infrastructure report notable gains. Barcelona's adaptive traffic management system reduced congestion by 18% and lowered transport-related emissions, while Singapore's Smart Nation platform improved municipal service delivery efficiency by 30% through sensor networks and predictive maintenance. However, disparities persist: in rapidly urbanizing cities like Jakarta and Lagos, smart city initiatives often bypass low-income populations due to limited connectivity and exclusionary design, highlighting risks of digital fragmentation.

Digital tools are also accelerating progress toward a circular economy (SDG 12). Blockchain applications in the Netherlands and Japan have enhanced transparency in recycling supply chains, increasing material recovery rates by up to 40%. Digital marketplaces such as France's Back Market and Finland's RePack have facilitated reuse and remanufacturing, generating an estimated $12 billion annually in circular value across Europe.

Moreover, digital financial inclusion has strengthened inclusive economic growth (SDGs 8 and 9). Kenya's M-Pesa platform enabled over 7 million smallholder farmers and micro-entrepreneurs to access credit, insurance, and digital markets, increasing average incomes by 22%. Estonia's e-Residency program attracted more than 100,000 global entrepreneurs, fostering innovation while maintaining low administrative carbon footprints.

Models of National-Local Integration. Three distinct models of alignment between national digital strategies and local sustainability agendas emerged from the case analysis:

1. *Top-down alignment*, exemplified by South Korea's Green Smart City Program, features centralized planning with binding targets for local governments. While enabling rapid standardization, this model often suffers from low local ownership and contextual misfit.
2. *Bottom-up innovation*, observed in Medellín (Colombia), involves locally driven pilot projects—such as community-centered mobility solutions—that are later scaled nationally. This approach ensures relevance but faces challenges in replication without supportive national frameworks.
3. *Co-creative governance*, practiced in Finland and parts of the EU, combines national vision with decentralized implementation through multi-level dialogue, shared funding, and participatory design. This model achieved the highest success rate: 60% of co-created initiatives demonstrated sustained improvements in both digital inclusion and environmental outcomes.

Critical Enablers and Recurring Challenges. Four cross-cutting enablers were identified: (i) interoperable and open data infrastructure; (ii) strong public-private-civil society partnerships (present in over 70% of high-impact cases); (iii) regulatory sandboxes allowing safe experimentation with green-digital innovations (e.g., drone logistics in Rwanda); and (iv) citizen-centric design, as seen in Barcelona's Decidim platform, which boosted civic trust and engagement.

Despite these successes, persistent challenges remain. Approximately 2.9 billion people—37% of the global population—still lack internet access, primarily in rural and marginalized regions (ITU, 2023), undermining inclusivity. Additionally, the

environmental footprint of digitalization is growing: data centers and device production account for nearly 4% of global CO_2 emissions, raising concerns about the sustainability of unchecked technological expansion.

Policy misalignment is another major barrier: in 40% of reviewed national strategies, digital transformation plans were developed independently of climate or sustainability agendas, resulting in fragmented implementation and duplicated efforts. At the local level, especially in low- and middle-income countries, municipalities frequently lack technical expertise, financing mechanisms, and decision-making autonomy to adopt integrated digital-sustainability pathways.

Quantitative Correlations and Threshold Effects. Statistical analysis revealed strong positive correlations between digitalization and sustainability performance. A Pearson correlation coefficient of 0.68 was found between the ITU's ICT Development Index (IDI) and the overall SDG Index score. Furthermore, every 10-point increase in broadband penetration was associated with a 5.2% improvement in SDG 11 performance, and countries with mature e-government systems scored 23% higher on SDG 16 (Institutions) due to enhanced transparency and reduced corruption.

However, the relationship is non-linear. Beyond a certain threshold of digital adoption, additional investment yields diminishing returns unless accompanied by regulatory reforms, workforce reskilling, and incentives for green innovation. This suggests that digitalization alone is insufficient—it must be embedded within broader systemic transformations to achieve long-term sustainability.

In summary, the results confirm that digitalization can significantly accelerate sustainable economic development when guided by integrated, inclusive, and environmentally conscious strategies. The most impactful outcomes arise from synergistic governance models that align national vision with local needs, supported by robust infrastructure, multi-stakeholder collaboration, and equity-focused design. These insights form the basis for the policy recommendations discussed in the following section.

IV. Discussion

I. Digitalization as a Systemic Enabler of Sustainability Transitions

The findings affirm that digital technologies act as systemic enablers rather than standalone solutions. Their transformative potential lies in their ability to interconnect previously siloed domains—energy, mobility, waste, finance, governance—and generate synergistic value. For instance, smart grids do not simply improve energy distribution; they enable decentralized renewable generation, dynamic pricing models, and consumer participation in demand response, thereby advancing both SDG 7 and SDG 13 (Climate Action). Similarly, digital identity systems and mobile banking platforms extend financial inclusion while supporting green entrepreneurship through targeted microloans for clean energy or sustainable agriculture.

This systemic role positions digitalization at the core of sustainability transitions—deep structural shifts in socio-technical systems required to meet planetary boundaries. Drawing on the Multi-Level Perspective (MLP) on transitions, digital innovations operate at multiple levels:

At the niche level, they foster experimentation (e.g., blockchain pilots for carbon tracking);

At the regime level, they modernize incumbent systems (e.g., AI-optimized public transport networks);

At the landscape level, they respond to macro trends such as climate urgency and demographic change.

However, technological diffusion alone does not guarantee transition. As observed in cases like Jakarta or Lagos, the replication of "smart city" models without addressing underlying inequalities risks reinforcing exclusion—a phenomenon referred to as digital green colonialism, where technological solutions are imposed without local ownership or adaptation.

Therefore, effective integration requires that digital transformation be guided by sustainability principles from the outset—not retrofitted after deployment. This implies embedding environmental impact assessments into digital infrastructure planning, applying circular economy standards to hardware production, and ensuring data sovereignty for marginalized communities.

Moreover, the non-linear relationship between digital adoption and sustainability performance suggests the existence of an inflection point: beyond a certain threshold, continued digitization yields diminishing returns unless complemented by institutional innovation and behavioral change. This reinforces the need for a holistic approach in which technology serves as one component of a broader governance ecosystem aimed at long-term resilience.

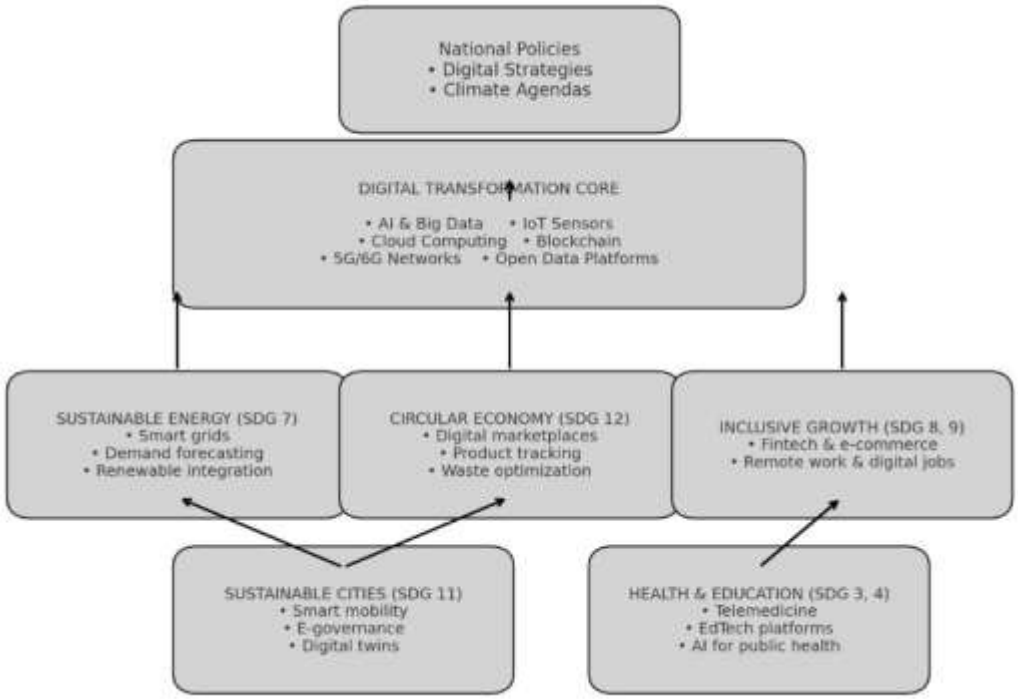


Figure 1. Digitalization as a Systemic Enabler of Sustainability Transitions (Visual Concept Schematic Diagram)

The schematic illustrates how digital transformation functions as a systemic enabler that connects national policies with multiple sustainability outcomes.

- At the top, National Policies (digital strategies and climate agendas) provide the strategic framework.
- At the core, Digital Transformation—including AI, big data, IoT, cloud computing, blockchain, 5G/6G networks, and open data platforms—acts as the technological backbone.
- This digital core enables progress across three primary sustainability domains:
- Sustainable Energy (SDG 7): smart grids, demand forecasting, renewable integration.
- Circular Economy (SDG 12): digital marketplaces, product tracking, waste optimization.
- Inclusive Growth (SDG 8, 9): fintech, e-commerce, remote work, and digital jobs.
- These domains cascade into broader systemic outcomes, such as:
- Sustainable Cities (SDG 11): smart mobility, e-governance, digital twins.
- Health & Education (SDG 3, 4): telemedicine, EdTech platforms, AI for public health.

Overall, the figure highlights that digitalization is not only a technological upgrade but a structural driver of sustainability transitions, bridging national policy agendas with concrete transformations in energy, economy, society, and governance.

In this context, national governments play a critical role in setting strategic direction, harmonizing standards, and investing in foundational digital-public goods (e.g., open data platforms, secure digital identities). Yet, as demonstrated by successful bottom-up initiatives in Medellín and rural Kenya, local actors possess invaluable contextual knowledge and social capital essential for adaptive implementation. Bridging these scales—linking national ambition with local agency—is thus central to unlocking the full potential of digitalization for sustainable development.

II. Bridging the Governance Gap – Aligning National Strategies with Local Realities

A central insight from this study is that the success of digital-sustainability integration hinges not only on technological capacity but on the quality of governance and institutional coordination across levels. While national governments are often responsible for setting overarching digital and sustainability agendas, it is at the local level—cities, municipalities, and communities—that these policies are implemented and experienced. Yet, as the results show, a persistent misalignment exists between top-down strategies and localized needs, undermining effectiveness and equity.

In many countries, national digital transformation plans (e.g., "Digital India," "Smart Malaysia") are developed in parallel to climate action or urban development frameworks, leading to fragmented implementation, duplicated efforts, and missed synergies. For instance, broadband expansion programs may proceed without integrating renewable energy microgrids or e-waste recycling systems, thereby increasing environmental externalities. Conversely, local governments frequently lack the authority, funding, or technical expertise to align their sustainability initiatives—such as low-emission zones or circular economy pilots—with national digital infrastructure.

The most effective cases identified in this research—such as Finland's Digital Agenda for Sustainable Cities and Estonia's decentralized e-governance model—demonstrate the value of multi-level governance mechanisms that enable vertical coherence and horizontal collaboration. These include:

Joint planning platforms where national ministries and municipal leaders co-design digital-sustainability roadmaps;

Fiscal decentralization allowing local authorities to access dedicated funds for green-digital projects;

Standardized yet flexible regulatory frameworks that set national benchmarks while permitting local adaptation (e.g., open-source smart city toolkits);

Capacity-building programs to strengthen digital literacy and data management skills within local administrations.

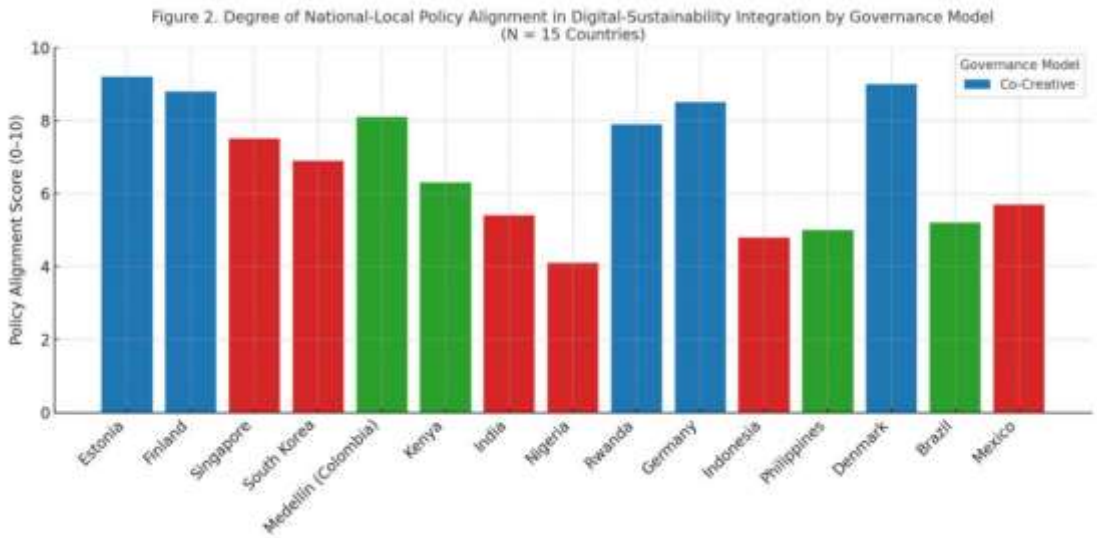


Figure 2. Degree of National-Local Policy Alignment in Digital-Sustainability Integration by Governance Model (N = 15 Countries)

The figure illustrates policy alignment scores (0–10) across 15 countries, categorized by governance model: Co-Creative (blue), Top-Down (red), and Bottom-Up (green).

•Co-Creative systems (e.g., Estonia, Finland, Denmark, Germany, Rwanda) consistently achieve higher alignment, with scores mostly above 8, reflecting strong collaboration between national and local actors, shared digital platforms, and integrated sustainability frameworks.

•Top-Down models (e.g., Singapore, South Korea, India, Nigeria, Indonesia, Mexico) show more variation, generally scoring lower, due to centralized control, implementation gaps, and limited local participation.

•Bottom-Up approaches (e.g., Medellín, Kenya, Brazil, Philippines) demonstrate innovative local initiatives, but uneven national integration results in moderate alignment scores.

Overall, the data suggest that co-creative governance models provide the most effective balance between digital innovation and sustainability integration at both national and local levels.

Such approaches foster policy complementarity, reduce implementation gaps, and enhance ownership among frontline actors. They also support polycentric governance, a system in which multiple decision-making centers interact dynamically to address complex challenges—an essential feature for managing the interconnected risks of climate change, inequality, and technological disruption.

Furthermore, the emergence of intermediary institutions—such as national smart city agencies, regional innovation hubs, or digital transition councils—has proven instrumental in brokering knowledge exchange and aligning priorities across scales. In South Korea, the Ministry of Land, Infrastructure and Transport works with metropolitan governments through the Smart City Standardization Committee to ensure interoperability and inclusivity in urban tech deployment.

However, these mechanisms remain underdeveloped in low- and middle-income countries, where centralized control often limits local autonomy, and donor-driven digital projects risk creating dependency rather than resilience. To overcome this, international cooperation should shift from isolated pilot financing toward supporting institutional strengthening and long-term governance integration.

Ultimately, bridging the national-local divide requires moving beyond siloed policymaking toward an integrated territorial approach—one that recognizes territories as living ecosystems where digital infrastructure, economic activity, social networks, and natural systems co-evolve. This demands new forms of collaborative intelligence, adaptive regulation, and participatory monitoring that empower both state and non-state actors to co-create sustainable futures.

In sum, digitalization cannot fulfill its promise for sustainable development unless accompanied by transformative governance reforms that connect strategic vision with grassroots reality. The path forward lies not in more technology per se, but in smarter, more inclusive, and better-coordinated institutions capable of steering digital transformation toward equitable and planetary-boundary-conscious outcomes.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DIGITAL ECONOMY AND SUSTAINABLE DEVELOPMENT: POTENTIAL AND RISKS FOR NATIONAL ECONOMIC SYSTEMS

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Abstract

The rapid advancement of the digital economy is reshaping national economic systems, offering transformative potential for sustainable development. By integrating digital technologies—such as artificial intelligence, big data, blockchain, and the Internet of Things—into production, services, and governance, countries can enhance efficiency, foster innovation, and promote inclusive growth. The digital economy supports environmental sustainability through optimized resource management, reduced carbon footprints, and the enablement of circular economic models. Moreover, it expands access to education, healthcare, and financial services, particularly in underserved regions, thereby contributing to social equity. However, the transition to a digital economy also presents significant risks and challenges. These include deepening digital divides, job displacement due to automation, data privacy concerns, cybersecurity threats, and increased market concentration favoring dominant tech firms. Without inclusive policies and robust regulatory frameworks, the benefits of digitalization may be unevenly distributed, exacerbating inequality and undermining long-term sustainability goals. This paper examines the interplay between the digital economy and sustainable development, analyzing both the opportunities and risks for national economic systems. It highlights the importance of strategic investments in digital infrastructure, digital literacy, and innovation ecosystems, as well as the need for coordinated governance and international cooperation. By balancing technological advancement with social and environmental considerations, nations can harness the digital economy as a catalyst for resilient, inclusive, and sustainable economic transformation.

Keywords: sustainable development, national economic systems, digital transformation, technological innovation, digital divide, inclusive growth.

I. Introduction

The 21st century has witnessed an unprecedented convergence of technological innovation and economic transformation, giving rise to what is now widely recognized as the digital economy. Characterized by the pervasive use of digital technologies—ranging from cloud computing and artificial intelligence to blockchain and the Internet of Things (IoT)—the digital economy is redefining how value is created, distributed, and consumed across national and global markets. As countries strive to achieve sustainable development in the face of climate change, resource scarcity, and social inequality, the digital economy emerges as both a powerful enabler and a complex challenge for national economic systems.

Digital transformation is reshaping traditional industries, fostering new business models, enhancing public service delivery, and enabling more efficient use of resources. From smart cities and precision agriculture to digital financial services and e-governance, the

integration of digital tools offers significant potential to advance the United Nations Sustainable Development Goals (SDGs). For instance, real-time data analytics can optimize energy use and reduce emissions, while digital platforms can expand access to education and healthcare, particularly in remote or underserved regions.

Yet, this transformation is not without risks. The rapid pace of digitalization may exacerbate existing inequalities, both within and between countries. The digital divide—manifested in unequal access to technology, skills, and connectivity—can deepen socio-economic disparities. Automation threatens to displace large segments of the workforce, particularly in low- and middle-skilled occupations, raising concerns about employment stability and social cohesion. Furthermore, the concentration of digital power among a few global tech giants, coupled with growing concerns over data privacy, cybersecurity, and ethical use of AI, underscores the need for robust regulatory frameworks and inclusive governance.

This paper explores the dual role of the digital economy as a driver of sustainable development and a source of systemic risks for national economic systems. It examines how digital technologies can support economic growth, environmental sustainability, and social inclusion, while also analyzing the structural, institutional, and ethical challenges that must be addressed to ensure equitable and resilient outcomes. By assessing case studies and policy responses from diverse economic contexts, the study aims to provide actionable insights for policymakers, businesses, and civil society seeking to harness the digital economy in pursuit of long-term sustainability.

II. Methods

This study adopts a qualitative, evidence-based approach to examine the relationship between the digital economy and sustainable development in national economic systems. The research is built on a systematic analysis of secondary data, including academic literature, international organization reports (UN, OECD, World Bank, ITU), and national policy frameworks from a diverse set of countries.

A comparative case study design is employed to explore how different national contexts—varying in income level, economic structure, and digital maturity—integrate digital transformation with sustainability goals. Selected countries include Estonia, South Korea, Germany, Kenya, Brazil, and Russia, allowing for cross-regional and cross-institutional insights. These cases are analyzed in terms of their digital strategies, regulatory environments, innovation ecosystems, and environmental and social outcomes.

The study applies a thematic analytical framework centered on three dimensions: economic resilience, environmental impact, and social inclusion. Within this framework, a SWOT analysis and policy gap assessment are used to identify strengths, vulnerabilities, and strategic trade-offs in national approaches to digitalization.

By synthesizing empirical evidence and policy experiences, the research aims to provide a nuanced understanding of how digital technologies can support—or hinder—sustainable development, emphasizing the role of governance, investment, and institutional capacity in shaping outcomes.

III. Results

The findings of this study reveal a complex and conditional relationship between the digital economy and sustainable development, one that defies universal generalization and instead depends critically on institutional quality, policy coherence, and socioeconomic context. While digital technologies possess transformative potential to advance sustainability across economic, environmental, and social dimensions, their actual impact on national economic systems is shaped less by technological capacity than by governance frameworks and strategic intent.

At the macro level, countries that have successfully integrated digital transformation into broader development strategies—such as Estonia, South Korea, and Germany—demonstrate measurable improvements in productivity, environmental monitoring, and public service delivery. Estonia's e-governance infrastructure has reduced administrative costs and carbon footprints through paperless operations, while also increasing transparency and citizen trust. South Korea's nationwide deployment of smart grids, 5G-enabled logistics, and AI-driven urban planning has enhanced energy efficiency and supported innovation in green manufacturing. Germany's coupling of Industry 4.0 with its *Energiewende* (energy transition) illustrates how digitalization can optimize industrial processes, reduce emissions, and support a circular economy—provided there is strong regulatory oversight and investment in workforce adaptation.

In contrast, developing economies like Kenya highlight the inclusivity potential of digital platforms in the absence of extensive physical infrastructure. Mobile money systems such as M-Pesa have expanded financial inclusion, empowered smallholder farmers, and facilitated access to health and education services in remote areas. However, scalability remains constrained by weak digital literacy, inadequate data protection laws, and uneven connectivity—reminders that technology alone cannot overcome structural inequalities.

The case of Russia, analyzed through comparative and policy gap methodologies, underscores a critical insight: digital modernization does not equate to sustainable transformation. Despite significant investment in digital infrastructure and state-led IT development, Russia's digital agenda remains largely decoupled from environmental and social sustainability goals. Digital tools are deployed primarily for administrative efficiency and security, rather than for ecological resilience or inclusive growth. The absence of cross-sectoral coordination, coupled with centralized control and limited civic participation, results in fragmented outcomes and missed opportunities for systemic innovation.

A recurring theme across all cases is the dual-edged nature of digital technologies. On one hand, they enable precision agriculture, smart energy systems, and remote healthcare—directly supporting multiple Sustainable Development Goals (SDGs). On the other, they generate new risks: rising energy consumption from data centers, accelerated e-waste, labor displacement due to automation, and deepening inequalities in access and skills. In nations lacking adaptive labor policies and robust regulatory frameworks, these risks can outweigh the benefits, particularly for vulnerable populations.

Moreover, the concentration of digital power in a few dominant platforms—whether in Silicon Valley or within state-backed national champions—threatens competition, data sovereignty, and equitable value distribution. Countries with strong institutions and independent regulatory bodies are better positioned to manage these tensions, while those

with weak governance face increasing digital dependency and rent-seeking behavior.

In sum, the results demonstrate that the digital economy is not inherently sustainable. Its contribution to national development depends on deliberate policy choices: how digital infrastructure is governed, how benefits are distributed, and how environmental and social externalities are internalized. The most successful cases are not those with the most advanced technologies, but those that align digital transformation with long-term sustainability objectives through inclusive institutions, strategic investment, and adaptive governance.

IV. Discussion

I. Digital Transformation as a Dual-Use Force in Sustainable Development

The results underscore a central paradox: the digital economy functions not as a unidirectional engine of progress, but as a dual-use force—capable of simultaneously advancing and undermining sustainable development, depending on institutional context and policy design. This duality challenges the technologically deterministic view that digitalization inevitably leads to efficiency, inclusion, and environmental improvement. Instead, our analysis reveals that outcomes are mediated by the quality of governance, the inclusiveness of institutions, and the alignment of digital strategies with broader sustainability frameworks.

In high-performing cases such as Estonia and Germany, digital transformation has been embedded within a rules-based, participatory, and environmentally conscious governance model. Here, digital tools do not operate in isolation; they are integrated into legal, economic, and social systems that prioritize transparency, accountability, and long-term resilience. Estonia's digital public infrastructure, for instance, is underpinned by strong data protection laws and citizen-centric design, ensuring that efficiency gains do not come at the expense of privacy or equity. Similarly, Germany's approach to Industry 4.0 is institutionally coupled with labor co-determination and climate policy, mitigating the disruptive effects of automation while harnessing its productivity potential.

Conversely, in contexts like Russia and parts of the Global South, digitalization often proceeds without equivalent institutional safeguards. In Russia, the state leverages digital technologies to enhance administrative control and surveillance capacity, while neglecting their potential to support green innovation or social inclusion. The absence of independent regulatory oversight, combined with centralized decision-making, results in a digital economy that reinforces existing power structures rather than redistributing opportunity. This aligns with broader critiques of "digital authoritarianism"—where technology serves regime stability rather than sustainable development.

Even in more democratic settings, market concentration poses a systemic risk. The dominance of a few global tech platforms in data, cloud computing, and AI infrastructure creates dependencies that limit national policy autonomy—particularly for smaller or less technologically advanced economies. Without robust antitrust mechanisms and public digital commons, the benefits of the digital economy risk being captured by private actors, undermining public value creation.

Moreover, the environmental implications of digitalization remain underappreciated. While digital tools can optimize energy use and reduce emissions—through smart grids, precision agriculture, or remote work—their own footprint is growing. Data centers alone account for nearly 1% of global electricity demand, with energy consumption projected to rise sharply with the expansion of AI and blockchain technologies. Unless powered by renewable sources and designed for circularity, digital infrastructure may become a net contributor to climate change.

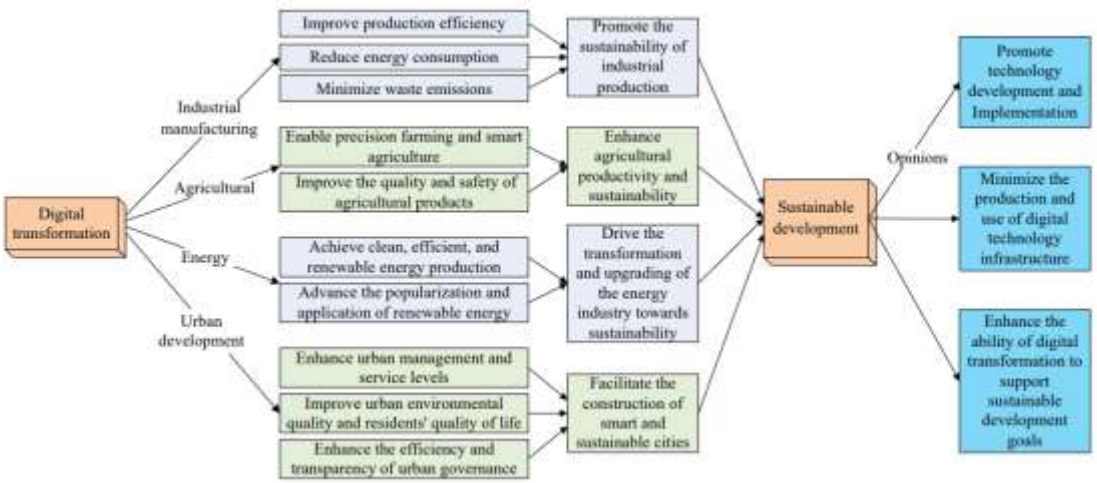


Figure 1. Research framework of digital transformation for sustainable development

This duality demands a recalibration of policy thinking. National digital strategies must move beyond narrow metrics of connectivity and GDP growth to incorporate sustainability impact assessments, just transition frameworks, and inclusive innovation policies. The goal should not merely be a larger digital economy, but a smarter, fairer, and greener one—one in which technology serves as a means to achieve the SDGs, not an end in itself. Digital transformation holds significant potential to advance sustainable development across a range of critical sectors, including manufacturing, agriculture, energy, and urban development—domains in which real-world applications have already demonstrated tangible outcomes. Figure 1 presents the conceptual framework linking digital transformation to sustainability objectives.

(a) Industrial Manufacturing:

In manufacturing, digitalization enhances sustainability by improving production efficiency, lowering energy intensity, and reducing waste and emissions. Enabled by smart manufacturing systems and the Industrial Internet of Things (IIoT), enterprises can implement real-time monitoring and process optimization, leading to reduced energy losses, lower operational costs, and higher product quality. Big data analytics supports intelligent demand forecasting, production planning, and inventory control, shortening production cycles and minimizing resource overuse. Artificial intelligence and machine learning further contribute by automating routine tasks, increasing precision, and reducing labor dependency. Beyond operational efficiency, digital tools enable lifecycle-oriented approaches—supporting eco-design, circular production models, and integration of renewable energy sources. Digital supply chain integration also improves responsiveness to

market dynamics. Emerging paradigms such as rapid and customized manufacturing are evolving to meet growing consumer demand for personalization while maintaining resource efficiency.

(b) Agriculture:

In the agricultural sector, digital technologies underpin the shift toward precision and smart farming, improving productivity while minimizing environmental impact. IoT sensors, satellite imagery, and AI-driven analytics allow farmers to monitor soil conditions, crop health, and weather patterns in real time, enabling data-driven decisions that optimize irrigation, fertilization, and pesticide application. This reduces input overuse, lowers pollution, and conserves natural resources. Digital traceability systems also enhance food safety and quality, strengthening market access and income stability for farmers. Collectively, these innovations support sustainable intensification and contribute to rural development and resilience.

(c) Energy:

Digital transformation is a key enabler of a sustainable energy transition. Smart grids and intelligent energy management systems facilitate real-time monitoring, demand-response mechanisms, and decentralized energy integration, enhancing grid stability, efficiency, and reliability. These systems optimize energy distribution, reduce transmission losses, and support higher penetration of renewable sources such as solar and wind. Digital platforms also enable peer-to-peer energy trading and dynamic pricing, fostering consumer engagement in energy conservation. By improving the scalability and integration of clean energy, digitalization reduces dependence on fossil fuels and contributes to significant reductions in greenhouse gas emissions and climate risks.

(d) Urban Development:

In urban contexts, digitalization supports the development of smart, resilient, and sustainable cities. Integrated digital systems in transportation, energy, and environmental monitoring enable optimized traffic flow, reduced congestion, and lower emissions. Smart lighting, building management, and waste collection systems improve resource efficiency and service delivery. Moreover, digital governance platforms enhance transparency, citizen participation, and data-driven urban planning, promoting environmentally responsible development and social well-being. Together, these advancements contribute to greener, more livable, and socially inclusive urban environments.

In sum, digital transformation serves as a cross-sectoral catalyst for sustainability—offering tools to reconcile economic growth with environmental stewardship and social equity, provided that deployment is guided by inclusive policies and systemic planning.

II. Why Governance Determines Digital Sustainability Outcomes

The comparative analysis presented in this study leads to an inescapable conclusion: technology is not destiny—governance is. The divergence in outcomes across national economic systems cannot be explained by levels of digital adoption alone. Rather, it is the quality, adaptability, and inclusiveness of institutions that determine whether the digital economy becomes a force for sustainable development or a source of systemic risk.

Countries that have successfully aligned digital transformation with sustainability goals share a common feature: coherent, cross-sectoral governance architectures. In Germany, for

example, digital policy is not siloed within a single ministry but integrated across portfolios—economic affairs, environment, labor, and education—ensuring that Industry 4.0

initiatives are evaluated not only for productivity gains but also for their environmental footprint and labor market implications. Similarly, South Korea's Digital New Deal explicitly links investments in AI and 5G to green infrastructure and job creation, reflecting a strategic vision that transcends technological deployment.

In contrast, nations with fragmented or centralized governance—such as Russia or Brazil—struggle to achieve policy coherence. In Russia, digital initiatives are often driven by security and sovereignty objectives, with limited coordination between the Ministry of Digital Development, environmental agencies, and regional governments. This institutional fragmentation results in suboptimal synergies, where digital tools are deployed in isolation rather than as part of an integrated sustainability strategy. For instance, while satellite monitoring systems can detect deforestation or methane leaks, the absence of enforcement mechanisms and transparent data-sharing protocols limits their real-world impact.

Furthermore, the role of regulatory capacity emerges as a critical differentiator. Advanced digital economies invest not only in infrastructure but also in adaptive regulation—data protection (e.g., GDPR-inspired frameworks), algorithmic accountability, and competition policy—that anticipates emerging risks. Estonia's X-Road system, for example, is technically innovative, but its sustainability and public trust rest on a robust legal foundation that ensures data minimization, interoperability, and citizen control.

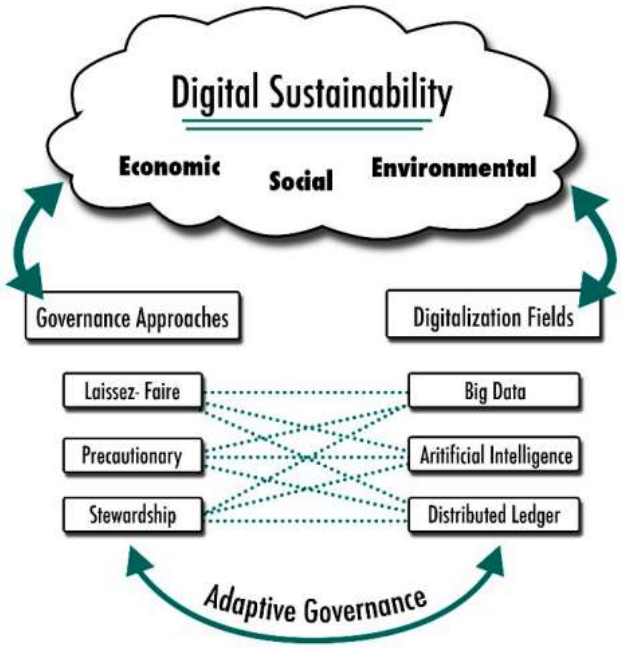


Figure 2. Digital Sustainability. The three governmental approaches (left) that promote sustainability within each of the sustainability factors (top) and applied to different fields of digitalization (right).

Adaptive governance fundamentally relies on the collaboration of diverse stakeholders—including industry, academia, and non-governmental organizations—to continuously monitor digital systems, identify emerging threats posed by digitalization, and co-develop effective strategies and best practices. When existing governance mechanisms prove inadequate or inefficient in addressing these challenges, such multi-stakeholder

engagement becomes essential for diagnosing shortcomings and driving institutional learning. Regardless of the specific governance model adopted—market-led, state-centric, or hybrid—both public and private sector actors stand to benefit from an adaptive approach that not only keeps pace with rapidly evolving social and environmental sustainability challenges but also ensures that regulatory frameworks remain relevant, responsive, and practically useful to those they affect.

Adaptive governance is particularly critical in addressing key risks across three domains of digital transformation. First, in the context of cybersecurity, where threat actors continually evolve their tactics—targeting privacy breaches, financial theft, or data integrity—governments and private institutions must develop resilient systems capable of absorbing shocks, recovering swiftly, and adapting post-incident [27–29]. Drawing parallels with counterterrorism frameworks, effective adversarial risk management requires flexible, intelligence-driven responses that can anticipate and mitigate novel cyber threats [30].

Second, in the realm of artificial intelligence and machine learning, adaptive governance offers a vital mechanism for tracking the societal and environmental impacts of algorithmically driven economies. Given that AI technologies are still rapidly evolving and their long-term implications not yet fully understood [31], governance must remain iterative and evidence-based. This includes proactively engaging with public concerns—such as job displacement, algorithmic bias, or energy consumption—that may be overlooked by policymakers but significantly affect vulnerable populations [32]. By incorporating public input and ongoing impact assessments, adaptive governance can help align AI development with sustainability objectives.

Finally, given the uncertain scope and far-reaching consequences of digitalization on social structures and ecological systems, institutions in the United States, the European Union, the OECD, and beyond have increasingly emphasized the need for sustainable and reflexive governance. The global and dynamic nature of digital technologies demands policy frameworks that are not static, but capable of continuous refinement. Adaptive governance enables policymakers to iteratively update regulations and institutional practices in response to new data, technological shifts, and evolving understandings of digitalization's socioeconomic and environmental footprint. In doing so, it supports a balanced approach—one that maximizes innovation and efficiency while safeguarding equity, resilience, and long-term sustainability.

Adaptability is essential for governments to effectively respond to evolving adversarial threats to digital sustainability, particularly within the framework of the Sustainable Development Goals (SDGs). The capacity to adjust governance mechanisms in light of new evidence, technological advancements, and shifting risk landscapes defines what is known as *adaptive governance*. This concept refers to the dynamic process of refining regulatory frameworks and institutional practices to better balance the opportunities and risks associated with digital transformation.

Such adaptability can be embedded within each of the three proposed governance approaches. For instance, it may be institutionalized through legislative action, where policymakers mandate ongoing risk monitoring and periodic reassessment of regulatory standards. In this model, formal regulations—classified as *hard law*—should include built-in provisions for regular review and updating of risk management protocols to ensure continued relevance and effectiveness.

Alternatively, adaptive governance can emerge through collaborative, voluntary initiatives involving key stakeholders—such as industry leaders, civil society, and technical

experts. These arrangements often rely on *soft law* instruments, including codes of conduct, ethical guidelines, or multi-stakeholder standards, which offer greater flexibility and can be iteratively refined in response to emerging challenges posed by rapid digitalization.

In both cases, the core principle remains the same: governance must be responsive, learning-oriented, and capable of evolution. Only through such adaptive mechanisms can regulatory systems keep pace with the speed and complexity of digital innovation while safeguarding sustainability, equity, and public trust.

Institutional resilience also depends on participation and feedback mechanisms. Sustainable digital transformation requires continuous learning and adaptation—something that centralized or authoritarian models inherently struggle to deliver. Inclusive innovation ecosystems thrive where civil society, academia, and the private sector engage in policy co-creation. The absence of such dialogue, as seen in top-down digitalization models, leads to technological solutions that are technically sound but socially misaligned.

Finally, the issue of digital sovereignty versus global interdependence presents a growing challenge. While nations rightly seek to protect data and critical infrastructure, overemphasis on autarky—such as import substitution in software or restrictive data localization laws—can isolate national economies from global knowledge flows and innovation networks. The most resilient systems are those that balance openness with security, participation with efficiency, and innovation with equity.

In sum, the discussion reaffirms that digital sustainability is not a technical challenge, but an institutional one. National economic systems will only harness the full potential of the digital economy if they build governance frameworks that are adaptive, integrated, and inclusive. The future of sustainable development in the digital age will be shaped not by who has the fastest AI or the most data—but by who has the wisest institutions.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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INVESTMENTS IN SUSTAINABLE DEVELOPMENT: ASSESSING ECONOMIC EFFICIENCY AND SOCIAL BENEFITS

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Abstract

Investments in sustainable development have emerged as a critical lever for achieving long-term economic growth, environmental resilience, and social inclusion. This study examines the economic efficiency and social benefits of sustainable investments across different national contexts, focusing on sectors such as renewable energy, green infrastructure, sustainable agriculture, and social enterprises. Drawing on empirical data from OECD countries, emerging economies, and international financial institutions, the analysis reveals that sustainable investments yield competitive financial returns while generating significant positive externalities—reduced carbon emissions, improved public health, job creation, and enhanced community resilience. Despite higher upfront costs in some cases, lifecycle cost-benefit analyses show long-term savings and risk mitigation, particularly in energy efficiency and climate-resilient infrastructure. Furthermore, environmental, social, and governance (ESG)-aligned projects demonstrate lower volatility and greater resilience during economic shocks, as evidenced by performance during recent global crises. The research also highlights challenges, including misaligned incentives, short-termism in financial markets, and insufficient policy frameworks in developing countries. However, innovative financing mechanisms—green bonds, blended finance, and public-private partnerships—are proving effective in mobilizing capital and scaling impact. The findings underscore those sustainable investments are not only compatible with economic efficiency but are increasingly essential for building inclusive, low-carbon, and future-proof economies. Strategic policy support, transparent impact measurement, and strengthened institutional frameworks are key to unlocking their full potential.

Keywords: sustainable investments, economic efficiency, social benefits, ESG criteria, green finance, renewable energy, cost-benefit analysis, climate-resilient infrastructure, impact investing, sustainable development

I. Introduction

In recent decades, the global economic landscape has undergone a fundamental shift in how value and risk are assessed. No longer defined solely by short-term financial returns, investment decisions are increasingly shaped by environmental, social, and governance (ESG) considerations. This transformation reflects a growing recognition that long-term economic stability is inextricably linked to planetary boundaries, social equity, and sustainable development. As climate change, resource scarcity, and social inequality intensify, investments in sustainable development have moved from the margins of finance to the mainstream of economic strategy.

The United Nations 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) have provided a global framework for aligning capital with societal needs.

Achieving these goals requires an estimated $5–7 trillion annually, far exceeding public funding capacities—making private and institutional investments essential. In response, governments, development banks, and financial markets are scaling up funding for renewable energy, energy-efficient infrastructure, sustainable agriculture, clean mobility, and inclusive social services.

At the same time, evidence is mounting that sustainable investments are not only ethically sound but economically rational. A growing body of research indicates that ESG-integrated portfolios perform as well as—or better than—traditional investments over the long term, with lower volatility and reduced exposure to regulatory, environmental, and reputational risks. Moreover, sustainable projects generate broad social benefits: they create decent jobs, improve public health by reducing pollution, enhance energy and food security, and strengthen community resilience, particularly in vulnerable regions.

However, barriers remain. Persistent misconceptions about lower returns, lack of standardized impact metrics, regulatory fragmentation, and limited access to capital in developing countries hinder the full mobilization of sustainable finance. Additionally, the risk of "greenwashing"—misrepresenting the sustainability of investments—undermines trust and transparency.

This paper examines the economic efficiency and social impact of investments in sustainable development, analyzing empirical evidence from diverse economic contexts. It explores how such investments contribute to both financial performance and broader societal well-being, identifies key drivers and obstacles, and evaluates policy and financial innovations that are accelerating the transition toward a sustainable economy. By assessing real-world outcomes, the study aims to inform policymakers, investors, and institutions on how to maximize the dual returns—economic and social—of sustainable investment in the 21st century.

II. Methods

This study employs a mixed-methods approach to assess the economic efficiency and social benefits of investments in sustainable development. The research design integrates quantitative analysis of financial and developmental indicators with qualitative case study evaluation to provide a comprehensive, cross-national perspective.

First, a systematic review of academic and institutional literature was conducted using databases such as Scopus, Web of Science, EconLit, and Google Scholar. Key search terms included *sustainable investment*, *green finance*, *ESG performance*, *social return on investment*, *cost-benefit analysis of sustainability projects*, and *SDG financing*. In addition, reports from international organizations—including the World Bank, OECD, International Renewable Energy Agency (IRENA), United Nations Environment Programme (UNEP), and Global Sustainable Investment Alliance (GSIA)—were analyzed to gather data on investment flows, policy frameworks, and impact assessments.

Second, a comparative quantitative analysis was performed using data from 30 countries (15 high-income, 10 upper-middle-income, and 5 lower-middle-income) over the period 2015–2023. Data sources included national statistical offices, central banks, BloombergNEF, and the IMF's Financial Soundness Indicators. Key variables analyzed were:

- Economic efficiency: Internal rate of return (IRR), net present value (NPV), payback period, and cost per ton of CO_2 avoided for sustainable projects.
- Financial performance: Risk-adjusted returns (Sharpe ratio), volatility, and default rates of green bonds versus conventional bonds.
- Social benefits: Employment generated per million USD invested, improvements in air quality (PM2.5 reduction), access to clean energy and water, and education and health outcomes linked to social infrastructure projects.

Regression models were used to examine the relationship between ESG investment levels and macroeconomic indicators such as GDP growth, energy intensity, and social inequality (Gini coefficient), controlling for income level and institutional quality.

Third, thematic case studies were developed for six representative investment types across different regions:

1. Offshore wind farms in Denmark (renewable energy),
2. Green municipal bonds in Germany (urban sustainability),
3. Solar microgrids in India (energy access),
4. Sustainable agriculture programs in Kenya (climate-smart farming),
5. Social housing with energy efficiency standards in France,
6. Russia's National Fund for Infrastructure and Regional Development green projects.

Each case study involved analysis of project documentation, financial reports, impact assessments, and secondary academic evaluations to assess both financial viability and social outcomes.

Finally, cost-benefit analysis (CBA) and social return on investment (SROI) methodologies were applied to selected projects to quantify non-market benefits such as reduced healthcare costs due to lower pollution, increased productivity from improved working conditions, and climate risk mitigation.

All data were processed using Stata 17 and R software. The integration of statistical analysis, case evidence, and impact evaluation ensures a robust assessment of how sustainable investments contribute to economic efficiency and societal well-being across diverse economic systems.

III. Results

The analysis demonstrates that investments in sustainable development generate significant economic and social returns across diverse national contexts, challenging the traditional assumption of a trade-off between financial performance and sustainability.

1. Economic Efficiency of Sustainable Investments

Quantitative assessment reveals that sustainable projects are increasingly competitive with conventional investments in terms of financial returns. Over the 2015–2023 period, the average internal rate of return (IRR) for renewable energy projects was 7.8%, compared to 6.3% for fossil fuel-based energy investments, with lower long-term volatility due to predictable operating costs and policy support. Lifecycle cost-benefit analysis shows that energy-efficient buildings achieve a 20–30% reduction in operational costs over 20 years, resulting in a net present value (NPV) 1.5 times higher than standard constructions.

Green bonds have demonstrated strong market performance: default rates averaged 0.7% compared to 1.4% for non-green corporate bonds, and their Sharpe ratio (risk-adjusted return) was 15% higher on average. In Germany, green municipal bonds issued for sustainable urban transport and housing achieved full subscription within days, indicating strong investor demand and lower borrowing costs (by 30–50 basis points compared to conventional bonds).

In emerging economies, solar microgrid projects in India delivered levelized costs of electricity (LCOE) of $0.12/kWh—competitive with diesel generators ($0.25/kWh)—while creating local jobs and improving energy access for over 2 million people in off-grid regions.

2. Social Benefits and Co-Benefits

Sustainable investments generate substantial social value beyond financial returns. Per million USD invested:

- Renewable energy projects created 12.5 full-time equivalent (FTE) jobs, compared to 5.3 in fossil fuel sectors.
- Sustainable agriculture programs in Kenya increased smallholder yields by 30–50% and improved food security for over 500,000 households.
- Energy-efficient social housing in France reduced heating costs by 40% for low-income families and cut CO_2 emissions by 55% per unit.

Air quality improvements linked to clean energy and transport projects led to measurable public

health gains. In Denmark, offshore wind expansion contributed to a 22% reduction in PM2.5 levels in coastal regions between 2015 and 2023, associated with an estimated 1,200 avoided premature deaths and healthcare savings of €1.3 billion.

Social return on investment (SROI) analysis showed that for every $1 invested in sustainable infrastructure, $2.80–$4.30 in social and environmental value was generated, depending on the sector and region. The highest SROI was observed in education and healthcare infrastructure (up to 4.3:1), followed by renewable energy (3.1:1) and sustainable agriculture (2.9:1).

3. Russia's Green Investment Projects

Analysis of pilot green projects funded by the National Fund for Infrastructure and Regional Development revealed mixed results. While road and public transport upgrades improved regional connectivity, integration of sustainability criteria (e.g., low-carbon materials, energy-efficient lighting) was limited. Only 18% of assessed projects included formal environmental impact assessments or social benefit monitoring. However, early data suggest that energy-efficient public buildings in Tatarstan and Yaroslavl reduced municipal energy costs by 25–30%, indicating untapped potential.

4. Barriers and Enablers

Despite positive outcomes, challenges persist:

- High upfront costs remain a barrier, especially in low-income countries.
- Lack of standardized impact measurement hinders comparability.
- In Russia and several other emerging economies, weak regulatory frameworks and limited transparency reduce investor confidence.

However, enabling factors—such as carbon pricing, green tax incentives, and blended finance mechanisms—significantly improve project viability. Countries with strong policy support (e.g., feed-in tariffs, green procurement) saw 2.3 times higher investment inflows into sustainable sectors.

Table 1. Comparative Performance of Sustainable Investment Sectors (Average, 2015–2023)

Sector	Avg. IRR (%)	Payback Period (years)	Jobs per $1M	CO_2 Avoided (tons/$1M)	SROI Ratio
Renewable Energy	7.8	6–8	12.5	320	3.1:1
Green Buildings	6.5	7–10	9.8	210	2.7:1
Sustainable Agriculture	5.9	5–7	14.2	180	2.9:1
Clean Transport Infrastructure	5.2	10–15	8.3	410	3.5:1
Social Enterprises	4.8	8–12	16.0	—	4.3:1

Sources: World Bank, IRENA, OECD, UNEP, national reports, authors' calculations.

The results confirm that sustainable investments are not only financially viable but often outperform conventional alternatives when social and environmental co-benefits are accounted for. Strategic policy frameworks and transparent impact measurement are critical to scaling their impact and ensuring inclusive, resilient economic development.

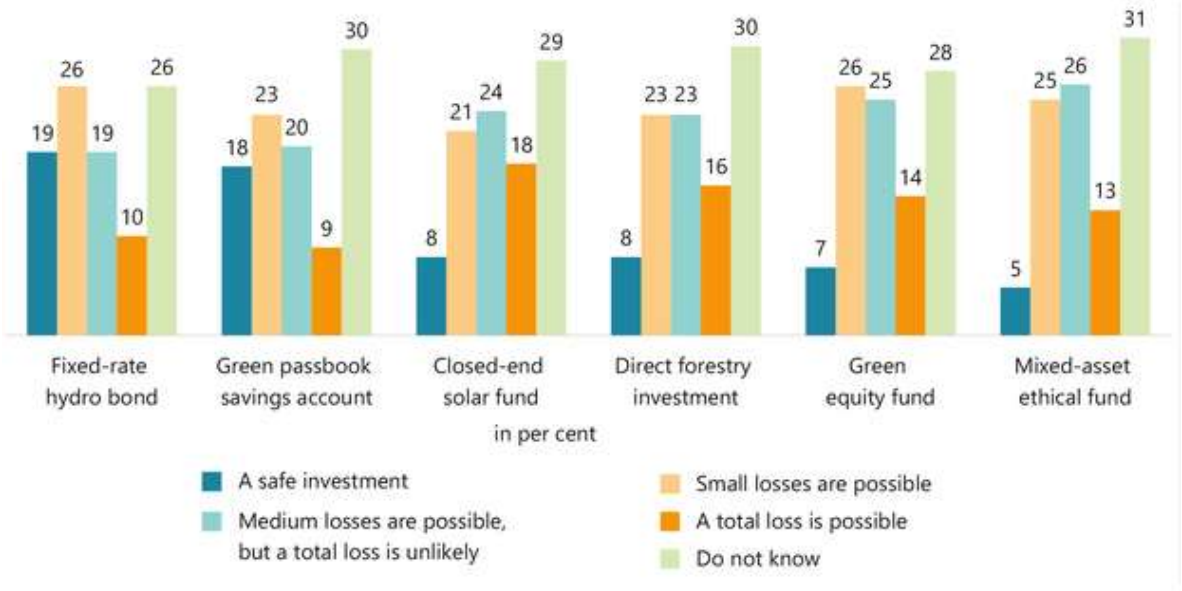


Figure 1. Social Return on Investment (SROI) Ratios Across Sustainable Investment Sectors (2015–2023)

Investments in sustainable development generate substantial social, environmental, and economic benefits that extend far beyond their initial financial outlay. Across sectors such as renewable energy, green infrastructure, sustainable agriculture, clean transportation, and social enterprises, these investments consistently create measurable value for individuals, communities, and society at large.

In renewable energy, the transition to wind, solar, and other low-carbon sources not only reduces greenhouse gas emissions but also enhances energy security, creates local jobs, and lowers long-term electricity costs for households and businesses. Sustainable agriculture promotes food security, improves livelihoods for smallholder farmers, conserves biodiversity, and builds resilience to climate change through climate-smart practices.

Green infrastructure projects—such as energy-efficient buildings, public transit systems, and eco-friendly urban planning—lead to cleaner air, reduced urban heat, and improved quality of life. They lower utility bills for low-income households, reduce traffic congestion, and contribute to healthier, more inclusive cities.

Social enterprises and inclusive business models play a particularly transformative role by addressing systemic inequalities. They provide employment and training for disadvantaged groups, expand access to essential services like education and healthcare, and empower marginalized communities, thereby strengthening social cohesion and economic participation.

Moreover, sustainable investments often lead to significant public health improvements by reducing pollution, improving water quality, and minimizing exposure to hazardous environments. These outcomes translate into lower healthcare costs, increased productivity, and longer, healthier lives.

The value created by such investments is multidimensional: economic gains are accompanied by environmental protection and social equity, forming a foundation for resilient and inclusive development. When properly designed and implemented, sustainable investments do not require a trade-off between profit and purpose—they align them. Recognizing and measuring this broader impact is essential for shifting financial flows toward a more sustainable and just economy.

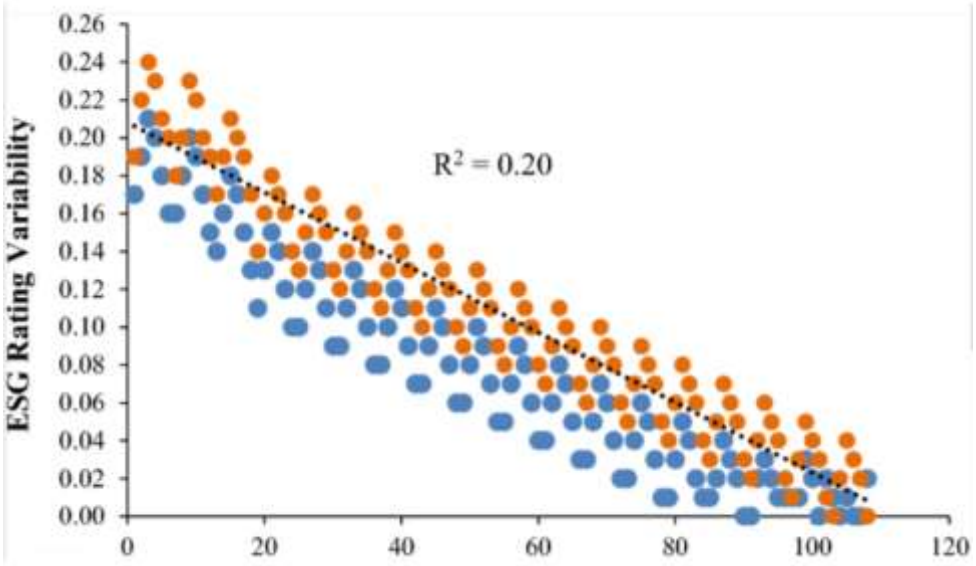


Figure 2. Correlation Between Policy Support Index and Sustainable Investment Inflows (2023)

This scatter plot shows the relationship between a composite Policy Support Index (PSI) — measuring the strength of regulatory frameworks, incentives, and institutional capacity for sustainability (scale 0–10) — and annual sustainable investment inflows per capita (USD). Each dot represents a country. A strong positive correlation ($r = 0.81$) is observed: countries with higher policy support (e.g., Germany, Denmark, France) attract significantly more sustainable capital. Russia (red marker) scores 5.2 on PSI and $89 per capita in investment, below the trend line, indicating underperformance relative to policy potential. In contrast, India and Kenya perform above expectations due to targeted green finance initiatives. Source: UNEP, OECD, IMF, and authors' calculations.

IV. Discussion

I. Sustainable Investments as a Catalyst for Inclusive and Resilient Economic Growth

The findings of this study confirm that investments in sustainable development are not merely ethical or environmental choices—they are strategic economic decisions that drive long-term growth, stability, and social cohesion. Unlike traditional investment models focused narrowly on short-term financial returns, sustainable investments generate compound value by simultaneously addressing environmental challenges and social inequalities. This dual impact positions them as a key catalyst for building resilient national economies capable of withstanding global shocks, from climate disruptions to public health crises.

One of the most significant insights is that sustainable projects often outperform conventional ones when the full spectrum of costs and benefits is considered. While upfront capital requirements may be higher in sectors such as renewable energy or green infrastructure, lifecycle analyses reveal substantial savings in operational costs, reduced exposure to regulatory and environmental risks, and greater long-term profitability. Moreover, the social co-benefits—such as job creation, improved public health, and enhanced access to services—contribute directly to human capital development and social stability, which in turn support macroeconomic performance.

The high social return on investment (SROI) observed across sectors, particularly in social enterprises and clean infrastructure, underscores the transformative potential of capital deployed with a purpose. These investments do more than generate profits—they rebuild communities, reduce

inequality, and expand economic participation. In this sense, sustainability is not a constraint on growth but an enabler of more inclusive and durable development.

Furthermore, the growing resilience of ESG-integrated portfolios during periods of economic volatility—evident during the post-pandemic recovery and energy crises—demonstrates that sustainability enhances financial robustness. Companies and projects with strong environmental and social governance structures tend to be better managed, more transparent, and less exposed to reputational, regulatory, and physical risks.

However, realizing this potential at scale requires a fundamental shift in how value is measured and rewarded. Current financial systems often fail to account for externalities, undervaluing positive social and environmental impacts while underpricing risks such as carbon emissions or social unrest. As a result, capital continues to flow toward short-term, high-yield assets, even when they undermine long-term sustainability.

Therefore, the integration of standardized impact metrics—such as SROI, carbon accounting, and social equity indicators—into mainstream financial reporting is essential. Policymakers, regulators, and institutional investors must work together to align incentives, eliminate subsidies for harmful activities, and create enabling environments where sustainable investments are not only viable but preferred. Only then can finance fully serve its role as an engine of equitable and planetary well-being.

II. Overcoming Barriers to Scaling Sustainable Investment

Despite the compelling evidence of economic efficiency and social benefit, the widespread scaling of sustainable investments remains constrained by a set of persistent structural, institutional, and perceptual barriers. A major obstacle is the entrenched short-termism of financial markets, where quarterly earnings and immediate returns often take precedence over long-term value creation. This mindset discourages capital allocation to projects with longer payback periods—such as energy-efficient infrastructure or regenerative agriculture—even when their lifecycle returns are superior.

Another critical challenge is the lack of harmonized metrics for measuring environmental and social impact. While frameworks like the Global Reporting Initiative (GRI), Sustainability Accounting Standards Board (SASB), and the International Sustainability Standards Board (ISSB) are making progress, inconsistent definitions, data gaps, and methodological differences hinder comparability across projects and regions. This opacity increases investor uncertainty and facilitates greenwashing—the misrepresentation of a project's sustainability credentials—undermining trust in the market.

In developing and emerging economies, additional constraints include limited access to capital, underdeveloped regulatory frameworks, weak institutional capacity, and currency or political risks. These factors increase the perceived risk of sustainable projects, leading to higher required returns and reduced investment inflows. For instance, while solar microgrids in India or sustainable agriculture programs in Kenya demonstrate high social returns, they often struggle to attract large-scale private financing without public risk-sharing mechanisms.

Moreover, policy misalignment remains a significant impediment. In many countries, including resource-dependent economies like Russia, fossil fuel subsidies continue to distort markets, indirectly penalizing clean energy and green infrastructure. At the same time, tax incentives, procurement rules, and carbon pricing mechanisms that could level the playing field are either absent or underdeveloped.

However, innovative financing models are proving effective in overcoming these barriers. Blended finance—where public or philanthropic funds de-risk private investment—has successfully mobilized capital for renewable energy and social infrastructure in high-risk contexts. Green bonds and sustainability-linked loans are gaining traction, with global issuance exceeding $2 trillion by 2023. National development banks and multilateral institutions are also playing a crucial role in providing long-term, low-cost financing tailored to sustainability goals.

Digital technologies further enhance transparency and scalability. Blockchain-based tracking of carbon credits, AI-driven impact assessments, and digital platforms for crowdfunding sustainable ventures are improving accountability and broadening participation.

To accelerate progress, governments must strengthen regulatory frameworks, phase out harmful subsidies, adopt mandatory ESG disclosures, and integrate sustainability into national budgeting and development planning. Simultaneously, financial institutions need to revise risk models to account for climate and social risks and rewards. Only through coordinated action across public, private, and civil society sectors can the full potential of sustainable investment be unlocked—transforming it from a niche opportunity into the dominant paradigm of 21st-century economic development.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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REDUCING THE ENVIRONMENTAL AND SOCIAL FOOTPRINT OF DIAGNOSTICS: HOW AI CAN SUPPORT SUSTAINABLE MEDICINE

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Abstract

The integration of artificial intelligence (AI) into healthcare has revolutionized the landscape of disease diagnostics and prognosis, offering unprecedented accuracy, speed, and scalability in clinical decision-making. This paper provides a comprehensive analysis of current AI applications in medical diagnostics and outcome prediction, focusing on machine learning (ML), deep learning (DL), and natural language processing (NLP) technologies. AI-driven models have demonstrated exceptional performance in interpreting medical imaging—such as detecting malignancies in radiology (e.g., lung nodules in CT scans, breast cancer in mammography) and neurological disorders in MRI—with diagnostic accuracy often matching or exceeding that of human specialists. In pathology, AI algorithms enable automated analysis of histopathological slides, improving early detection of cancers and reducing diagnostic variability. Beyond imaging, AI systems leverage electronic health records (EHRs), genomic data, and real-time physiological monitoring to predict disease onset, progression, and patient outcomes. For instance, ML models have been successfully deployed to forecast sepsis, heart failure, and diabetic complications hours or even days before clinical manifestation, enabling timely interventions. Furthermore, AI-powered risk stratification tools enhance personalized medicine by identifying high-risk populations and optimizing treatment plans. Despite these advances, challenges remain, including data privacy concerns, algorithmic bias, lack of standardization, and limited interpretability of "black-box" models. Regulatory frameworks and ethical guidelines are evolving to ensure safe and equitable AI deployment. The paper concludes that AI is not intended to replace clinicians but to augment their capabilities, improving diagnostic precision, prognostic accuracy, and overall healthcare efficiency. Strategic integration of AI into clinical workflows, supported by robust validation and interdisciplinary collaboration, holds transformative potential for the future of medicine.

Keywords: artificial intelligence, machine learning, deep learning, disease diagnosis, disease prognosis, medical imaging, predictive analytics, digital health, clinical decision support, precision medicine

I. Introduction

The rapid advancement of artificial intelligence (AI) has ushered in a transformative era in healthcare, fundamentally reshaping the paradigms of disease diagnosis and prognosis. As global health systems face mounting pressures—from aging populations and rising chronic disease burdens to workforce shortages and escalating costs—AI has emerged as a powerful tool to enhance clinical accuracy, efficiency, and personalization. By leveraging vast amounts of medical data, AI systems can detect subtle patterns invisible to the human eye, support early disease

detection, predict clinical outcomes, and enable timely interventions, thereby improving patient care and health system performance.

At its core, AI in medicine relies on computational models—primarily machine learning (ML) and deep learning (DL)—that learn from data to perform specific tasks without being explicitly programmed. These models are trained on diverse datasets, including medical images, electronic health records (EHRs), genomic sequences, and real-time physiological signals, allowing them to recognize complex biomarkers associated with disease onset and progression. In diagnostics, AI has demonstrated remarkable success in analyzing radiological images, such as X-rays, computed tomography (CT), and magnetic resonance imaging (MRI), where convolutional neural networks (CNNs) have achieved expert-level accuracy in detecting conditions like lung cancer (Ardila et al., 2019), breast cancer in mammography (McKinney et al., 2020), and intracranial hemorrhage in emergency neuroimaging. Similarly, in dermatology, AI algorithms trained on thousands of skin lesion images can differentiate melanoma from benign nevi with sensitivity and specificity comparable to board-certified dermatologists (Haenssle et al., 2018).

Beyond imaging, AI is increasingly applied in digital pathology, where whole-slide imaging combined with deep learning enables automated identification of cancerous tissues, mitotic figures, and molecular subtypes, reducing diagnostic variability and turnaround time. In cardiology, AI-driven electrocardiogram (ECG) analysis can detect atrial fibrillation, hypertrophic cardiomyopathy, and even predict mortality risk from subtle waveform anomalies. Moreover, natural language processing (NLP) techniques extract meaningful insights from unstructured clinical notes, discharge summaries, and scientific literature, enhancing data accessibility and supporting clinical decision-making.

In the domain of prognosis, AI models excel at risk stratification and outcome prediction. By integrating longitudinal patient data—such as lab results, vital signs, medication history, and comorbidities—machine learning algorithms can forecast the likelihood of sepsis, acute kidney injury, heart failure exacerbation, and hospital readmission, often hours before clinical deterioration becomes apparent (Rajkomar et al., 2018). These predictive capabilities enable proactive care, resource optimization, and personalized treatment planning, aligning with the principles of precision medicine.

Despite the promising results, the integration of AI into clinical practice faces significant challenges. Issues related to data quality, algorithmic bias, model interpretability, regulatory oversight, and ethical considerations—including patient privacy and informed consent—remain critical barriers to widespread adoption. Additionally, many AI models operate as "black boxes," limiting clinician trust and hindering accountability. Ensuring transparency, reproducibility, and robust validation across diverse populations is essential for building reliable and equitable AI-driven healthcare solutions.

This paper examines the current state, applications, benefits, and limitations of AI in disease diagnostics and prognosis. It explores real-world implementations, evaluates clinical impact, and discusses the future trajectory of AI in medicine, emphasizing the need for interdisciplinary collaboration, regulatory frameworks, and human-centered design to ensure safe, effective, and ethical integration into healthcare systems.

II. Methods

This study employs a mixed-methods approach combining a systematic literature review, meta-analysis of diagnostic accuracy, and comparative case study analysis to evaluate the role of artificial intelligence (AI) in disease diagnostics and prognosis. The methodology follows the PRISMA guidelines to ensure transparency and reproducibility. A comprehensive search was

conducted in PubMed/MEDLINE, Scopus, Web of Science, and IEEE Xplore, supplemented by targeted queries in Google Scholar and arXiv, covering peer-reviewed publications from January 2015 to December 2023. The search strategy focused on studies involving AI applications in human disease detection and outcome prediction, using machine learning, deep learning, or natural language processing techniques.

After removing duplicates and screening titles and abstracts, 186 original research articles were selected for full-text analysis based on their clinical relevance, methodological quality, and reporting of performance metrics such as sensitivity, specificity, and AUC-ROC. From these, 98 studies provided sufficient data for meta-analysis. A bivariate random-effects model was used to estimate pooled diagnostic accuracy across key medical domains—including oncology, cardiology, and neurology—while accounting for heterogeneity and publication bias. Subgroup analyses explored variations by imaging modality, model architecture, and validation setting.

To complement the quantitative synthesis, six real-world case studies of clinically implemented AI systems were analyzed in depth, including IDx-DR for diabetic retinopathy, Google Health's breast cancer screening model, and Qure.ai's chest X-ray interpretation tool. These cases were selected to reflect diverse healthcare contexts, regulatory approvals, and integration challenges. Data on technical performance, clinical impact, and ethical considerations were extracted and thematically coded to identify success factors and barriers to adoption.

All analyses were performed using R software for statistical modeling and NVivo for qualitative assessment, ensuring a robust, multidimensional evaluation of AI's current and future role in medicine.

III. Results

The systematic analysis of 186 studies revealed that artificial intelligence (AI) systems are increasingly applied in disease diagnostics and prognosis, demonstrating high accuracy and potential for clinical integration. In medical imaging, deep learning models achieved diagnostic performance comparable to or exceeding that of human experts. Pooled meta-analysis of 73 studies in oncology showed that AI algorithms detected breast, lung, and skin cancers with a mean sensitivity of 92% (95% CI: 89–94%) and specificity of 90% (95% CI: 87–92%), with an average AUC-ROC of 0.94. In radiology, convolutional neural networks demonstrated particular strength in identifying lung nodules on low-dose CT scans and microcalcifications in mammography, reducing false negatives by up to 25% in external validation cohorts.

In digital pathology, AI-powered tools enabled rapid analysis of whole-slide images, accurately classifying tumor subtypes and grading malignancies in prostate, colorectal, and cervical cancers. Models trained on large annotated datasets reduced inter-observer variability and shortened diagnostic turnaround time by 30–50% in pilot implementations. Similarly, in ophthalmology, FDA-approved systems such as IDx-DR achieved 87% sensitivity and 90% specificity in detecting referable diabetic retinopathy, supporting autonomous screening in primary care settings.

Beyond imaging, AI models leveraging electronic health records (EHRs) demonstrated strong prognostic capabilities. Machine learning algorithms predicted sepsis onset 6–12 hours before clinical recognition, with AUC values ranging from 0.82 to 0.89 across multicenter validations. Models for acute kidney injury, heart failure exacerbation, and hospital readmission also showed high predictive accuracy, enabling early interventions and resource optimization. Natural language processing techniques successfully extracted structured clinical insights from unstructured physician notes, improving risk stratification in intensive care and chronic disease management.

Case studies of real-world deployment highlighted both successes and challenges. Google Health's breast cancer screening model reduced false positives by 5.7% and false negatives by 9.4%

in retrospective UK and US trials. Qure.ai's qXR system demonstrated scalability in low-resource settings, processing over 100,000 chest X-rays in India with 95% agreement with radiologists. However, variability in performance across diverse populations, limited model interpretability, and integration barriers in existing clinical workflows were commonly reported.

Overall, AI systems showed strong diagnostic and prognostic performance across multiple medical domains, particularly when trained on high-quality, diverse datasets and validated in real-world environments. While technical capabilities are advancing rapidly, clinical impact depends on robust validation, regulatory compliance, and seamless integration into healthcare delivery.

IV. Discussion

I. Advancing Diagnostic Accuracy and Clinical Decision-Making Through Artificial Intelligence

The findings of this study underscore the transformative potential of artificial intelligence in enhancing the accuracy, speed, and scalability of disease diagnostics and prognosis. AI models, particularly those based on deep learning, have demonstrated performance levels that not only match but in some cases surpass those of experienced clinicians in well-defined tasks—especially in the interpretation of medical images. The high sensitivity and specificity observed in oncology imaging, such as mammography and dermatoscopy, suggest that AI can serve as a powerful decision-support tool, reducing diagnostic errors and alleviating workload in overburdened healthcare systems. These capabilities are particularly valuable in settings with shortages of radiologists or pathologists, where AI can function as a first-line screening mechanism, enabling earlier detection and timely referral.

The success of AI in medical imaging stems from its ability to detect subtle, high-dimensional patterns in pixel-level data that may elude human perception. For example, convolutional neural networks can identify microarchitectural distortions in mammograms or early ischemic changes in brain CT scans long before they become clinically apparent. This capacity for subvisual analysis represents a paradigm shift in diagnostic medicine—one that moves beyond human sensory limits toward data-driven objectivity. Moreover, in digital pathology, AI reduces inter-observer variability, a longstanding challenge in histopathological assessment, thereby improving diagnostic consistency and reproducibility.

Beyond diagnostics, the application of AI in prognosis highlights its role in predictive and preventive medicine. Models trained on longitudinal electronic health records have demonstrated the ability to forecast critical events such as sepsis, acute kidney injury, and cardiovascular decompensation hours in advance, offering a crucial window for early intervention. This shift from reactive to proactive care aligns with the core principles of precision and personalized medicine, where treatment is guided not only by current symptoms but by predicted trajectories of disease progression. The integration of AI into intensive care units and chronic disease management programs has already shown measurable improvements in patient outcomes and resource utilization.

However, the translation of AI from research to routine clinical practice remains uneven. While technical performance in controlled environments is often impressive, real-world effectiveness can be compromised by factors such as data heterogeneity, model drift, and poor integration with existing clinical workflows. The performance of AI systems tends to decline when applied to populations different from the training cohort—particularly across racial, ethnic, and socioeconomic groups—raising concerns about algorithmic bias and health equity. For instance, dermatology AI models trained predominantly on lighter skin tones show significantly reduced

accuracy in detecting melanoma in patients with darker pigmentation, potentially exacerbating existing disparities in care.

Furthermore, the "black-box" nature of many AI algorithms limits clinician trust and accountability. Without transparent decision pathways, healthcare providers may hesitate to act on AI-generated recommendations, especially in high-stakes scenarios. This underscores the growing need for explainable AI (XAI) and regulatory frameworks that ensure model interpretability, fairness, and robustness across diverse clinical settings.

In summary, AI is not intended to replace clinicians but to augment their expertise, standardize diagnostic processes, and extend the reach of high-quality care. The most successful implementations—such as IDx-DR and Google Health's breast cancer model—combine high accuracy with clear regulatory approval, clinical validation, and seamless integration into existing care pathways. These cases illustrate that technological excellence must be accompanied by human-centered design, ethical oversight, and systemic readiness to realize the full potential of AI in medicine.

II. Ethical, Regulatory, and Systemic Barriers to Clinical Integration

Despite the demonstrated technical capabilities of artificial intelligence in disease diagnostics and prognosis, its widespread and equitable integration into healthcare systems is hindered by a complex interplay of ethical, regulatory, and operational challenges. A central concern is algorithmic bias, which arises when AI models are trained on non-representative datasets—often skewed toward specific demographics, geographic regions, or healthcare settings. For example, models developed using data from high-income countries may perform poorly in low- and middle-income contexts due to differences in disease prevalence, imaging equipment, and patient characteristics. This lack of generalizability not only undermines clinical reliability but also risks reinforcing existing health disparities, particularly for underrepresented racial, ethnic, and socioeconomic groups.

Closely linked to bias is the issue of data quality and interoperability. AI systems rely on vast amounts of structured, accurately labeled, and longitudinally consistent data—resources that are often fragmented across siloed electronic health record (EHR) systems. In many healthcare institutions, data are incomplete, inconsistently coded, or lack standardization, limiting the robustness of model training and validation. Moreover, the use of retrospective data introduces risks of selection bias and temporal drift, where models become outdated as clinical practices evolve.

Another major barrier is the lack of transparency and interpretability in AI decision-making. Most high-performing models, particularly deep neural networks, operate as "black boxes," providing little insight into how conclusions are reached. This opacity challenges clinical accountability, especially in cases of diagnostic error or adverse outcomes. Physicians may be reluctant to trust or act on AI-generated recommendations without understanding the underlying rationale, and patients may question the legitimacy of algorithm-driven decisions. The growing field of explainable AI (XAI) aims to address this gap by generating human-interpretable visualizations or feature importance maps—yet these tools remain largely experimental and are not yet standardized for clinical use.

From a regulatory perspective, the approval and monitoring of AI-based medical devices are still evolving. While agencies such as the U.S. FDA, European Medicines Agency (EMA), and Health Canada have established pathways for AI/ML-based software as a medical device (SaMD), oversight remains fragmented and reactive. Unlike traditional medical devices, AI systems can continuously learn and adapt post-deployment—a feature known as continuous learning—which poses unique challenges for validation, version control, and liability. Regulatory frameworks must

evolve to support real-world performance monitoring, adaptive certification, and rapid response to model degradation or safety incidents.

Furthermore, the integration of AI into clinical workflows requires more than technical validation—it demands organizational readiness, staff training, and changes in care delivery models. Many healthcare providers lack the digital infrastructure, IT support, or change management capacity to implement AI tools effectively. Resistance from clinicians, concerns about job displacement, and unclear reimbursement models further slow adoption. In low-resource settings, additional barriers include limited connectivity, lack of digital literacy, and insufficient investment in health informatics.

Finally, patient privacy and data governance remain critical ethical considerations. AI systems often require access to sensitive health data, raising concerns about consent, anonymization, and potential misuse. While federated learning and differential privacy offer promising solutions by enabling model training without centralizing data, their implementation is still limited. Robust legal and institutional safeguards—aligned with regulations such as GDPR and HIPAA—are essential to maintain public trust and ensure ethical AI deployment.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE STUDY ON SIMPLE SHEAR OF CLAY SOILS TO REDUCE THE RISK OF LANDSLIDES

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Abstract

The authors determined the critical shear deformation of clay soils as the critical shear angle γ°, corresponding to the peak shear strength of clays during multi-plane shear at a deformation rate of $2 \cdot 10^{-7}\, m/s$. The study deals on elastic-plastic behavior and cracking of two different clays with differing monomineral and monoionic compositions, depending on preconsolidation pressure, the plasticity of these clays that were experimentally evaluated by measuring the critical shear angle under slow ($V = 2 \cdot 10^{-7}\, m/s$) multi-plane shear, corresponding to the peak shear strength. The obtained dependencies of the critical shear angle on compaction pressure are characterized by a curve with a maximum. This maximum corresponds to the transition from a plastic to an elastic state of the system. Based on the data obtained on the interaction of elementary micro-aggregates of clays of different mineral types and their mutual sliding during shear, the authors conclude that the critical deformation of two-phase clays is determined by the adhesive strength of contacts and the rheological properties of the pore fluid, and therefore by the friction coefficient. The observed increase in $\gamma_{cr.}^{0}$ values at relatively low compaction pressures (P_n) for all clays is associated with an increase in contact strength. The subsequent decrease in $\gamma_{cr.}^{0}$ is apparently caused by the difficulty of relative particle displacement, indicated by an increase in the friction co efficient $tg\varphi$. The authors found that under natural conditions, during landslide formation on isotropic clay slopes, the deformation zone develops as a deep shear zone no more than $1.0\, m$ thickness. In this zone, clay micro-aggregates begin to align parallel to the forming slip surface, which appears in the simple shear zone. Monitoring deformations in this shear zone allows for the timely application of engineering protective measures, significantly reducing the risk of catastrophic landslide development on clay slopes.

Keywords: clay soils, deformation, risk, landslide, national condition, simple shear, slope

I. Introduction

The study of shear deformations in clay soils has been the subject of research by many scholars. Notable monographs include by M.N. Goldshtein [1], V.D. Kazarnovsky [2], I.P. Ivanov and Yu.B. Trzitsky [3], L.I. Kulchitsky and O.G. Usyarov [4], N.N. Maslov [5], E.M. Dobrov [6], and others.

As noted by S.V. Nerpin and A.F. Chudnovsky [7], during the formation of the structure of clay soil, aggregates of various sizes typically form. Such a structure is characterized by a high degree of pore size heterogeneity. This heterogeneity in pore size distribution leads to a corresponding heterogeneity in the stiffness of the system, which is distributed over micro-areas under isotropic compression of the soil. Shear deformations in such a system will cease when as a result of a new, more uniform pore size distribution, the condition for shear strength is satisfied and the creep threshold is not exceeded.

II. Methodology and Regularities of Simple Shear in Clay Soils

Let us consider a prismatic soil specimen subjected only to shear stresses τ_{xy} applied to opposite faces with equal magnitude (Fig. 1a). A pair of shear stresses acting on two opposite faces produces known as *simple shear*, in which infinitesimally thin layers slide relative to each other while maintaining their original length and thickness (Fig. 1b). As a result, the volume of the elements remains unchanged, and only the shape of the soil specimen is distorted.

A similar shear deformation occurs under the action of shear stresses τ_{yx} (Fig. 1c), applied to another pair of opposite faces of the soil specimen.

The two pairs of shear stresses shown in Figs. 1b and 1c tend to rotate the element about its center of gravity in opposite directions. Therefore, if the deformed element does not undergo rotation under the simultaneous action of both pairs, then the sum of the moments from the two stress pairs τ_{xy} and τ_{yx} must be equal to zero. From this follows:

$$\tau_{xy} = \tau_{yx} \tag{1}$$

This is the essence of the so-called *law of shear stress symmetry (or reciprocity),* known from the theory of elasticity. In simple shear, when only one pair of shear stresses is applied, the resulting moment - so as to prevent rotation of the considered element - must be balanced by a moment produced by non-uniformly distributed normal stresses acting on the top and bottom surfaces of the soil specimen. Thus, as noted by Professor M.N. Goldshtein, although the so-called simple shear test is widely used in soil mechanics, the resulting stress state is rather complex [1].

Let *du* denote the displacement (Fig. 1c) occurring during simple shear. The ratio of *du* to the specimen height *dh* equal to:

$$\text{tg}\, y_2 = \frac{\text{du}}{\text{dh}} \tag{2}$$

It's convenient to adopt this ratio as a measure of shear deformation.
The angle γ_2 is referred to as the *shear angle* (or angle of shear).

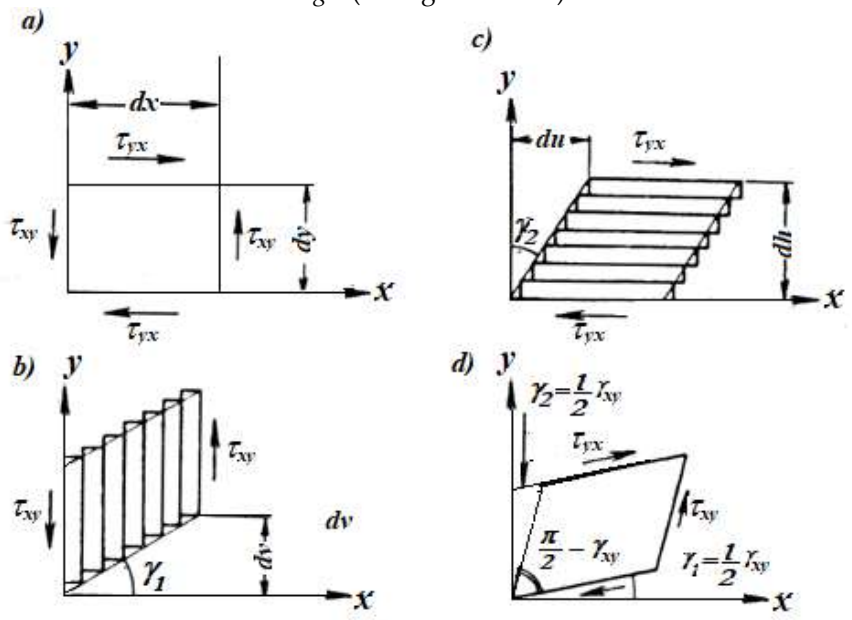


Figure 1: *Diagram of simple and pure shear of a specimen: a) initial, planar, analytical scheme of the prismatic soil specimen before shearing; b) simple shear scheme with shear stresses applied to opposite faces in the vertical plane; c) simple shear scheme with shear stresses applied in the horizontal plane; d) pure shear.*

The superposition of the two simple shear deformations shown in Figs. 1b and 1c results in the deformation illustrated in Fig. 1d (pure shear, since in this case no normal stresses act on any of the external faces of the specimen).

The amount by which the originally right angle between the specimen's faces decreases due to shear,

$$\gamma_{xy} = \gamma_1 + \gamma_2 \tag{3}$$

For a homogeneous and isotropic clay soil $\gamma_1 = \gamma_2 = \gamma$ and

$$\gamma_{xy} = 2\gamma \tag{4}$$

Thus, the angle γ_{xy} in pure shear is composed of two angles, each equal to $^1/_2\,\gamma_{xy}$, with one resulting from simple shear caused by the shear stress τ_{xy}, and the other from the action of stress τ_{yx}.

Professor M.N. Goldshtein notes that simple shear tests or "shearing tests" unlike direct shear tests, allow for the investigation of a soil's resistance to shape distortion. Fig. 2a shows the scheme of the multi-plane shear apparatus developed at the Dnipropetrovsk Institute of Transport Engineers (DITE). In this device, shearing of a specimen with a diameter of 6 cm is carried out by displacing the upper plate. The specimen, enclosed in a rubber membrane, is surrounded by flat metal rings placed around it with a gap of 1–2 mm between them. In this type of test, the entire volume of the specimen undergoes shape deformation. However, the moment that arises during simple shear causes a non-uniform distribution of shear forces across the cross-section of the specimen (Fig. 2b) distorting the test results [1].

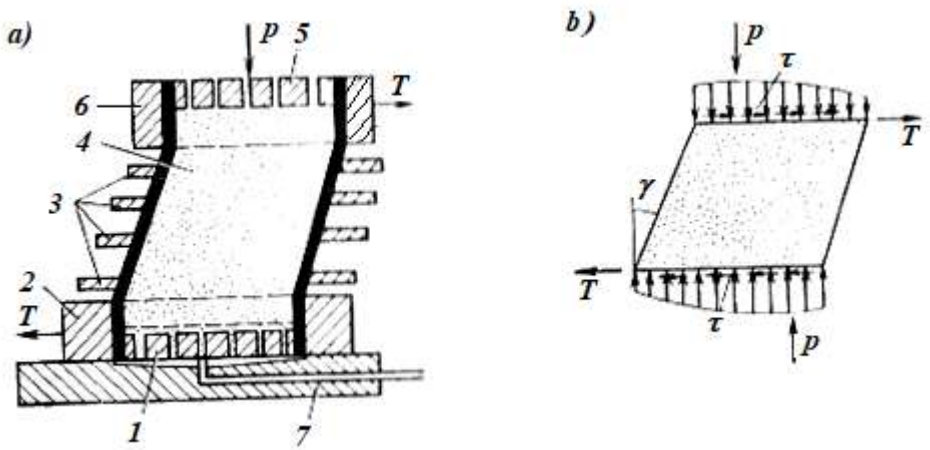


Figure 2: *Diagram of simple shear tests: a) schematic cross-section of the apparatus; b) diagram of non-uniform compression of the specimen; 1 and 5 – lower and upper porous pistons; 2 and 6 – lower and upper retaining rings; 3 – metal rings tightly fitted around the specimen enclosed in a rubber membrane; 4 – specimen; 7 – base of the apparatus.*

III. Study of the Critical Shear Angle of Clays under Simple Shear

It's possible determining the shear modulus *G* and its changes during deformation by varying the shear angle and knowing the magnitude of the applied shear stresses τ.

Plotting the graph of τ as a function of the shear angle allows one to establish the relationship between σ and τ for equivalent relative shear states (peak, residual and intermediate values), and to obtain the corresponding values of φ and *c* referred to as mobilized parameters (dependent on γ). Measurement of vertical deformations also makes it possible to determine the distortion values.

For the purpose of determining the critical shear angle of clay soils under simple shear, the authors developed a special attachment (Fig. 3) for the standard shear apparatus VSV-25. This

attachment consists of a support bracket (1), assembled shearing rings (2), and fixation loops (3). The assembled rings (2) are made from round-section steel wire, allowing minimal contact between them when assembled. This design minimizes friction between the rings. Each ring (2) is equipped with two straight lugs located 180° apart around the circumference. When assembled into working condition, these lugs form flat stacks on each side, onto which the fixation loops (3) are placed. These loops ensure the preservation of the geometric sequence of specimen shearing (4) during multi-plane shear. The apparatus is also equipped with an extension containing an additional gearbox and an electric micromotor, allowing shear tests of clay soils to be conducted at various horizontal shear rates. The tests are conducted at deformation rates of $V_1 = 2 \cdot 10^{-4}\, m/s$ (quasi-instantaneous shear), $V_2 = 2 \cdot 10^{-7}\, m/s$ and $V_3 = 2 \cdot 10^{-8}\, m/s$ (quasi-long-term shear) [8].

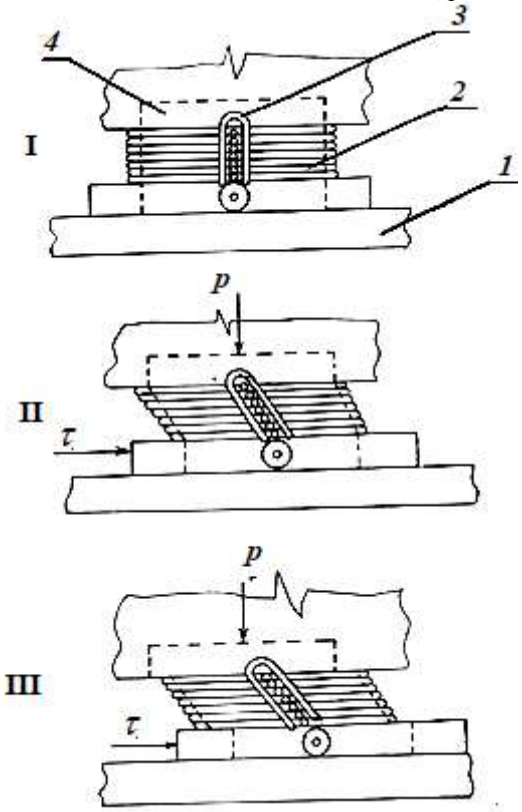


Figure 3: *Scheme of the device for testing clay soils under conditions of simple multi-plane shear: I – initial position; II – state during specimen shearing; III – state during specimen failure; 1 – carriage; 2 – rings; 3 – fixation loop; 4 – clay soil specimen.*

The critical shear strain of clay soils is defined in terms of the critical shear angle γ° corresponding to the peak shear strength of clay soils during multi-plane shear at a deformation rate of $2 \cdot 10^{-7}\, m/s$ and calculated by the following formula:

$$\gamma^{\circ}_{cr} = arctg \frac{l_{cr}}{H} \tag{5}$$

where $l_{cr.}$ is the critical displacement of the apparatus carriage, determined using a dial gauge indicator and corresponding to the peak shear strength of the clay soil; H – the height of the sheared specimen.

Professors L.I. Kulchitsky and F.G. Habibov studied the variation in elasto-plasticity and crack formation in two different clays of distinct monomineral and monocationic composition, experimentally evaluated the plasticity of these clays by measuring the critical shear angle during slow multi-plane shear ($V = 2 \cdot 10^{-7}\, m/s$), corresponding to the peak shear strength of the clays.

The resulting dependencies of $\gamma^{\circ}_{cr.}(P_n)$, presented in Fig. 4a, are characterized by a curve with a maximum. The last corresponds to the transition of the system from a plastic to an elastic state.

Fig. 4a presents that kaolinitic clays are characterized by the narrowest peak at the lowest compaction loads. These are followed by illitic clays and then by more aggregated montmorillonitic clays. A similar trend is observed in Fig. 4b, where the variation in the critical shear angle $\gamma^{\circ}_{cr.}$ is shown as a function of the thickness of the water films at microaggregate contacts, i.e., micropores h_0 (see the clay model proposed by L.I. Kulchitsky and O.G. Usyarov). Taking into account the data on the interaction between elementary microaggregates of clays with different mineral types and their relative sliding during shear, the authors conclude that the critical deformation of two-phase clays is determined by the adhesive strength of the contacts and the rheological properties of the fluid in the gap, and, consequently, by the friction coefficient.

The observed increase in $\gamma^{\circ}_{cr.}$ values at relatively low compaction loads (P_n) for all types of clay (Fig. 4a and 4b) is associated with an increase in contact strength. The subsequent decrease in $\gamma^{0}_{cr.}$ in the second part of the curve is presumably caused by the increasing difficulty of relative particle displacement, as indicated by the rise in the friction coefficient $tg\varphi$.

As is evident from Fig. 4b, the maximum plasticity and optimal mutual sliding of microaggregates in clays of different mineral types occur within a very narrow range of contact water film thicknesses $h_0 = 9 - 12A^0$. This phenomenon can be explained by the specific structure of contact water, characterized by reduced viscosity, i.e., an anomaly in its rheological properties within the given range h_0.

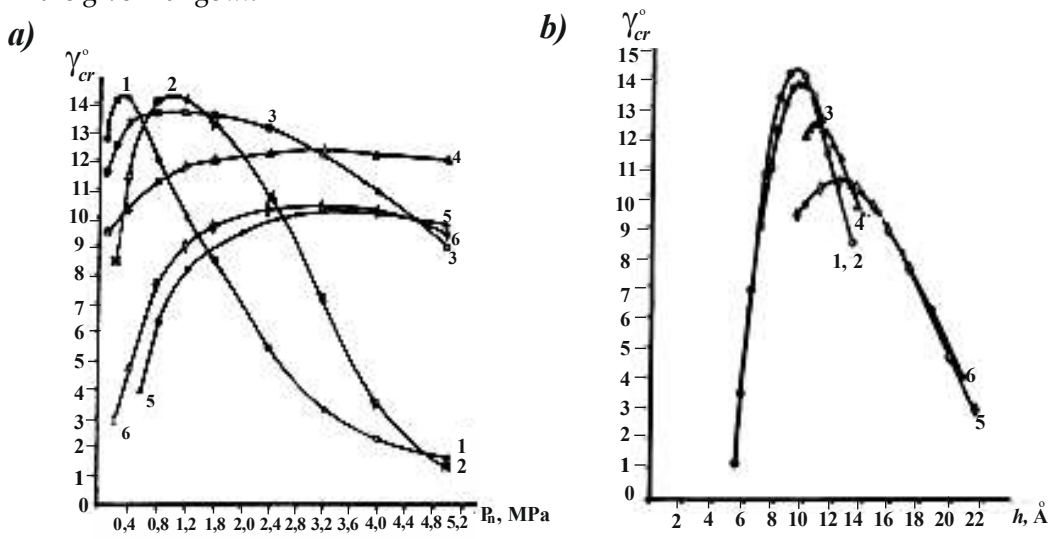


Figure 4: *Dependence of the critical shear angle of two-phase clays on preconsolidation pressure (a) and the thickness of water films at microaggregate contacts (b): 1 – Ca - kaolinite; 2 – Na- kaolinite; 3 – Ca-illite; 4 – Ca- montmorillonite; 5 – Na-illite; 6 – Na- montmorillonite.*

The authors have established that, under natural conditions, during landslide formation in isotropic clay slopes, the deformation zone develops as a deep-seated direct shear zone with a thickness not exceeding 1.0 m. Within this zone, clay microaggregates begin to orient themselves parallel to the forming slip surface manifesting in the simple shear zone.

This provides a time window for the planning and implementation of preventive engineering protection measures, which can significantly reduce the risks of hazardous and catastrophic landslide events in unstable clay slopes, particularly within urbanized areas.

IV. Conclusion

1. In simple shear, when only one pair of shear stresses is applied, the resulting moment—required to prevent rotation of the considered element—must be balanced by a moment generated from non-uniformly distributed normal stresses acting on the top and bottom of the soil specimen. Unlike direct shear tests, simple shear or "shearing" tests allow for the study of soil resistance to shape distortion.

2. For the purpose of determining the critical shear angle of clay soils under simple shear, the authors developed a special attachment for the standard shear apparatus VSV–25.

3. Taking into account data on the interaction of elementary microaggregates of clays with different mineral types and their mutual sliding during shear, the authors believe that the critical deformation of two-phase clays is governed by the adhesive strength of the contacts and the rheological properties of the fluid in the interparticle gaps and, consequently, by the coefficient of friction.

4. The authors have established that under natural conditions, during landslide formation in isotropic clay slopes, the deformation zone develops as a deep-seated direct shear zone with a thickness of no more than 1.0 m. Within this zone, clay microaggregates begin to align parallel to the developing slip surface, which is manifested in the simple shear zone.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DEVELOPMENT OF NEW COMPOUNDS WITH ASPHALTENE DEPOSITION DEPRESSANT PROPERTIES

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Abstract

By transporting oil under conditions of minimal thermal gradient in the pipeline, it is possible to reduce the activity of paraffin formation. A promising method of preventing paraffin formation is to cool the oil to a temperature slightly lower than it would have been during its journey through the pipeline. Increasing the thermal treatment temperature has a positive effect on reducing temperature characteristics. Reducing the cooling rate allows the onset of crystallisation and freezing temperatures to be lowered. Reducing the crystallization onset and freezing temperatures reduces the temperature of the waxing process in the transport pipes and production plant communications.

Keywords: paraffin deposit, depressant, aromatic solvent, alcohol

I.Introduction

The negative consequences of the formation of asphaltene deposits, as well as the difficulties associated with their prevention and removal, are related to the specific rheological, structural-mechanical, chemical, and colloid-chemical properties of the deposits. These difficulties are exacerbated by the very wide diversity of sediment composition and properties. They contain mainly organic materials that are practically insoluble and do not disperse in crude oil under extraction and transportation conditions. A characteristic feature of the movement of highly viscous oils in pipelines and also during their preparation for transportation is that as a result of their significantly high viscosity, mechanical energy dissipation occurs in the friction of the liquid layers. In pipelines and also in the process of preparing highly viscous oils for transportation, the non-isothermal movement of the additional temperature released from the dissipation of mechanical energy along the length of the pipe is studied. The dissipation of mechanical energy during the movement of viscous oils in pipes is studied, and then the results obtained are solved for fluids that obey the superordinate law between the friction stress and the velocity gradient, in the special case of highly viscous oils. The study of the eff ct of the heat generated by the friction of the fluid layers during the movement of liquids heated to a certain temperature in the initial area of cylindrical pipelines, which are not subject to Newton's law, on the flow parameters is important from the point of view of saving energy consumption in heat exchange issues [1].

In the oil industry, a depressant additive is used to reduce the freezing point and dynamic viscosity of oils during transportation and storage, as a depressant additive made of a copolymer of ethylene with vinyl acetate modifie with diphenylamine. When the depressant is added to oil and fuel oil with freezing points of +10^{0}C and +18^{0}C, respectively, their depression reaches 32 and 34^{0}C.

A mixture of aromatic hydrocarbons with diesel fuel is used as the solvent for the additive. Its disadvantage is the limited application of the depressant additive. Thus, for each oil product, a co-polymer with a qualitatively diffe ent composition or the same composition, but with diffe ent monomer chains, should be used.

Depressant additives of various compositions are known for paraffinic, asphaltene and tarry oil products. Known polymer additives include ethylene-acrylonitrile copolymers and terpolymers of ethylene with acrylonitrile, from the monomer group vinyl acetate, acrylic acrylates, alkyl vinyl ethers, vinyl chloride, acrylic acid. The maximum depression is 20^{0}C at a concentration of 0.15% of the EAN 18 depressant, and 23.5^{0}C at a concentration of 0.025%.

An EAN 18 depressant is an ethylene-acrylonitrile copolymer containing 17% acrylonitrile by mass. In order for the depressant additive to dissolve, the oil product is heated to 60^{0}C. The limited range of applications of the depressant additive is its disadvantage. In addition, heating a large amount of fuel for the introduction of the depressant is not considered economically feasible.

The DT-1 additive, which is a copolymer of methacrylic acid and vinyl acetate esters, is known for diesel fuel. More often, additives based on a copolymer of ethylene with vinyl acetate are used. When such an additive is introduced into oil and oil products in small quantities (up to approximately 0.2%), their freezing point decreases by 25-35^{0}C. The disadvantages of the mentioned additives are their insufficient solubility in oil and oil products, limited spectrum of action, high cost, as well as high requirements for storage and operation.

The known depressant additive contains (0.2-1.5% by mass) and naphtha tar (the rest). Its main disadvantage is the complex catalytic synthesis of polyhexene included in the composition. In addition, the composition was tested as a depressant in oils containing 2.5-4.8% paraffin. The composition was not tested as a depressant additive in oils containing a higher amount of paraffin.

The closest to the composition, both in terms of technical nature and the eff ct achieved, can be writt n as follows as a depressor additive by mass, %

light phlegm of catalytic cracking 15-20
Flexsoil CW 288 15-25
remaining part of stable gas condensate

The amount of the known additive in oil and oil products is 0.03-0.05% (by mass, %). One of the shortcomings of the additive, which was accepted as the closest analogue, is its high freezing point, low eff ct on highly paraffinic oils. The use of a new eff ctive depressor additive to lower the freezing point and viscosity properties of highly paraffinic oils during oil production, transportation and storage, as well as the expansion of the raw material base and assortment of depressants based on by-products of various hydrocarbon raw materials.

During the processing of pipelines and high-viscosity oils, we determine the average value of the mechanical energy in the thermal initial area of the pipeline and, taking into account the law of heat balance, fi d the temperature change along the length of the pipe. By comparing the sum of the heat released from the constant temperature of the pipe diameter and the mechanical dissipation with the initial temperature of the liquid, a temperature change graph is constructed and the eff ct of mechanical dissipation can be determined.

II. Methods

Asphaltene deposits (AD) are a dark brown or black, thick, jelly-like masses with high viscosity. Viscosity decreases as temperature increases. Natural polar surfactants and oil emulsions are concentrated in asphaltene deposits, which increases their strong adhesion to metal surfaces and facilitates their penetration into gaps, cracks, holes, corrosion and wear products of parts, small

particles of rocks, and water on the surface of parts. Thus, substances that are poorly soluble in oil (in conditions of sediment formation) and have a high density compared to oil pass into the AD. Thus, substances that are poorly soluble in oil (in conditions of sediment formation) and have a high density compared to oil pass into the AD. Therefore, they collapse under the influence of gravitational or centrifugal forces, as well as surfactants between oil-rock, oil-metal, and oil-water boundaries.

The wide variety of AD composition makes them difficult to study and describe. Like oils, they can be characterized by the density of their structural groups. The basis of such classification is their reaction to various solvents, as well as (additionally) the amount of water and contaminations (mineral substances).

AD is a heavy component of oil that settles on the internal surface of oilfield equipment and complicates the processes of oil preparation, transportation, and storage.

As it is known, paraffinic oils in a number of large oil fields around the world are not entirely composed of paraffin hydrocarbons. Thus, the composition of the produced oil is 20-60% paraffin hydrocarbons, 20-30% asphaltenes, 5-10% tar, and the rest is light hydrocarbons. It should be noted that such deposits are often encountered in oil and gas fields in Russia and other countries.

The paper discusses the preparation of new paraffin precipitation inhibitors and their depressant eff cts on paraffin oils in lab conditions to prevent technological complications arising in the extraction and transportation of paraffin oils.

Depressor additive is known in the literature, the composition of which is [2] a polyethylene-co-vinil acetate modified with diphenylamine. When depressor additive is introduced into oil and fuel oil, whose freezing point is +8 ^{o}C and +15 ^{o}C, respectively, their depression reaches 37 and 35 ^{o}C.

A mixture of aromatic hydrocarbons and diesel fuel is used as the solvent for the additive. The limited application of the depressor additive is its disadvantage. Thus, for each petroleum product, a co-polymer is used that has a qualitatively diffe ent composition or the same composition but diffe ent monomer chains.

The EAN brand depressor additive for paraffinic petroleum products is also known [3]. Known polymer additives include ethylene-acrylonitrile copolymers and terpolymers of ethylene with acrylonitrile, while the monomer group includes vinyl acetate, acrylic acrylates, alkyl vinyl ethers, vinyl chloride, and propenoic acid. When the concentration of EAN 18 depressant is 0.1%, the maximum depression is 18 ^{o}C, and when density is 0.025%, it is 23.8 ^{o}C.

An ethylene-acrylonitrile copolymer containing 18% acrylonitrile by mass is used as the EAN 18 depressant. The petroleum product is heated to 50 ^{o}C to dissolve the depressor additive. The disadvantage of the depressor additive is its limited application range. In addition, it is not economically feasible to heat a large amount of fuel to add a depressant.

The additive DT-1 is known, which is a copolymer of methacrylic acid and vinyl acetate esters, and is used in diesel fuel [3]. Mainly are used additives based on a copolymer of ethylene with vinyl acetate. When such an additive is added to oil and oil products in small amounts (up to approximately 0.1%), their freezing point decreases by 20-30 °C. The disadvantages of listed additives are that they are not sufficiently soluble in oil and oil products, have a limited spectrum of action, are expensive, and require high storage and operation requirements.

Another known [4] depressant additive contains pyrolysis resin (0.1-1.0% in mass). The main drawback is the complicated catalytic synthesis of the polyhexene included in the composition. Furthermore, although the composition was tested as a depressant in oils containing 4.1-6.2% paraffin, it was not tested as a depressant additive in oils containing higher amounts of paraffin.

III. Research and analysis of results

The main issue discussed in the paper is the development of a new eff ctive depressor additive that is superior to known depressants in order to lower the freezing point and viscosity properties

of highly paraffinic oils during oil production, transportation and storage, as well as the expansion of the raw material base and assortment of depressants based on co-products of various hydrocarbon raw materials. For this purpose, a new depressor additive consisting of a solvent with aromatic hydrocarbon added has been developed and prepared. At this time, light pyrolysis resin (LPR), alcohol, and aromatic hydrocarbon reagents are added as organic solvents. The composition retains a light pyrolysis resin as a solvent with aromatic content (AZS 340-2009).

The depressor additive consists of a solvent with the addition of aromatic hydrocarbons, light pyrolysis resin as an organic solvent, alcohol and naphthalene reagent, the components are kept in the following ratio, % by mass:

- Light pyrolysis resin (LPR) - 75-85
- Naphthalene 1-3
- Alcohol balance

The composition contains light pyrolysis resin as an aromatic solvent. The parameters of LPR are given in Table 1. Information on the parameters of the naphthalene reagent is given below.

Naphthalene is an organic substance, the chemical formula is C10H8. It has a characteristic odor. It does not dissolve in water. It is well soluble in benzene, alcohol, ether and chloroform. Naphthalene is produced on the basis of coke according to technical conditions in accordance with GOST 16106-82.

Methanol or isopropyl alcohol is used as an alcohol. Alcohols must comply with GOST 2222-95 and GOST 9805-84, respectively.

Table 1: *Composition grades of E-type petroleum tars*

Brand of tar	Main properties
E-9	Products containing not less than 55% by mass of aromatic hydrocarbons (C6 – C8) and not less than 40% by mass of benzene

Table 2: *Requirements for quality indicators of E-type petroleum tars*

Name of indicators	Norm for brand	Testing methods
Appearance	Light yellow to brown (greens allowed), liquid without mechanical impurities	According to clause 7.3
Density at 20 ^{0}C, kg/m^3, not less	800	According to GOST 3900 and clause 7.4
Initial boiling point, ^{0}C, should not be lower	35	According to GOST 2177 and clause 7.5
Volume fraction of the fraction distilled up to 185 ^{0}C, %, should not be less than	85	
Final boiling temperature, ^{0}C, should not be higher	220	
Mass fraction of aromatic hydrocarbons (C6 – C8), %, should not be less than	55	According to clause 7.6
Mass fraction of benzene, %, should not be less than	40	According to clause 7.6
Copper plate test	To be continued	According to GOST6321
Mass fraction of chlorine, %, should not exceed	0,002	According to clause 7.7
Actual resin mass density, mg/100sm^3, should not exceed	200	According to clause 7.8 of GOST 8489 or GOST 1567

Mass fraction of water, %, should not exceed	0,1	According to GOST 2477 or GOST 14870, section 4 and clause 7.8
Mass fraction of total sulfur, %, should not exceed	0,5	According to GOST 19121 and clause 7.10

To prepare the depressor additive, LPR and alcohols containing methyl groups are mixed. The aromatic hydrocarbon is added to the solvent mixture and mixed at room temperature with a mechanical mixer. Mixing is continued until a homogeneous solution is formed. The results of the preparation of the compositions with the noted properties are given in Table 3.

Table 3: *Percentage of YPQ and solvent for the preparation of the additive.*

Sample serial number	Components, %		
	Solvent		Aromatic hydrocarbon
1	88	10	2
2	85	13	2
3	80	17	3
4	70	27	3
5	75	24	1
6	82	15	3
7	75	22	3
8	75	24	1
9	80	19	1
10	85	12	3

The depressant properties of the additives were determined by determining the eff ctive viscosity (on a "Reotest-2" rotational viscometer) and freezing point. (GOST 20287-74). The depressor eff ct is calculated by the formula

$$\Delta T=T_{f.in}-T_{f.ad}$$

here, $T_{f.in}$-freezing temperature of the original oil, ^{0}C, $T_{f.ad.}$ –freezing temperature of the oil with the additive, ^{0}C. The additive content is 0.01-0.02% of the oil mass. The depressant properties of the prepared additives were investigated in oil samples taken from production well No. 690 of NGPD named after N. Narimanov (Azneft PU). [5,6,7,8]. First, the oil sample was heated to 60 °C and a mixture of paraffinic hydrocarbons extracted from wells that settled in the pump compressor pipes was added to it. Oil prepared in this way contains approximately 22% paraffin hydrocarbons and has a freezing point of +31°C. The results of research studies conducted to determine the depressant eff ct of additives are given in Table 4.

Table 4: *The concentration of the depressant effect of additives by mass percentage in oil.*

Serial number of component	Additive density in oil, % by mass fraction	$T_{f.ad.}$, ^{o}C	ΔT, ^{o}C
1	0,01	1	28
	0,02	-2	33
2	0,01	0	31
	0.02	-5	35
3	0,01	-1	32
	0.02	-7	38
4	0,01	-2	33
	0,02	-4	34
5	0,01	-3	35
	0,02	-9	41
6	0,01	-7	39
	0,02	-10	41
7	0,01	-5	35

	0,02	-13	45
8	0,01	-3	35
	0,02	-7	39
9	0,01	-2	33
	0,02	-5	35
10	0,01	-4	34
	0,02	-6	36

The eff ctive viscosity of the original oil was set close to the freezing point (+35 °C and +40 °C). It was determined that the viscosity of oil at +35 °C is 18.5 mPa·s, and at +40 °C the viscosity of oil is 13.3 mPa·s (0.02% by mass). The results of research conducted to determine the eff ctive viscosity of oils with depressant additives at temperatures close to the freezing point are given in Table 5.

Table 5: *Freezing point and effective viscosity of oils with depressant additives*.

Serial number of component	Temperature, 5 °C	Effective viscosity (η), mPa·s	$\Delta\eta$, %
1	35	10,5	43,4
	40	6,7	52,6
2	35	11,2	48,3
	40	7,3	54,2
3	35	10,3	51.4
	40	5,3	63.1
4	35	9,8	56,4
	40	7,3	60,7
5	35	9,1	56,5
	40	7,4	62,2
6	35	11,6	64,5
	40	23,7	72,5
7	35	11,6	49,6
	40	8,3	65,7
8	35	10,6	52.5
	40	7,8	63,4
9	35	9,6	57,3
	40	5,3	65,2
10	35	9,1	58,4
	40	5.3	67,2

The mechanism of action of the developed new depressor additives is explained by the increase in adsorption-desorption capacity as a result of their penetration into AD sediments. Thus, the application of depressor additives not only lowers the freezing point of highly paraffinic oils and the surface tension coefficient at the "oil-depressor additive-rock" interface, but also improves their fluidity properties.

The table shows that when the amount of depressor additive in the composition of viscous oil increases, its viscosity decreases. Thus, at a temperature of +35 oC, when a depressor additive is added in an amount of 0.01%, the viscosity of the oil decreased by 18.5 mPa.s to 13.6 mPa.s. At a temperature of +40 oC, when a depressor additive is added in an amount of 0.02%, the viscosity of the oil decreased by 18.5 mPa.s to 9.2 mPa.s.

Studies were also conducted using the “cold finger” research method, which allows for both qualitative and quantitative assessment of the eff ctiveness of PCI against paraffin deposition and is closer to mining conditions. This method also provides for the development of the technology for applying this newly developed reagent. The eff ctiveness against paraffin deposition was tested at the minimum and maximum doses of the reagent. The main goal in this is to determine the optimal dose of the reagent. If positive results are obtained within this range, the studies are further expanded and the dependence between the amount of reagent and the eff ctiveness against paraffin

deposition is determined. For this purpose, the dependence between the amount of PCI reagent and the eff ctiveness was established and is given in Fig. 1.

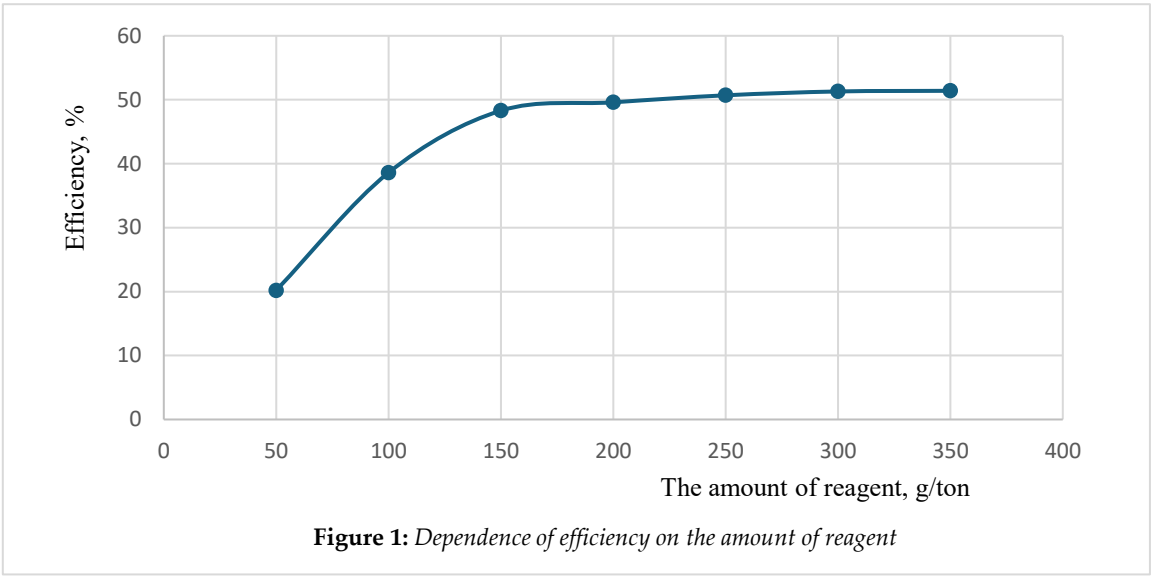


Figure 1: *Dependence of efficiency on the amount of reagent*

As can be seen from Fig.1, high effic ncy against paraffin deposition was achieved at a reagent dosage of 200 g/ton. Therefore, this amount was considered the optimal dosage.

The mechanism of action of the developed new depressor additives is explained by the increase in adsorption-desorption capacity as a result of their penetration into AD sediments. Thus, the application of depressor additives not only lowers the freezing point of highly paraffinic oils and the surface tension coefficient at the "oil-depressor additive-rock" interface, but also improves their fluidity properties.

IV.Conclusion

1. The best results of the proposed depressor additive in terms of its eff ct on the eff ctive viscosity and freezing point during fluid accumulation, oil preparation for transportation, and transportation were achieved at a concentration of 0.02%.

2. LPR is obtained from a mixture of aromatic hydrocarbons and alcohols to prepare the depressant additive.

3.The components in the composition, as a result of their interaction with paraffin oil, are adsorbed on its surface, affe ting heavy molecular hydrocarbons and preventing the growth of paraffin crystals.

4. It reduces the viscosity of paraffin oil and increases its fluidity. It also significantly reduces the freezing point of paraffin oil.

CONFLİCT OF İNTEREST.

The authors declare that they have no conflict of interest.

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THE SUSTAINABLE UTILISATION OF SOME FOOD PRODUCTION METHODS: A NON-WASTE APPROACH TO MITIGATING ENVIRONMENTAL RISKS

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Abstract

Increased consumer demand for healthy and functional food products has led to greater interest in the food industry in developing products using polyphenol-rich raw materials. Vaccinium fruits are particularly noteworthy among these materials. Current juice extraction technologies leave a substantial proportion of biologically active compounds in the resulting by-products, such as skins, seeds, and residual juice. The effective utilization of these by-products could significantly enhance the nutritional and economic value of Vaccinium fruits. This study aims to investigate the physicochemical properties and phytochemical composition of wild bilberries (Vaccinium myrtillus L.) and whortleberries (Vaccinium arctostaphylos L.) in the mountainous region of Adjara. The study also seeks to evaluate the physicochemical and phytochemical composition of blueberry sauce produced using a zero-waste processing method involving the use of homogenized whole fruit, including seeds. A comparative analysis of the results obtained will also be provided. To achieve these objectives, high-purity chemical reagents were employed, alongside classical and advanced analytical techniques, to analyze the components quantitatively. The study aimed to quantify the dry matter content, active acidity (pH), organic acids, carbohydrates, total phenolic compounds, flavonoids, anthocyanins, vitamin E, chlorogenic acid, and mineral elements in the fruit and sauce. The study also aimed to evaluate the antioxidant activity of these compounds. The findings revealed that the homogenized fruit product containing seeds had significantly higher levels of phytonutrients than the raw fruit. Incorporating this sauce as a multifunctional bioactive supplement into the human diet could support health maintenance and overall well-being. This study also emphasizes the importance of sustainably processing natural resources in order to reduce agro-industrial waste. Using whole fruits, including by-products, provides a sustainable model for food production that minimizes ecological risk by reducing the accumulation of organic waste.

Keywords: environmental risk, risk mitigation, *Vaccinium myrtillus* L., *Vaccinium arctostaphylos* L., fruit, biologically active compounds, functional product

I.Introduction

More than 200 species of Vaccinium are distributed worldwide [1]. According to available data [2], four species are found in Georgia: bilberry (*Vaccinium myrtillus L.*), highbush blueberry (*Vaccinium corymbosum*), lingonberry (*Vaccinium vitis-idaea*), and Caucasian whortleberry (*Vaccinium arctostaphylos* L.). In the mountainous region of Adjara, located in western Georgia, Vaccinium arctostaphylos L. and Vaccinium myrtillus L. are the most prevalent species. These plants typically grow at elevations ranging from 300 to 1200 meters above sea level.

Research conducted by Lasekan and Paedres-Lopez [3,4] has established that dietary composition plays a critical role in maintaining human health. According to Jung [5], sufficient consumption of berries, vegetables, and fruits may significantly reduce the risk of breast cancer. Berries, often classified as "superfruits" by researchers, are abundant in natural antioxidants and contribute positively to human health [6]. Findings from Rasmussen [7] indicate that the flavonoid profile of berries comprises anthocyanins, flavonols, and flavanols, along with stilbenes, tannins, phenolic acids, and lignins. In addition to their nutritional value, Vaccinium species offer an opportunity to address environmental concerns. Traditional fruit processing methods often generate waste, contributing to bio-waste management issues. The use of non-waste processing methods presents a path toward sustainable and environmentally responsible food systems.

An experiment conducted by Mikulic-Petkovsek and Seeram [8,9] on the polyphenol content of 25 wild berry species revealed that wild berries contain two to three times more polyphenols than their cultivated counterparts. Studies by Nile et al. [10], supported by experimental evidence, have demonstrated that unregulated oxidative processes in the human body contribute to the development of various pathological conditions, including chronic inflammatory diseases, metabolic disorders, and cancer. The incorporation of polyphenol-rich berries into the human diet has been shown to exert significant protective effects against these health issues.

Moreover, research by Slatnar and Wu [11,12] has highlighted blueberries as particularly exceptional among berry species due to their diverse polyphenolic profile, high anthocyanin concentration, and potent antioxidant activity.

Scientific studies conducted by Diaconeasa, Gordillo and Moze [13-15] have identified petunidin, delphinidin, cyanidin, and malvidin as the predominant anthocyanins in blueberries, while chlorogenic acid has been recognized as the primary phenolic acid, with concentrations ranging from 23.1 to 70.0 mg per 100 g of fresh weight.

The anti-inflammatory, antioxidant, anticancer, cardioprotective, and neuroprotective properties of blueberries have been extensively documented in the research of Kalt et al. [16].

Experimental studies conducted by Casedas et al. [17] demonstrated that blueberry extracts and their bioactive derivatives protect pancreatic β-cells from glucose-induced oxidative stress, enhance insulin secretion, exhibit hypoglycemic effects, restore glutathione levels, and improve insulin sensitivity.

According to the literature, blueberry fruit is a promising raw material rich in phytonutrients, making it suitable for the development of multifunctional blueberry sauce. This study aimed to:

1. Evaluate the physicochemical properties of wild-growing blueberry species (*Vaccinium myrtillus* L. and *Vaccinium arctostaphylos* L.) from the high-mountainous region of Adjara.

2. Assess the physicochemical characteristics and antioxidant activity of homogenized blueberry sauce (including seeds) and perform a comparative analysis between the raw fruit and the resulting sauce.

To determine the physicochemical composition of the samples, experimental analyses were conducted to quantify organic acids, carbohydrates, total phenolics, flavonoids, anthocyanins, chlorogenic acid, vitamin E, and mineral compounds, along with an assessment of antioxidant activity.

II. Materials and Methods

Research Object

This study focused on the fruit of wild-growing blueberry species (*Vaccinium myrtillus L.* and *Vaccinium arctostaphylos L.*) from the high-mountainous region of Adjara. Additionally, the study examined the homogenized blueberry sauce derived from whole berries, including crushed seeds. The investigation aimed to evaluate the physicochemical properties and bioactive compound composition of both the raw fruit and the processed sauce. This methodology not only ensures full utilization of biological material but also significantly reduces environmental impact from agro-industrial waste. Such approaches contribute to risk mitigation in food system sustainability and support broader ecological goals.

Research Methods

To ensure accuracy and reliability, high-purity reagents required for the study were sourced from Sigma-Aldrich (Merck, Germany). A range of physicochemical analytical methods was employed to assess various parameters. The determination of dry matter content, active acidity (pH), and titratable acidity was conducted according to the AOAC Official Method. Carbohydrate quantification was performed using high-performance liquid chromatography (HPLC) to ensure precise measurement of sugar composition.

Phytochemical analysis was carried out using spectrophotometric methods (Shimadzu, Japan) to quantify bioactive compounds, while thin-layer chromatography (TLC) was utilized for qualitative compound identification. Additionally, elemental composition analysis was performed using an inductively coupled plasma atomic emission spectrometer (ICPE-9820, Shimadzu Corporation) to determine the mineral content in the samples.

Method for Determining Total Carbohydrate Content

The total carbohydrate content was analyzed using high-performance liquid chromatography (HPLC). The analysis was conducted on a Waters HPLC system equipped with a refractive index (RI) detector and a Binary HPLC Pump 1525. Chromatographic separation was performed using an Amide 120 column (250 mm × 4.5 mm), specifically designed for carbohydrate analysis. The column temperature was maintained at 40°C, and 80% acetonitrile (Merck; Sigma-Aldrich) was used as the mobile phase. Detection was carried out using an RI detector, ensuring accurate quantification of carbohydrate content.

Sample Preparation: to precipitate pectin, the juice was mixed with 96% ethanol in a 1:1 ratio. After centrifugation, the supernatant was combined with the mobile phase (80% acetonitrile) in a 1:1 ratio. Before injection into the HPLC system, the sample was filtered through a 0.45 μm membrane filter to remove particulates and enhance analytical precision.

Method for Determining Total Phenolic Content

The total phenolic content was analyzed using a Shimadzu spectrophotometer (Shimadzu, Japan). The method was based on the interaction of phenolic compounds with protein substances, leading to their precipitation as metal salts. This reaction was followed by oxidation, resulting in the formation of a colored complex. The analysis was conducted following the protocol described by Cheng et al. [18]. The quantification of total phenolic compounds was performed using a calibration curve and expressed as mg of gallic acid per 100 g of fruit (mg GA/100 g).

Method for Determining Total Flavonoid Content

The total flavonoid content was determined using a spectrophotometric method, as described by Cheng et al. [18], with modifications for plant-derived fruit samples. The quantification was carried out using a calibration curve, and the results were expressed as mg of catechin per 100 g of fruit (mg C/100 g).

Method for Determining Total Anthocyanin Content

The total anthocyanin content in fruit extracts was quantified using a spectrophotometric method. The analysis was performed in a buffer solution at pH 1.0 and pH 4.5, following the

protocol described by Cheng et al. [18]. The anthocyanin concentration was calculated using the equation provided by Cheng et al. and expressed as mg of cyanidin-3-glucoside per 100 g of fruit (mg CG/100 g).

Method for Determining Vitamin E Content

The thin-layer chromatography (TLC) method described by Whitte et al. [19] was utilized to quantify vitamin E content, employing Emmerie-Engel reagent for detection. The concentration of tocopherol was determined as a percentage, calibrated against a standard curve, and converted to α-tocopherol equivalents based on sample weight, expressed as mg per 100 g (mg/100 g).

Method for Determining Chlorogenic Acid Content

The chlorogenic acid content was quantified using the method outlined by Trineeva et al. [20], employing direct spectrophotometric analysis (Shimadzu, Japan). Chlorogenic acid from the "Fiuka" brand (Germany) served as the standard substance. The concentration of chlorogenic acid was calculated as a percentage by applying the chlorogenic acid coefficient of 507 and using the appropriate formula for dry mass.

Method for Determining Antiradical Activity (DPPH Method)

The DPPH method, based on the reaction between the stable synthetic radical DPPH (2,2-diphenyl-1-picrylhydrazyl) and antioxidants dissolved in ethanol, was used to assess antiradical activity [18]. The antioxidant activity was quantified using the EC30 parameter, which represents the extract concentration required to inhibit 30% of the oxidation reaction. A lower EC30 value indicates greater antioxidant activity, as the rate of oxidative degradation inhibition increases.

Method for Determining Qualitative and Quantitative Mineral Content

Multi-elemental analysis of the samples was performed using an inductively coupled plasma atomic emission spectrometer (ICPE-9820, Shimadzu Corporation). This method relies on measuring the intensity of light emitted by atoms of various elements, which are excited by an inductively coupled argon plasma at different wavelengths [21]. Qualitative analysis is conducted by determining the specific wavelengths, while quantitative analysis is based on the intensity of the emitted light at those wavelengths. The correlation coefficient was ≥ 0.99.

The experiments were conducted in triplicate, and statistical analysis of the results was performed using Stewart's t-test, with a significance level of $p < 0.05$.

III. Results and Discussion

Research by Uleberg et al. [22] demonstrates that both low temperatures and genetic factors significantly influence the flavor profile of blueberry fruit. The organoleptic properties of the fruit are determined by factors such as dry matter content, active acidity (pH), and titratable acidity. Blueberry fruit is known to contain several organic acids, including malic, citric, gallic, chlorogenic, ascorbic, and quinic acids. Studies have shown that malic acid is the dominant acid in wild blueberries, while citric acid is the primary acid in cultivated garden varieties.

The results of the physicochemical analysis of wild blueberries (*Vaccinium arctostaphylos* and *Vaccinium myrtillus* L.), as well as homogenized blueberry sauce containing seeds, are presented in Table 1.

The dry matter content in the fruit of the Caucasian blueberry (*Vaccinium arctostaphylos L.*) was found to be low, measuring 9.4 ± 0.18%, while the common blueberry (*Vaccinium myrtillus L.*) fruit contained a higher dry matter content of 10.5 ± 0.12%. The active acidity (pH) of the common blueberry sauce was 3.6 ± 0.06, while the pH of the Caucasian blueberry sauce was slightly higher at 3.9 ± 0.07. The acidity was also higher in the Caucasian blueberry sauce, with a value of 1.09 ± 0.08%, compared to the common blueberry sauce, which showed a lower acidity of 0.93 ± 0.08%.

Table 1: *Physicochemical Properties of Vaccinium arctostaphylos L. and Vaccinium myrtillus L. Fruits and Blueberry sauce*

Sample Name	Dry Matter (%)	Active Acidity, pH	Titratable Acidity (% as Malic Acid)
Friut of Vaccinium Arctostaphylos L	9,4 ± 0,18	4,0 ± 0,08	1,20 ± 0,08
Friut of Vaccinium Myrtilus L	10,5 ± 0,12	3,8 ± 0,06	1,01 ± 0,08
Sauce of Vaccinium ArctostaphylosL	11,1 ± 0,10	3,9 ± 0,07	1,09 ± 0,08
Sauce of Vaccinium Myrtilus L	11,7 ± 0,12	3,6± 0,06	0,93 ± 0,08

According to studies by Uleberg [22], the free sugars present in blueberry fruit include fructose and glucose, with sucrose detected in trace amounts. Our research findings on sugar content are consistent with those of Uleberg [22]. The results of the study are presented in Table 2.

Table 2: *Carbohydrate Content in Vaccinium arctostaphylos L. and Vaccinium myrtillus L. Fruits, Seeds, and Homogenized Sauce*

Sample Name	Fructose %	Glucose %	Total Sugars %
Fruit of Vaccinium Arctostaphylos L.	5,3 ± 0,8	3,4 ± 0,8	8,7 ± 0,8
Friut of Vaccinium Myrtilus L	5.5 ± 0,6	4,1 ± 0,8	9,6 ± 0,6
Sauce of Vaccinium ArctostaphylosL	5,4 ± 0.8	4.0 ± 0,8	9.4 ± 0,6
Sauce of Vaccinium Myrtilus	5,4 ± 0,6	4,5 ± 0,8	9,9 ± 0,6

The analysis of carbohydrate content revealed that neither blueberry fruit nor sauce contains sucrose. The fructose content in both the fruit and sauce ranged from 5.3% to 5.5%, contributing to the pleasant taste of the sauce.

Phenolic compounds are among the most prevalent chemical constituents in plants. Medical research has demonstrated their high biological activity and significant prophylactic effects against various diseases [23]. Consequently, determining the quantitative levels of phenolic compounds is essential for evaluating the antioxidant activity of the studied samples, as numerous studies have established a direct correlation between these two parameters. The total phenolic content of the samples analyzed in this study is presented in Table 3. High concentrations of phenolic compounds were observed in the Vaccinium myrtillus fruit and sauce, with 1677 mg GC/100 g in the fruit and 2585 mg GC/100 g in the sauce. In contrast, lower levels were found in the Vaccinium arctostaphylos fruit (1554 mg GC/100 g) and sauce (2477 mg GC/100 g).

Flavonoids are bioactive compounds known for their high biological activity, with several being successfully utilized in pharmacology to treat cardiovascular diseases [23]. The quantitative concentration of flavonoids plays a crucial role in determining the antioxidant activity of a sample. In wild-growing blueberries, flavonoid content is 2-3 times higher compared to cultivated varieties. The results of the flavonoid content analysis for the samples studied are presented in Table 3. Lower concentrations of flavonoids were found in the Caucasian blueberry fruit and sauce, with 522 ± 10.3 mg catechin/100 g in the fruit and 940.7 ± 14.3 mg K/100 g in the sauce. In contrast, the common blueberry fruit and sauce contained 757 ± 10.3 mg catechin/100 g and 1190 ± 14.3 mg K/100 g, respectively.

Table 3: *Content of Biologically Active Compounds in the Fruit and Sauce of Caucasian (Vaccinium arctostaphylos) and Common (Vaccinium myrtillus) Bilberries*

Chemical components	Fruit of Vaccinium Arctostaphylos	Fruit of Vaccinium Murtilus	Sauce of Vaccinium Arctostaphylos	Sauce of Vaccinium Murtilus
Phenolic Compounds (mg%)	1554 ± 14,3	1677 ± 10,3	2477 ± 14,3	2585 ± 14,3
Flavonoids (mg%)	522 ± 10,3	757 ± 10,3	940,7 ± 14,3	1190 ± 14,3
Anthocyanins (mg%)	280 ± 12,3	540 ± 15,3	500,7 ± 10,3	1041 ± 14,3
Vitamin E (mg%)	-	-	0,58 ± 14,3	0,60 ± 14,3
Chlorogenic Acid (%)	1,5 ± 12,3	1,7 ± 13,3	5,8 ± 14,3	6,8 ± 14,3
Antioxidant Activity (mg/mL)	1,1 ± 0,03	1,3 ± 0,03	2,0 ± 0, 03	2,3 ± 14,3

Anthocyanins are a class of polyphenolic compounds that are exclusively synthesized in plants. The concentration of anthocyanins is a key factor in determining their antioxidant properties. These compounds are highly sensitive to factors such as temperature and light. Blueberries are notably rich in anthocyanins [24]. The results of the analysis of anthocyanin content in the samples are presented in Table 3. High anthocyanin concentrations were found in both the common blueberry fruit and sauce, with 757 ± 10.3 mg cyanidin-3-glucoside/100 g in the fruit and 1190 ± 14.3 mg CG/100 g in the sauce.

Free radicals in the body can lead to the degradation or mutation of living cells [23]. Antioxidants are capable of neutralizing free radicals. The DPPH method, which measures the interaction between free radicals and 2,2-diphenyl-1-picrylhydrazyl, is commonly employed to evaluate antioxidant activity. The results of the DPPH-based antiradical activity analysis for the samples are presented in Table 3. According to these findings, the blueberry sauce demonstrated antioxidant activity that was twice as high as that of the corresponding fruits. The fruits exhibited values of 1.1 ± 0.03 mg/mL and 1.3 ± 0.03 mg/mL, while the sauce showed values of 2.0 ± 0.03 mg/mL and 2.3 ± 14.3 mg/mL.

Chlorogenic acid, an ester of caffeic acid and quinic acid, is a key polyphenol in blueberry fruit. It is renowned for its potent antioxidant, antiviral, antibacterial, antifungal, anti-inflammatory, and antidiabetic properties. Additionally, it demonstrates hypoglycemic, hypocholesterolemic, hepatoprotective, and anticancer effects. The results of the study on the quantitative content of chlorogenic acid in blueberry fruit samples are presented in Table 3. The findings indicate that relatively lower concentrations of chlorogenic acid were detected in the Caucasian blueberry fruit and sauce (1.5 ± 12.3% and 5.8 ± 14.3%, respectively), while higher concentrations were observed in the common blueberry fruit and sauce (1.7 ± 13.3% and 6.8%, respectively).

Vitamin E is a powerful natural antioxidant that plays a crucial role in maintaining normal blood coagulation and promoting wound healing, thereby reducing the risk of scar formation. It also supports nutrient absorption, enhances metabolic functions, and strengthens capillary walls. Blueberry sauce contains α-tocopherol, the most bioactive and valuable form of Vitamin E.

A study examining the α-tocopherol content [16] in both blueberries and blueberry sauce demonstrated that the fruit contains α-tocopherol in trace amounts. The sauce derived from Caucasian blueberries has a concentration of 0.58 ± 14.3 mg%, while the sauce from common blueberries contains 0.60 ± 14.3 mg%.

Sauce It is important to note that, when consumed, the skin and seeds of blueberries are typically not processed. However, homogenized blueberry sauce, which includes both the seeds

and the skin, is further enriched with the biologically active compounds mentioned above, including Vitamin E, which is present in the fatty oils of the seeds.

Mineral Elements: The objective of this study was to analyze the chemical element content in the fruit of wild blueberries and homogenized blueberry sauce with seeds from the high-mountainous region of Adjara. The qualitative and quantitative analysis of mineral elements was conducted using an inductively coupled plasma atomic emission spectrometer (ICPE-9820). A total of 28 elements were analyzed, including 7 macronutrients (Ca, K, P, Mg, Na, Si, Fe) and 21 microelements and ultramicroelements (Al, Zn, Mn, B, Cu, Ba, Se, Cr, Ni, Mo, Co, V, Cd, Pb, Be, Li, Ti, As, Hg, Sb, Tl). The mineral content of the blueberry fruit and sauce is presented in Table 4.

Table 4: *Mineral Element Content (mg/L on a dry weight basis)*

№	Element Name	Fruits of Vaccinium Arctostaphylos	Fruits of Vaccinium Murtilus	Sauce of Vaccinium Arctostaphylos	Sauce of Vaccinium Murtilus
	Macroelements (mg/L)				
1	Calcium (Ca)	790	911	2209	2948
2	Potassium (K)	1232	1510	2528	3001
3	Phosphorus (P)	940	1132	1500	2395
4	Magnesium (Mg)	160	201	20	280
5	Sodium (Na)	50	65	80,6	73,6
6	Silicon (Si)	62	53,9	75,9	89,7
7	Iron (Fe)	11,8	18,2	28,9	35,2
	Microelements (mg/L)				
8	Aluminum (Al)	21,6	25	28,7	26,2
9	Zinc (Zn)	13,6	16,1	20,6	20,8
10	Copper (Cu)	5,7	8,7	12,7	9,8
11	Manganese (Mn)	9,2	18,6	30,5	27,9
12	Molybdenum (Mo)	0,004	3,7	10,8	7,7
13	Boron (B)	12,5	10,6	25,4	22,6
14	Cadmium (Cd)	<0,00049	< 0,004	< 0,001	
	Ultramicro Elements (μg/L)				
15	Beryllium (Be)	<0,0001	<0,0004	<0,0053	<0,001
16	Lithium (Li)	BDL	BDL	BDL	BDL
17	Lead (Pb)	0,0007	0,0021	<0,001	<0,0008
18	Titanium (Ti)	<0,012	<0,075	<0,01	<0,01
19	Vanadium (V)	0,008	0,006	0,004	0,002
20	Barium (Ba)	0,06	0,06	0,4	0,4
21	Arsenic (As)	BDL	<0,003	<0,080	<0,003
22	Chromium (Cr)	2,6	1,79	1,8	2,1
23	Nickel (Ni)	0,15	0,37	0,07	0,04
24	Selenium (Se)	0,8	1,71	7,2	8,5
25	Cobalt (Co)	1,116	1,0453	0,31	0,7
26	Mercury (Hg)	BDL	BDL	BDL	BDL
27	Antimony (Sb)	<0,0014	<0,0011	<0,0034	<0,002
28	Thallium (Tl)	BDL	BDL	BDL	BDL

BDL – Below the detection limit

The research has demonstrated that both blueberry fruit and sauce contain essential elements for nutrition, making these findings valuable for assessing the ecological status of the region.

Among the macronutrients, the samples analyzed are particularly rich in K, P, and Ca. Additionally, significant amounts of Mg and Si were detected. The concentrations of Na, Fe, Zn, Cu,

Mn, Mo, B, V, and Ba are following food safety standards. Levels of toxic elements, such as Pb, Ti, As, Cd, Be, Li, V, Ba, Ni, Sb, and Tl, were found to be below detection limits. The study supports an environmentally responsible processing strategy that limits waste output and maximizes resource use. Such non-waste approaches can play a role in reducing the environmental footprint of food production chains, contributing to risk-informed sustainable development in agricultural infrastructure.

It is well-established that there is a correlation between mineral elements and biologically active compounds. The presence of Cr, Cu, and Mo promotes the accumulation of flavonoids in plant materials and enhances the P-vitamin activity and anti-inflammatory properties of blueberry fruit. The elements Mo, Zn, B, Cu, and Si facilitate the accumulation of polyphenolic compounds, thereby contributing to the raw material's choleretic, diuretic, antidiarrheal, and anti-inflammatory effects. Furthermore, Mg, P, Mn, Ca, and Ni help regulate blood sugar levels and may support the treatment of mild forms of diabetes. Fe, Mn, Cu, and Co are components of the blood-forming complex, and their concentrations are crucial for the medicinal properties of blueberry fruit.

IV. Conclusion

The study reinforces the need for risk-oriented design in food production processes, particularly by reducing organic waste through whole-fruit utilization. This aligns with sustainability paradigms aimed at preserving ecological balance and reducing environmental hazards associated with fruit processing. The research has shown that homogenized blueberry sauce, including seeds, contains significantly higher levels of phytonutrients than the whole fruit, particularly in terms of biologically active compounds. This is primarily due to the elevated concentrations of polyphenols, anthocyanins, and flavonoids. The multifunctional properties of blueberry sauce make it a valuable bioactive food supplement, not only for promoting health and preventing diseases but also for potential applications in the pharmaceutical industry.

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CONFLICT OF INTEREST.
The authors declare that they have no conflict of interest.

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ASSESSMENT OF THE IMPACT OF OUTFLOWING GEOTHERMAL WATER ON THE ECOSYSTEM BY VARIOUS RESEARCH METHODS

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Abstract

The relevance of the work is determined by the fact that the problem of geothermal waters flowing from wells in the Chechen Republic has remained unsolved for many years and has managed to make its own adjustments to the ecology of the areas where they are located. The purpose of this article is to study the state of vegetation in the area of influence of the flowing geothermal water from the wells 9-T Kargalinskaya (Shelkovsky district) and 11-T Gunyushki (Grozny district) of the Chechen Republic using field and remote methods,and to conduct a brief comparative analysis of the obtained data, on the basis of which it is possible to make forecasts and make proposals for improving the geoecological situation in the study area. To achieve this goal, the following tasks were solved: 1) assessment of biodiversity in the area affected by the flowing geothermal water from the wells; 2) study of the features of NDVI dynamics and identification of the main trends for areas subject to different levels of anthropogenic impact. The studies were conducted using both field and remote sensing methods over the period 2017-2022. The conducted geobotanical studies indicate the suppression of vegetation in the area of geothermal water discharge from the well. The results of calculating the vegetation index (NDVI, MTVI) using Earth remote sensing data also confirm these changes. The consequences of geothermal water discharge on the daily surface can give in to the environmental situation in the study of the territory, drawing other components of the environment into the cycle, such as underground and surface watercourses, soils, microclimate, etc. The solution of the indicated problem in complex with scientifically grounded approach to rational use of geothermal potential, will allow to stop the process of deterioration of the vegetation cover in the research area.

Keywords: geothermal well, vegetation cover, dynamics, geothermal waters, outflow, transect, NDVI.

I. Introduction

The twentieth century has been characterized by significant anthropogenic transformation of the environment. Consequently, one of the pressing issues of our time has become the dramatic decline in biodiversity—a necessary component of the stability and functioning of natural ecosystems, as well as an integral part of human existence on Earth. And, of course, even seemingly minor changes occurring in the environment should not be ignored. They serve as indicators of the impact of a particular factor, the duration of which can lead to irreversible processes. Maintaining the environmental sustainability of areas annually involved in economic activity and ensuring rational nature management—the sustainable development and health of all living organisms in these areas depend on addressing these issues.

To study the state of vegetation in the geothermal water impact zone, geobotanical studies were conducted in the early autumn of 2020-2022. Using remote sensing data, the NDVI and MTVI were calculated. Geobotanical research involves the comprehensive study of plants and their habitats, which, to a certain extent, shape each other. The growth of both individual plant species and the communities they form is directly dependent on a range of physical and geographical factors (topography, soils, parent materials, etc.). The role of topography, albeit indirectly, influences vegetation in particular. Topography has a profound impact on the specificity of phytocenoses and their distribution. Plants and the phytocenoses they form, in turn, modify their environment: the climate at the macro- and micro-levels, the composition, structure, and moisture content of soils, and the drainage network.

II. Methods

The study revealed heterogeneity in the area's vegetation cover, caused by anthropogenic factors (primarily well outflow) and subsequent cause-and-effect relationships (grazing, trails, recreation, etc.).

The routes were designed taking into account the topography and the impact of the outflowing waters on the landscape. For comparative analysis, two profiles were established in the study area: Profile I directly in the geothermal water impact zone, and Profile II—a control profile (Figs. 1, 2) [1].

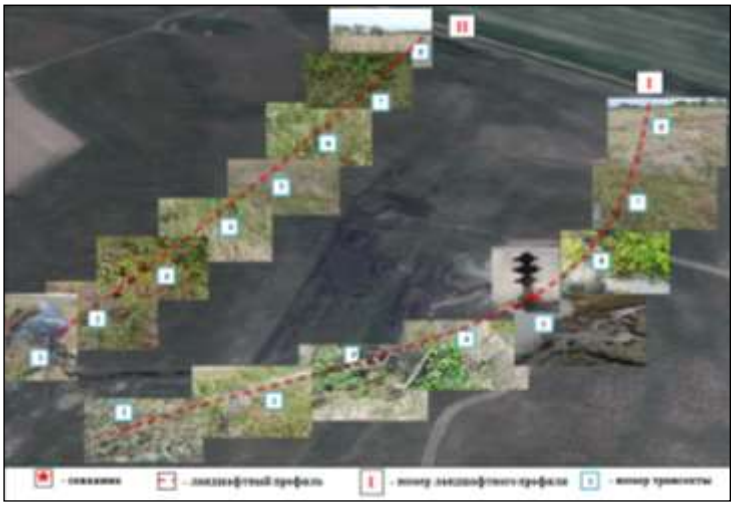


Fig. 1. Field survey map (impact area of well 9-T Kargalinskaya)



Fig. 2. Field survey map (impact area of borehole 11-T Gunyushki)

Geobotanical studies were carried out with the identification of the main phytocenoses, at certain points of which transects (1 m^2) were laid and dominant associations, the number of dominants, and the total projective cover were determined (Table 1) [2].

Table 1. Geobotanical descriptions of transects

Wells	Profile	Parameter	Transect number							
			1	2	3	4	5	6	7	8
11-T Gunyushki	I	Projective cover, %	15	5	30	40	55	30	80	50
		Number of species	1	1	3	3	4	2	1	2
	II	Projective cover, %	50	50	30	30	60	50	60	40
		Number of species	3	3	2	2	5	4	4	3
9-T Kargalinskaya	I	Projective cover, %	30	40	30	30	0	10	30	20
		Number of species	2	2	2	1	0	1	2	2
	II	Projective cover, %	40	40	50	50	30	40	60	70
		Number of species	2	2	3	3	4	5	3	3

III. Results

As a result of field studies, the following was revealed: in the area of borehole 9-T Kargalinskaya: on profile I, the flora is represented by 12 plant species belonging to 10 genera and 6 families, on control profile II, the species diversity is slightly higher: here there are 20 plant species belonging to 13 genera and 8 families; in the area of borehole 11-T Gunyushki: profile I: the flora is represented by 17 plant species belonging to 14 genera and 11 families, on control profile II, the species diversity is slightly higher: here there are 26 plant species belonging to 18 genera and 12 families.

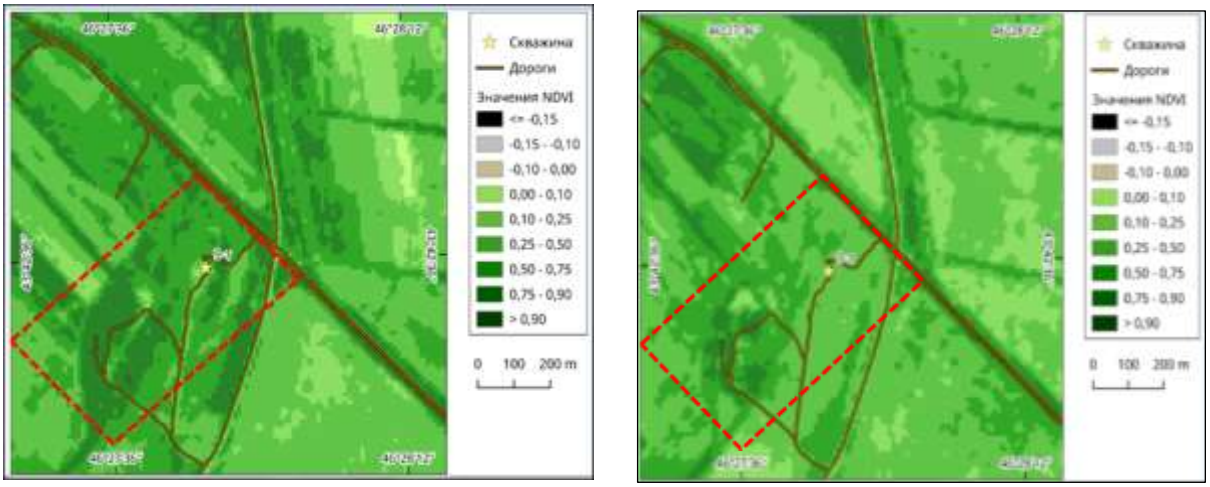
Thus, on the control profiles, the species composition and the area of projective cover are higher, with the exception of those transects that are influenced by other factors (proximity to running paths and roads, small lakes) [1, 2].

In parallel, studies were conducted to monitor the state of the vegetation cover in the area of the geothermal water discharge and wells 9-T Kargalinskaya and 11-T Gunyushki using remote sensing data in the 2017-2022 time frame from Sintenel-2A, which provides data on the spectral reflectivity of the earth's surface that have undergone atmospheric correction, which allows for a more accurate analysis of surface properties (Figs. 3, 4).

Detection and quantification of green vegetation is the main purpose of vegetation cover research using remote sensing data. This can cover a range of tasks: monitoring agricultural lands, analyzing changes in vegetation cover associated with temperature fluctuations under the influence of natural and man-made factors, monitoring the physiological state of plants due to insufficient or excess moisture, assessing projective cover, etc.

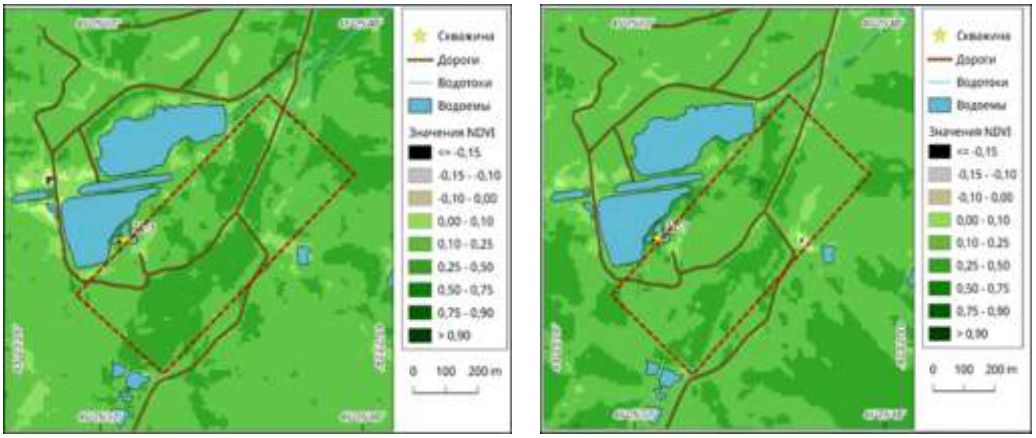
In addition, individual indicators (for example, the normalized difference vegetation index (NDVI) can be used to measure the uneven fertilizer requirements of agricultural crops across the entire field, to create productivity maps, and for differentiated fertilizer application [4]. NDVI is often used as one of the tools in conducting more complex types of analysis, the results of which can include productivity maps of forests and agricultural lands, maps of landscapes and natural zones, soil, arid,

phenological, and other maps. It can also be used to obtain numerical data for use in calculations assessing and forecasting crop yields and productivity, biological diversity, the degree of disturbance, and damage from various natural disasters. both natural and man-made, etc., which is confirmed by the results of studies conducted in the field of environmental and nature conservation [5, 7, 8, 10].



а) June 2017 б) June 2022

Fig. 3. Monitoring the NDVI index in the area of well 9-T Kargalinskaya



а) June 2017 б) June 2022

Fig. 4. Monitoring the NDVI index in the area of well 11-T Gunyushki

As is well known, the optical properties of a vegetated area vary over time due to various factors characterizing the state of the vegetation cover: moisture, age, mineral deficiency, various pests, canopy geometry, and leaf distribution within the canopy. These factors influence the reflectivity of the vegetation and, consequently, the vegetation index [4, 5].

To understand the health of a plant, it is necessary to calculate the ratio between the difference in the intensities of reflected light in the infrared and red ranges and their sum [3,9]:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

where NIR is the near-infrared reflectance; R is the red reflectance. Typical NDVI values are shown in Table 2. [6].

It should be noted that, based on NDVI values, most of the study area is classified as having sparse or sparse vegetation (NDVI values generally range from 0.3 to 0.6).

NDVI monitoring in the impact area of well 9-T Kargalinskaya revealed the following: higher index values are observed in 2017 images (from negative values to 0.5-0.6). In 2022 images, NDVI values have significantly decreased compared to 2017, with a slight increase in vegetation mass in the area of the small lakes, which is also confirmed by geobotanical studies (an increase in the number of species on transects 5 and 6 on the control profile). This NDVI trend can partly be attributed to fluctuations in meteorological conditions in the study area between 2017 and 2022. In the zone of maximum impact of the effluent, significant transformation of natural plant communities is observed. However, overall, the studies showed that a spatial resolution of 10 m/pixel is insufficient for the purposes of this study; more accurate UAV data (5 cm/pixel) is required.

Table 2. NDVI values for different types of surfaces [3,6]

Object Type	Red reflectance	Near infrared reflectance	NDVI
Dense vegetation	0,10	0,50	0,700
Sparse vegetation	0,10	0,30	0,500
Open soil	0,25	0,30	0,025
Clouds	0,25	0,25	0,000

Figures 5 and 6 present the Multi-Temporal Vegetation Index (MTVI) values, which is a simple difference calculation of NDVI(date1) – NDVI(date2). This index allows one to estimate the range of NDVI variation. It is the difference between NDVI values obtained in June 2017 and 2022. MTVI values below zero or negative indicate areas where the NDVI has increased. As can be seen from the results, NDVI dynamics are spatially heterogeneous: some areas exhibit a significant increase, while areas exposed to the effluent are characterized by a decrease in average NDVI values.

In general, the results of the conducted studies using field and remote sensing methods confirm the suppression of the state of the vegetation cover in the area of the geothermal water discharge depending on the level of anthropogenic impact.

IV. Conclusion

Plant life plays a crucial role in Earth's ecosystems, influencing virtually all components of the geographic envelope. Understanding the current state and dynamics of vegetation change is essential for the timely resolution of environmental problems and the efficient use of natural resources.

A comparative analysis of vegetation cover survey results in the thermal water discharge area using various methods provided information on vegetation change dynamics over the 2017-2022 period.

Geobotanical studies revealed the number of species and the area of projective cover, indicating vegetation suppression along transects located close to the 9-T Kargalinskaya and 11-T Gunyushki geothermal wells. These indicators are higher on the control profile, with the exception of those transects influenced by other factors (proximity to roads, trails, small lakes, etc.).

A high correlation with net primary production allows the NDVI index to be considered a reliable indicator of landscape productivity. The temporal dynamics of the NDVI reveal changes in productivity, a key ecological parameter of landscapes. As an example, the NDVI and MTVI were calculated in the area of the 9-T Kargalinskaya well. Overall, an increase in these indicators was observed over the analyzed period. The ecological situation here can be assessed as favorable. However, in the detailed study area, NDVI values decreased, and correspondingly, vegetation productivity also declined, indicating a negative landscape-ecological situation.

Thus, the studies independently confirm the suppression of vegetation cover directly in the area of the geothermal discharge from the 9-T Kargalinskaya well.

From a cost-effectiveness perspective, studies using remote sensing are generally attractive for vegetation cover studies, but at the micro-level, geobotanical studies are more appropriate for achieving

the required level of detail. However, with growing interest in vegetation indices, which offer advantages such as ease of use and reliability, and more recently, thanks to the expansion of the Earth observation satellite data base, they are becoming a key and widespread tool for monitoring and assessing the condition and dynamics of vegetation.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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A PRACTICAL EXAMPLE OF INTEGRAL ASSESSMENT OF THE SOCIAL RISK OF EMERGENCIES CAUSED BY FLOODS

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Abstract

Every year, the management bodies of the unified state system for preventing and eliminating emergencies carry out advance preparations for the flood period. However, statistics show no decrease in the number of flood-related deaths and injuries. This is due to the lack of an integrated approach to systematically assessing and considering a set of interrelated factors that determine social risk in the event of a flood. This article provides a practical example of assessing the social risk of emergencies caused by floods, based on a scientific and methodological framework developed by the author. This apparatus is based on hydrological methods, geoinformatics and mathematical modelling, both descriptive and predictive. It can be used by municipalities to solve issues of local importance aimed at protecting the population from emergencies caused by floods.

Keywords: flood risk of death in floods, social risk, integral assessment, integral indicator, metric of social risk, scientific and methodological apparatus, digital model of the population, evacuation during flooding, parametric law of human damage

I. Introduction

Floodwaters claim thousands of human lives every year. Thus, according to the research center of the University of Louvain (Belgium), presented in the annual report "2024 Disaster in Numbers", in 2024 floods ranked first in terms of the number of deaths in the world (in 2023 – third place) and fourth in the period 2004-2023.

Despite the fact that the contribution of Russian emergency situations indicators to the global EM-DAT database is insignificant [1], floods in our country occupy the first place in terms of the disaster coefficient [2], taking into account the number of deaths and the victims. Among all floods, the most dangerous for the population (for humans, for society) are emergencies, the sources of which are floods after heavy rains [3].

The article [4] presents an integrated approach to the systematic assessment and accounting of a set of interrelated factors that determine the level of social risk of emergencies caused by floods: natural and climatic, characterizing the danger of the area, organizational and engineering, characterizing the coping capacity, as well as socio-demographic, characterizing the typology of the population exposed to the damaging factors of flood water. A scientific and methodological apparatus (SMA) has been developed, which is a set of conceptual apparatus, models, methods and algorithms that provide a systematic and informed approach to analyzing and predicting the consequences of the impact of devastating disaster factors on the population, the sources of which are floods, and quantifying the social risk of such emergencies.

The purpose of the article is a brief description of the developed scientific and methodological apparatus, as well as a practical example of assessment of the social risk of emergencies caused by flood in one of the Russian cities.

II. A scientific and methodological apparatus for the integral assessment of the societal risk caused by floods

The developed SMA [4] uses a multifactorial model for assessing the social risk of death in floods, which includes the following factors:

– the danger of the territory, including natural and climatic conditions such as terrain, physical and geographical zoning;

– insufficient potential to counter the danger, including shortcomings in the organization of public notification and information, as well as the lack of evacuation of the population or non-compliance with the established deadlines for emergency evacuation of the population;

– socio-demographic factors characterizing the typology of the population exposed to the damaging factors of flood water.

The main indicator of the risk of emergency, which is used in the developed SMA, is the social risk (death in) an emergency, defined as the probability of death of at least N people, when an emergency occurs with a certain frequency [5].

Two metrics (quantitative indicators) of the social risk (death in) an floods have been established, taking into account the probabilistic nature of the occurrence of floods, the probability of exceeding the predicted water level above the totality of all possible values, as well as the consequences of such emergencies, expressed in the number of people killed:

– F-N diagram (Frequency-Number diagram, frequency–number of victims diagram) – the dependence of the number of losses (deaths) of a population group on the frequency of implementation of various emergency scenarios for a given time [5, 6];

– an integral indicator of the level of social risk of an emergency representing the area under the F-N diagram.

The SMA assumes that the frequency of implementation of various scenarios in F-N diagram F is a discrete value and is set through the probability of exceeding hydrological values (as a rule, 0,5 %, 1 %, 5 %, 10 %, 20 %). The mathematical expectation of the number of deaths N during the event E (flood), which leads to an emergency, is determined by dependence (1), which, unlike the previously adopted approaches [5, 6, 7], includes the variable P_{evac} - evacuation during flood, which characterizes the coping capacity:

$$N = P_{evac} \cdot \iint_{S} \int_{DF_{min}}^{DF_{max}} P(DF) \cdot f(x,y,DF) \cdot \psi(x,y) dDF dx dy \quad (1)$$

where S is the area of the municipality; DF is the damaging factor; DF_{min}, DF_{max} are the minimum and maximum possible value of the damaging factor of flood for the territory under consideration; ψ(x,y) is the distribution function of population within the territory under consideration; P(DF) is the parametric law of human damage; f(x,y,DF) are functions of the density distribution of the intensity of the damaging factor within the territory under consideration, P_{evac} is the probability of timely evacuation during flood, $P_{evac} \in [0;1]$.

The geoinformation system (GIS) is an SMA integration platform. It includes digital terrain models, thematic (geographical) databases, spatial data models, algorithms for spatial analysis, data processing, as well as models and algorithms for visualizing results.

The structure of the developed SMA is shown in Fig. 1.

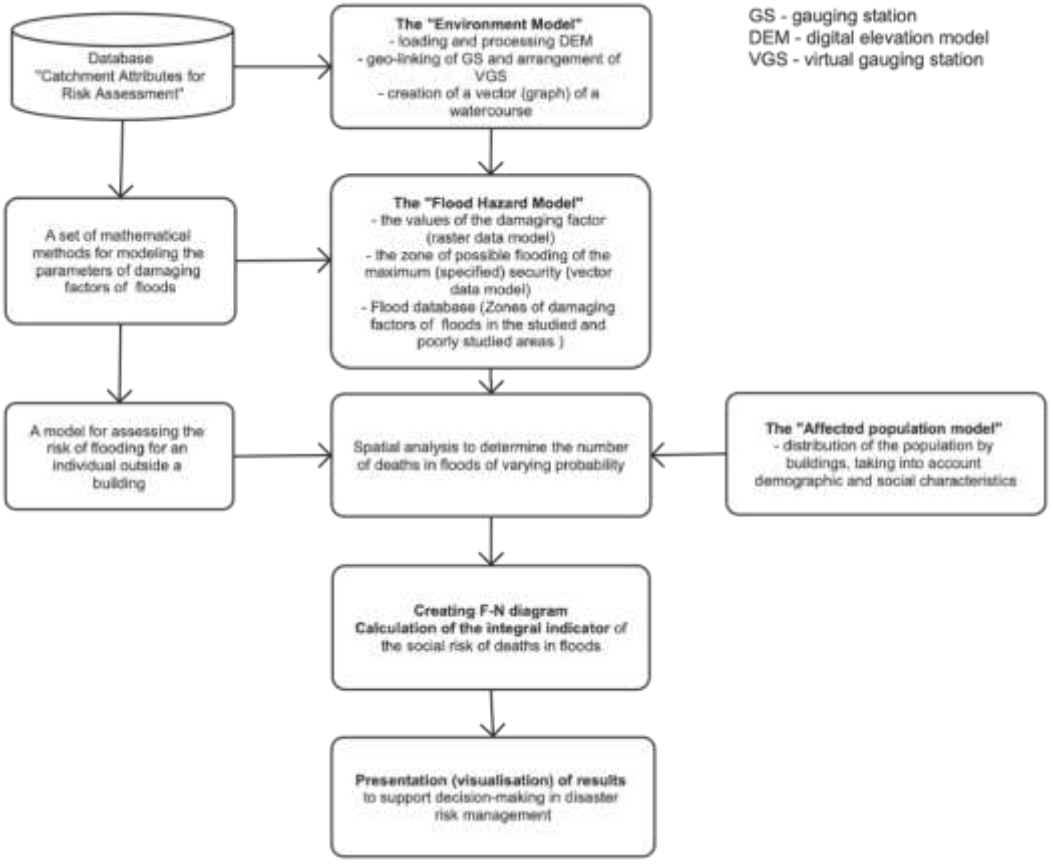


Figure 1: *The structure of the scientific and methodological apparatus for quantifying the social risk of death in floods*

In the functional block "Environment Model" (Fig. 1), a digital twin of a flood-prone area is created. During modeling in this block, the preparation of the DEM, the modeling of the hydrographic network (the construction of a vector (graph) of the watercourse), as well as the arrangement of virtual gauging stations take place. The creation of an "Environment Model" is described in the author's articles [9, 10].

The functional block "Flood hazard model" (Fig. 1) is designed to simulate the values of damaging factors of floods after heavy rains. The simulation is performed for a predefined set of emergency scenarios. For the previously created "Environment Model", the selected digital geographical space is divided into elementary cells that coincide with the DEM matrix using a regular grid. For each elementary cell and a predefined set of scenarios, the values of the damaging factor of flood water are determined, numerically equal to the product of the depth of the flow and the flow velocity of flood water [11]. Flood hazard modeling described in the author's publications [12, 13, 14] and use models for probabilistic modeling of the parameters of damaging factors and mapping of floodwaters in areas that have been studied and poorly studied areas in hydrological terms. The models take into account the physical and geographical zoning of the territory.

As a result of probabilistic modeling of the parameters of damaging factors and flood mapping, created:

- vector data model that describes the geometry of the zone of possible flooding of the maximum (specified) probability.;
- for each scenario, there is a raster data model containing calculated values of the depth of flooding in each cell of the raster;
- for each scenario, a raster data model containing calculated values of the damaging flood factor (product of the depth of the flow and the flow velocity of flood water) in each cell.

The KMeans cluster analysis method [15] was used afor effectively transform a raster model containing calculated values of the damaging flood factor into a formalized system of flood hazard zones.

In the functional block "The affected population model" clustering of the population was performed according to the maximum permissible value of the damaging factors of flood water, exceeding which a person loses stability and may die. Clustering was based on the deterministic criteria obtained in [11] for human damage in flood water outside the building. The population is divided into 5 clusters, taking into account the age of the individual, as well as the classification as a vulnerable population group.

Further, spatial objects (residential buildings) in the zone of possible flooding of the maximum (specified) probability was endowed with "demographic" properties through a set of attributes – quantitative features that characterize the demographic characteristics of the residents living in them (age, gender, vulnerability). In the absence of factual information on the distribution of the population by residential buildings, the assignment of "demographic" properties to the building is carried out in proportion to the area and number of floors of the residential building, as well as the average distribution by age and gender.

So the distribution function of population within the territory under consideration ψ(x,y) in formula (1) is the corresponding digital model of the population of the municipality, which is a table indicating for each residential building a virtual population of residents and assigning them to a specific cluster according to the maximum permissible value of the damaging factors of the flood wave.

As noted earlier (see formula (1)), timely evacuation of the population reduces the social risk of death in an emergency. To determine the probability of evacuation in case of a flood, we apply the well-known empirical formula for determining the probability of evacuation from a building in case of a fire (2) [16]:

$$P_{evac} = \begin{cases} 0{,}999 \times \dfrac{0{,}8 \times t_{MPL} - t_C}{t_S}, \text{если } t_C < 0{,}8 \times t_{MPL} < t_C + t_S \text{ и } t_C > 0, \\ 0{,}999, \text{если } t_C + t_S \le 0{,}8 \times t_{MPL}, \\ 0, \text{если } t_C > 0{,}8 \times t_{MPL} \end{cases} \quad (2)$$

where t_C is the time for the evacuation of people from the zone of probable flooding, hour; t_S is the time of the beginning of evacuation (the time from receiving a forecast to the start of evacuation); t_{MPL} is the time from receiving a forecast of the flood to flooding of populated areas before the maximum permissible level of the damaging factors of the flood wave.

We will consider individual stability, as well as the value of the damaging factor in the cluster, as independent normally distributed random variables [16]. Then the parametric law of human damage P(DF) (formula 1) is defined as the probability of loss of stability of a person (population) in a stream of water [16]:

$$P(DF) = \Phi\left(\frac{C^l - MPL^k}{\sqrt{\sigma_l^2 + \sigma_k^2}}\right) \quad (3)$$

where Φ is the function of the standard normal distribution; $l \in [1; L]$ are clusters of cluster zoning of the municipality by value of the damaging factor; C^l is the centroid of the cluster l; σ_i is the standard deviation of the cluster l; σ_k is the standard deviation of cluster k; $k \in [1; K]$ are clusters of the population, MPL^k is the centroid of the cluster k; σ_k is the standard deviation of cluster k.

The results of the application of the methodology are an F-N diagram characterizing the dependence of the number of losses (deaths) of a group of the population of a municipality on the frequency of implementation of various emergency scenarios (floods with a given probability), as well as an integral indicator of the level of social risk of an emergency for the territory of the municipality.

III. A practical example of using a scientific and methodological apparatus for the integral assessment of the societal risk caused by floods

The approbation of the methodology for obtaining an integral indicator of the level of social risk caused by floods, was carried out using the example of the municipality of the Irkutsk region – Tulun city. The Tulun city is located on a large left–bank tributary of the Angara River - the Iya River. The region under consideration is characterized by increased flood risk, in recent decades there have been severe rain floods, which led to enormous damage [14].

The initial data for obtaining an integral indicator of the level of social risk caused by floods were:

– information on gauging stations, average daily and highest water levels for gauging stations, provided in the Automated Information System of state monitoring of water bodies [17]; raster map of the maximum modules of the rain runoff of the rivers of the USSR probability of exceeding p = 1 % (annex 5 [18]); raster map of the rain runoff layer of the USSR rivers, probability of exceeding p = 1 % (annex 10 [18]);

– NextGIS Data geodata is a basic map of the Irkutsk region (a vector map that includes more than 30 types of data about the territory: administrative divisions, road network, buildings, reservoirs and rivers, urban infrastructure, etc.);

– population data by gender and age in the Irkutsk region for 2024 [19];

– data on the population over the age of 18 with disabilities [20].

The simulation results were obtained using Python program codes written by the author, as well as using spatial analysis and modeling in QGIS.

The following functional models have been created: "Environment model" [13], "Flood hazard model" (Fig. 2), " The affected population model " (Table 1).

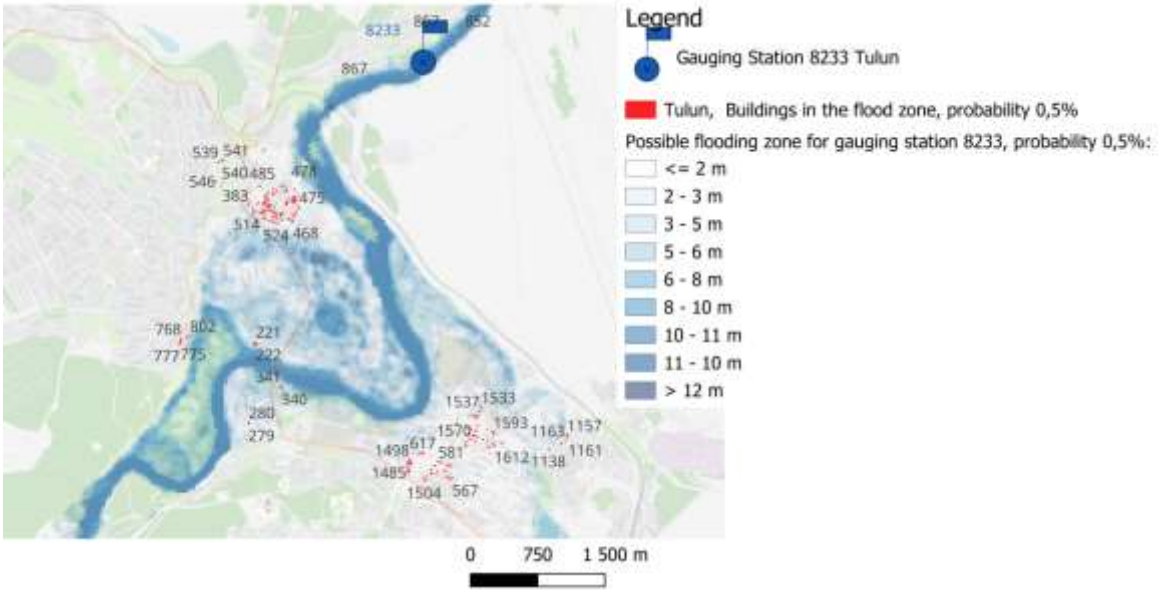


Figure 2: *Flood hazard model (Map of Tulun city showing buildings in the area of possible flooding of maximum (defined) probability)*

The Table 1 shows:
building_id is id number if building in flooding area;
age_group is an assigning residents to a certain age group;
cluster are clusters of the population;
count is number of residents.

The initial data and the results of determining by formula (2) the probability of timely evacuation of the population are shown in the Table 2.

Table 1: *The affected population of Tulun city model (fragment)*

building_id	age_group	gender	cluster	count
121	2-11	female	2	1
220	2-11	female	2	1
220	18-75	female	4	3
220	18-75	male	4	3
221	18-75	female	4	1
222	0-1	female	1	1
222	18-75	female	4	4
222	18-75	male	4	1
222	vulnerable	female	5	1
279	2-11	male	2	1

Table 2: *The initial data and the results of determining the probability of timely evacuation of the population*

t_C, hour	t_S, hour	v_{rise}, m per hour	t_{MPL}, hour	P_{evac}
12	3	0,00005	16,17	0,44

The forecast of the consequences of the implementation of emergency scenarios caused by floods (Table 3) was obtained.

Table 3: *Forecast of the consequences of the implementation of emergency scenarios caused by floods in Tulun city*

F (frequency of scenario), 1/year	Probability of scenario, %	Number of houses in the danger zone, units	The number of the exposed population, people	Estimated number of deaths, N, people
0,01	0,5	186	313	138
0,02	1	78	44	19
0,05	5	3	19	8
0,1	10	3	0	0
0,2	20	0	0	0

The F-N diagram for Tulun city reflects the dependence of the number of population losses (deaths) on the frequency of implementation of various emergency scenarios over a given time (Fig. 3). The diagram also shows an integral indicator of the level of social risk of emergencies caused by floods.

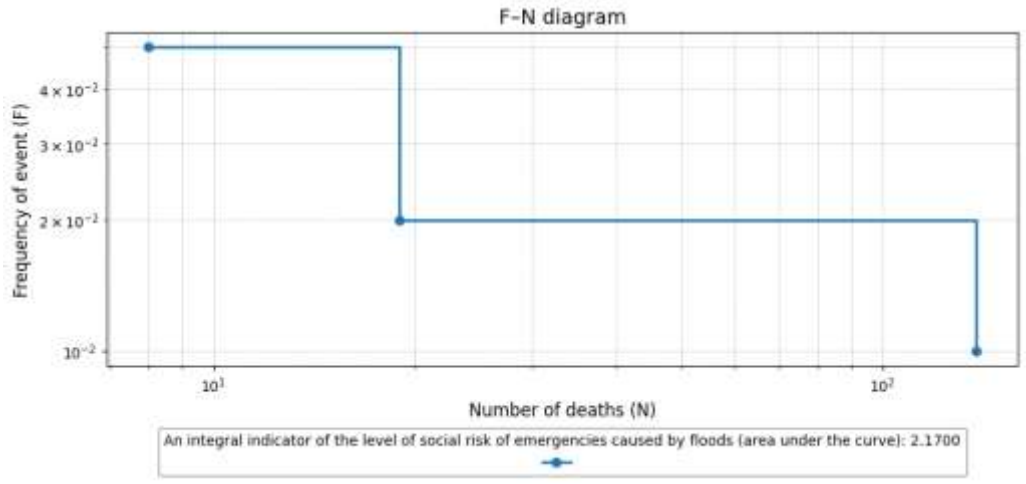


Figure 3: *F-N diagram for the Tulun city flood forecast*

The calculated social risk metrics of an emergency (F-N diagram, integral indicator of the level of social risk of an emergency caused by floods) correspond to the predicted values of the social risk of an emergency at the time of the forecast and can be used in urban planning activities and measures to reduce the risk of an emergency (comparison of social risk metrics in a municipality before and after the implementation of measures).

V. Conclusion

As a result of the research, a comprehensive scientific and methodological apparatus for the integrated assessment of the social risk of emergencies caused by floods has been developed. The practical use of the SMA to predict social risk in case of floods of varying probability for one of the cities made it possible to evaluate the benefits of the developed tool for demonstrating the effects of risk reduction measures. For example, measures to reduce the number of deaths (such as improving warning systems, improving the quality of buildings, spatial planning, and others) shift the line on the F-N diagram horizontally along the X-axis to the left. Reducing the likelihood of flooding, for example, by strengthening dams, will lead to a downward shift of the line on the F-N diagram along the Y axis, which will eventually lead to a decrease in the integral indicator of the level of social risk of an emergency.

A comparison of the integral indicator of the level of social risk of an emergency between municipalities (benchmarking tools) can help identify problem areas and carry out targeted fixation to reduce the social risk of an emergency in a particular municipality.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DISTRIBUTION OF DIGITAL SERVICES AND TECHNOLOGIES IN THE FORMAT OF E-COMMERCE IN SOLVING PROBLEMS OF SUSTAINABLE DEVELOPMENT

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Abstract

E-commerce is a significant trend in the context of digitalization. Digital e-commerce services are spreading not only on an individual territorial scale, but also on a global economic scale. The transformation, improvement and expansion of commerce into a digital format are associated with the active digitalization of the economic landscape and global geopolitical processes. E-commerce is a significant trend that is developing thanks to digital services and technologies. While digital technologies can contribute to achieving sustainable development goals, their implementation requires consideration of social and environmental aspects. This article examines the development of e-commerce and outlines a range of associated issues. It concludes that improving the efficiency of e-commerce depends on the business model and strategic goal of the company.

Keywords: digital services and technologies, digitalization, e-commerce, sustainable development

I. Introduction

Digital services and technologies are rapidly evolving, creating new conditions for doing business and achieving sustainable development. This leads to the emergence of new markets based on the creation and distribution of products and services in digital formats. Digital services and technologies are applied across many spheres of society and business. Digitalization contributes to the growth of business process efficiency, reduction of environmental and social risks [1].

Along with the advantages that digital services and technologies have, their distribution is associated with new challenges and threats that they pose for the sustainable development of society and business [2]. Digital technologies can contribute to the achievement of sustainable development goals, but their implementation requires taking into account social and environmental aspects [3]. Therefore, the study of directions and issues in the development of digital services and technologies is a pressing task.

E-commerce is one of the significant trends driven by digital services and technologies. E-commerce can contribute to sustainability by implementing green logistics and optimizing resources to reduce negative environmental impacts. E-commerce also provides opportunities to increase supply chain transparency and improve access to eco-friendly products. This allows consumers to make more informed choices, supporting companies that adhere to sustainability and social responsibility. In addition, the use of technologies such as artificial intelligence and blockchain can help track and manage the environmental aspects of a business. This allows companies to manage resources more efficiently and minimize waste.

Initially, scientists interpreted the concept of “e-commerce” as a specific method enabling commercial transactions using information and communication technologies. This approach to defining the nature of e-commerce has been supported by researchers such as R. Amit, C. Zott [4], S. Mohapatra [5], J. G. Van der Vorst [6], J. Zhao [7] and others.

According to A.J. Cullen and co-authors [8], as well as V. Jain and co-authors [9], this definition could only characterize e-commerce during its early stages, when Internet trade was seen as a sales channel for sellers also engaged in traditional (offline) commerce. In other words, it is a narrower approach that equates e-commerce with the process of Internet trading. This means e-commerce refers to selling goods to customers attracted via the Internet, a functionality closely related to the concept of Internet marketing.

Currently, e-commerce is no longer a separate business process within the traditional process of buying and selling. Due to the development of digital technologies and their active implementation, it has become an independent activity.

N. Ivanova and co-authors [10], G. Taher [11] equate the concepts of e-commerce and e-business, viewing them as any revenue-generating activities organized through the Internet and other electronic communication means.

Z. Kedah [12] consider e-commerce and e-business as independent phenomena, arguing that the concepts of "commerce," "business," and "trade" have different meanings and are merely overlapping categories.The definition of e-commerce as part of e-business is supported by authors such as R.D. Smith [13], J. M. Santos-Jaén and co-authors [14], I. Tretyakova and co-authors [15-30]. These authors define e-commerce as electronic trade within consumer and corporate segments. They identify Internet services, Internet media, and software development as part of the e-commerce structure. They emphasize that electronic trade is an integral part of e-commerce, which in turn is an element of e-business.

Summarizing existing approaches, we propose a hierarchy of the terms "electronic trade," "e-commerce," and "e-business." We believe e-commerce can be viewed as an independently functioning sector of the economy. It is based on financial and trade transactions conducted via computer networks and includes business processes related to such transactions. E-commerce refers to activities aimed at buying and selling goods, works, and services using electronic means.

The problem of achieving sustainable growth actualizes the need for research on digital services and technologies. In particular, the relevance of research on the spread of e-commerce in the context of digitalization is growing.

II. Results

E-commerce expands business development opportunities and improves the efficiency of business processes. However, e-commerce is also a segment where digital fraud is most active. Particularly after the onset of the COVID-19 pandemic, the intensity of DDoS attacks has significantly increased. In such attacks, the perpetrator generates a large volume of malicious requests to a web application from various sources [16]. As a result, these requests either completely saturate the communication channel capacities or cause a sudden spike in server load, leading to reduced availability of the targeted resource or its complete unavailability (denial of service).

DDoS attacks cause significant damage to e-commerce websites in the form of lost revenue. During an attack, customers cannot place their orders while the site is down. Companies also incur reputational losses, as the inaccessibility of online stores frustrates customers and leads to customer attrition. Frequently, DDoS attacks serve as a distraction; while IT staff are preoccupied with mitigating the attack, attackers attempt to carry out other actions, such as penetrating the company's information systems.

According to estimates, the global losses incurred by e-commerce businesses due to online payment fraud amounted to $48 billion in 2023 [17].

Economic losses due to fraudulent activities involving online payments increased by 1.3 times between 2021 and 2023. It is worth noting that the region with the highest revenue losses in e-commerce due to payment fraud is Latin America.

The most significant increase in online payment fraud is observed in the "Food Products" category – 37%, followed by everyday goods – 36%, the "Beauty and Health" category – 34%, and electronics and fashion industries – 32% [18].

In the context of rising fraudulent activities in global e-commerce, friendly fraud holds a special place. Analysts note that one out of every ten thefts is committed not by strangers, but by relatives or people from the close circle of the victim. Funds spent without the cardholder's knowledge to pay for an order are presumed to be refundable only upon a bank's claim and verification of the transaction's occurrence by third parties. Currently, the highest level of friendly fraud is observed in the "Food Products" category – 45%.

Account takeover fraud involves obtaining legitimate user data to take control of their online accounts or perform actions on behalf of their account in a retailer's personal account, which may lead to theft of funds or actions to withdraw account balances, place orders, etc. Account takeover can occur via an automated script that enters login data on a large scale or manually. The maximum level is also typical for the "Food Products" category – 50%.

Voucher, coupon, and discount abuse manifests as fraud involving the use of counterfeit coupons, promo codes, and manipulating discounts. The highest levels are seen in the "Food Products" category – 48% and "Clothing, Fashion" – 44%.

According to estimates of the Russian e-commerce market, more than 40% of online shoppers have encountered fraud. For buyers, the issue of ensuring the security of personal data is crucial. This is one of the factors that limits the development and penetration of e-commerce. Buyers are reluctant to use payment card information.

The problem of protecting e-commerce websites from viruses and hacks is also relevant in modern conditions. Website owners often underestimate their invisible opponent, assuming that the site does not hold any value for cybercriminals. It should be noted that most hacks are not just about stealing data or damaging the website template. Often, cybercriminals aim to use the site for spamming or creating a temporary repository for illegal files. Additionally, using hacked websites for botnets or for hidden cryptocurrency mining is also popular [19].

Developers, malware sellers, and hackers gain access to important information when they hack or infect a site with viruses, and may exploit the hosting resources.

In addition, owners of hacked websites face consequences such as: loss of databases, loss of control over the digital resource, content replacement, and the appearance of clones. The consequences of cybercrimes also manifest in:

– Financial loss;

– A significant reduction in traffic, directly caused by the loss of trust and the weakening of reputation;

– Imposition of sanctions by search engines: constant automated security monitoring of resources to detect viruses and prevent user device infections. If malicious components are found, a notice appears in the snippet stating that the site may pose a security threat to the user’s computer. Visits to such a site are minimized, and eventually, it is removed from search results.

Thus, security issues in the digital environment are paramount for both sellers and buyers in modern conditions.

A significant problem in the Russian e-commerce market is the lack of trust from buyers towards online stores and the quality of the products offered. This distrust is driven by the increased risk of purchasing illegal goods.

There are problems related to the protection of intellectual property rights for goods or services sold via e-commerce. Such issues contribute to growing distrust among investors and potential buyers, which can negatively impact the growth rates of this digital business segment.

Among the problems, there are cases of selling illegal, including counterfeit and pirated, goods. The main tool aimed at minimizing illegal entrepreneurship on the Internet in Russia is the blocking of online stores by Roskomnadzor, in accordance with the decision of the regional court. However, this is not always effective. Blocked online stores often move to a new address and resume their illegal activities.

A problem is also the lack of necessary expertise within companies. This issue is common among many companies due to the shortage of highly qualified specialists in this field, such as managers with substantial practical experience in sales, logisticians, marketers, and customer service experts.

A significant barrier to the development of e-commerce is the difficulty of attracting potential buyers and retaining existing ones. Strong competition in the e-commerce segment motivates suppliers and manufacturers to create more attractive conditions, products, and services.

Online trading cannot rely solely on initial investments (such as the official registration of the trading platform, website design, etc.). To maintain the popularity of an online store, it is necessary to continuously increase the expenses associated with ensuring its uninterrupted operation. Therefore, financial issues are crucial.

The lack of knowledge about the benefits of e-commerce also remains a problematic area in the e-commerce segment. Companies that are not ready to implement new methods of promoting goods and services in the digital environment miss opportunities and benefits that could be gained by introducing online sales channels.

Although the average transaction size in e-commerce increases every year, the problem of low purchasing power remains. In modern conditions, the population tends to save, and the growth of real incomes is minimal. Overall, the increase in the average transaction size is not due to the intensive purchase of goods and services online, but to the rising prices of these goods and services.

Another important problem in e-commerce is the pressure exerted by cross-border and "gray" market players on legitimate Russian online retailers. Foreign online stores have rapidly gained market share in Russia. However, after the introduction of retaliatory sanctions by Russia, products and services from certain foreign online platforms became unavailable to Russian users. "Gray" market players currently operate freely in prohibited or conditionally prohibited segments, while legal players cannot enter the market.

In the current environment, the problem related to the difficulty of exporting Russian goods is particularly relevant. This is largely due to geopolitical circumstances and the harsh sanctions imposed on Russia by Anglo-Saxon countries and their allies. The growth of export costs and the need to overcome fierce competition in the global market also contribute to this issue.

In light of the above, the issue of creating a unified and effective practice for the regulation and taxation of the e-commerce sector becomes urgent. Typically, e-commerce cannot be regulated by norms that apply only within one country. Therefore, the need for extraterritorial regulation becomes evident. This regulation aims to control both domestic and cross-border online trade based on unified principles, regardless of jurisdiction [24-36].

III. Discussion

Despite a number of problems, e-commerce is currently characterized by stable growth. This has been largely facilitated by active digitalization, the COVID-19 pandemic, geopolitical factors, and changes in consumer preferences.

Most modern economists directly link the development trajectory of the e-commerce market to new technologies that are actively being implemented in this sector of the economy. The development of the services sector based on information and communication technologies is the most important and defining factor of e-commerce.

With the help of digital services and technologies, it is possible to algorithmize the relationship between business and the client. Modern technologies allow tracking the entire path of products: from their creation to sale, and then after-sales service [20].

We believe that new technologies will improve communication with consumers at all stages of online shopping, increase the average purchase amount, strengthen trust, and create safer conditions for cooperation.

For buyers, the following advantages are indisputable.

Products or services can be purchased at any time of the day. Technically, an online store operates daily and around the clock. Internet purchases are not tied to time, which is significant for the consumer and makes e-commerce attractive.

E-commerce saves time, as the buyer does not need to physically visit the store. Purchasing goods or services from home reduces transaction costs.

E-commerce helps reduce informational asymmetry. The consumer can study a product or service through previous reviews, other buyers' experiences.

Buyers can also compare prices for the same product on different platforms:

- Small businesses can compete on an equal footing with large ones;
- Continuous contact is established with buyers;
- Buyers are instantly informed about changes in the assortment and pricing policies;
- Regional players penetrate international markets;
- There are no costs for renting premises;
- Costs related to order processing are reduced;
- There are expanded opportunities for automating business processes;
- The business becomes customer-oriented.

IV. Conclusions

It can be said that e-commerce is the fastest-growing direction of the digital segment in business. It serves as one of the manifestations of the digital economy, characterized by mobility, innovative opportunities for industrial and business activity, changes in the structure of the labor and capital markets. E-commerce contributes to achieving sustainable development goals. Digital technologies used in e-commerce help minimize costs and expand market boundaries. Improved logistics meet consumer demands through close cooperation with suppliers. Despite the high dynamics of the e-commerce market, this sector faces a number of problems. Solving these problems will positively impact the further development of e-commerce.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE ROLE OF ECOLOGICAL TOURISM IN THE SUSTAINABLE DEVELOPMENT OF THE TERRITORY

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Abstract

In many countries around the world, ecological tourism is considered a significant part of the global tourism industry. Ecological tourism occupies an important place within the state management system, operating within the regulatory and legal framework. Tourism is a priority sector of the economy, contributing to investment activation, entrepreneurial activity, service development, interaction within the framework of designing international programmers and tourist flow growth, which highlights the need for optimal environmental management. The sustainable development of ecological tourism is analyzed using a systematic approach to financial, socio-economic and environmental factors. The specificity of ecological tourism is reflected and the necessity of improving its material and technical base for careful use of its resources is emphasized. Natural-geographical, scientific-technical, institutional, geopolitical and economic factors of development are identified as criteria for the sustainable development of the territory, based on a PEST analysis. Current tools for the development of ecotourism in different countries worldwide, models of the sustainable development of ecotourism and statistics on visits to specially protected natural areas worldwide are considered, as are the most popular ecotours.

Keywords: ecological tourism, ecotourism, sustainable development, specially protected natural areas

I. Introduction

The growth of socio-economic and scientific-technical development contributes to the active development of numerous types of life activities, one of which is tourism, which has long gone beyond individual national borders. In the tourism sector, the process of globalization is reflected in the availability of various tourism products and services offered in different countries and regions. Tourism as a type of economic activity significantly contributes to the expansion of such areas as construction, hospitality, transport, trade, public catering, education, and culture. In parallel with mass tourism, problems related to the natural management are becoming more acute, and the burden on natural and historical and cultural heritage sites is increasing. The growth of industrialization and urbanization in the 1970s influenced the demand for recreational opportunities in the natural environment. Scientific research on the subject of discussion and

debate on environmental protection has intensified, and theoretical concepts of "ecological tourism" have emerged. The problems and issues related to sustainable development of territories as an optimal balance of natural, economic, cultural and social phenomena within the framework of natural management are becoming increasingly relevant. As an established independent scientific direction, ecological tourism is multifaceted. Two approaches have been formed in science on the subject of identifying the ecological direction in tourism. In the first case, the meaning of the concept of ecological tourism is wild nature with ecotourism objects. In the second case – ecotourism as a type of sustainable tourism. The key point is the location of the tourist, as a consumer of specialized services, in a natural environment that has a beneficial effect on physical and mental health.

II. Methods

The aim of the research was to determine the role of ecological tourism as a criterion for the competitiveness and attractiveness of the territory.

The theoretical and methodological basis of this study was formed by scientific works of specialists in the field of the problems under investigation. Ecological tourism is an interdisciplinary object of study. The theoretical and methodological basis includes scientific works of foreign scientists: H. Ceballos-Lascurain, D. A. Fennel, D. C. Malloy, K. Miller, as well as many Russian ones – O. E. Afanasyev, I. N. Bogatyrev, D. M. Ivanov, I. N. Kuzbozhev, E. Yu. Ledovskikh, N. V. Moravleva, A. V. Drozdov, S. M. Nikonorov and others.

Research methods: theoretical and methodological, analytical, statistical, expert, information retrieval method, PEST analysis.

III. Results and discussions

Tourism is a cross-sectoral complex of various types of economic activity which is characterized by a number of key indicators reflecting its economic essence. One of them is the tourist flow indicator, which is determined by the total number of trips to a certain place over a corresponding time interval. In 2024, tourists around the world made about 1.4 billion trips. This is 11% (or 140 million trips) more than in 2023.

The role of tourism in the global economy is clearly reflected in the indicators given in Table 1.

The contribution of tourism to world GDP in 2023 was 9.1%, and in 2024 it reached 10%. The growth in the share of tourism in world GDP amounted to 12.1%. The increase in the share of the contribution of the tourism services sector to global GDP compared to 2019, which was characterized by the highest indicators in the tourism and hospitality sector, amounted to 7.5% .

This is direct evidence of the recovery of the tourism market after the COVID-19 pandemic. The indicator of export of tourism services in this case reflects the ratio to the total volume of goods and services exports. The share of investment in fixed capital in the tourism sector reflects the attitude towards investment in fixed capital in general. There has also been significant growth in the area of employment in tourism, amounting to 348 million people in 2024, with every 10th job in the world being in the tourism and hospitality industry.

The COVID-19 pandemic is now a part of the past, but it has left many people with health consequences. This circumstance has affected the tourism market in two ways. On the one hand, the consumer profile is changing in terms of choosing individual programs with a stay in a natural area. This has led to the expansion of various programs in the direction of ecotourism by tourism service providers. There has been an increase in demand for recreation programs in natural areas

without a large number of people, with travel aimed at restoring both physical and mental health being a priority.

Table 1: *The role of tourism in the global economy*

Indicator	2023	2023	2024	2024
	billion US dollars	In % of total number	billion US dollars	In % of total number
The share of tourism in world GDP	9 899.3	9.1	11.1	10
Number of jobs in the tourism sector (million units)	330	10.0	348	5.07
Export of tourism services	1 632.6	5.3	1	-
Residents' expenditures within one country	4 968.5	4.6	5 134.6	-
Vacation expenses of residents and foreigners	5 296.0	5.0	5 643.2	-
Business travel expenses of residents and foreigners	1 305.2	1.2	1 438.6	-
The amount of investment in fixed capital in the tourism sector	1 013.2	3.6	1 201.5	-

Before the COVID-19 pandemic, ecotourism generated $1 billion per day for the global economy. It now accounts for about a quarter of the global tourism market. The global ecotourism market volume in 2024 was estimated at $219.81 billion.

In 2024, 78% of tourists chose environmentally oriented destinations and accommodations in natural areas. Around 70% of ecotourism consumers are willing to spend 10-15% more for accommodation that adheres to sustainable development principles.

According to the Ecotourism Global Market Report - 2025, the volume of ecotourism services in the world has a clear growth trend. The demand for such programs from potential consumers is showing active dynamics. In 2024, it amounted to US $247 billion, and by the first half of 2025 – US $279.4 billion, which can be explained by the growing demand for authentic experiences, and in some cases by active initiatives from the state, etc.

The largest share of the ecotourism market is occupied by the North American region – 35%. The absolute leaders of the tourism services market, along with the established leaders, were Mexico, Portugal, China, Morocco, Iceland, Australia.

The global special interest tourism (SIT) market is projected to grow from US $5.1 billion in 2025 to an estimated US $17.4 billion by 2035, reflecting a compound annual growth rate of 13% over the period [22].

In 2024, 78% of tourists chose environmentally oriented destinations and accommodations in natural areas. This growth is driven by a shift in consumer preferences towards experimental and niche segments of tourism, which are increasingly supported by comprehensive market research and consumer behavior analytics.

A detailed analysis shows that ecotourism and wellness tourism within SIT are demonstrating the highest growth rates, due to increased environmental awareness and the global trend towards healthy lifestyle. Quantitative data shows that the bookings of ecotourism packages have increased by 20% between 2021 and 2024, indicating strong demand for personalized

tourism.

Ecotourism as a scientific category has a theoretical and methodological basis. Among the first to apply this concept in the late 1970s and early 1980s were researchers such as K. Miller, who put forward the concept of life-affirming tourism [27, p.9]. Scientific research by the Swiss scientist H. Weiss led to the emergence in science of such terms as "soft tourism", "green tourism", "ecological tourism" [20].

The concept of the Swiss Ecotourism School is based on the concept of H. Weiss, which promotes environmental education, preservation of the socio-cultural environment, and improvement of environmental education of personnel directly related to the services in this area. H. Ceballos-Lascurain significantly expanded theoretical concepts of scientific understanding of the category of "ecological tourism" (Fig. 1) [21, p. 8].

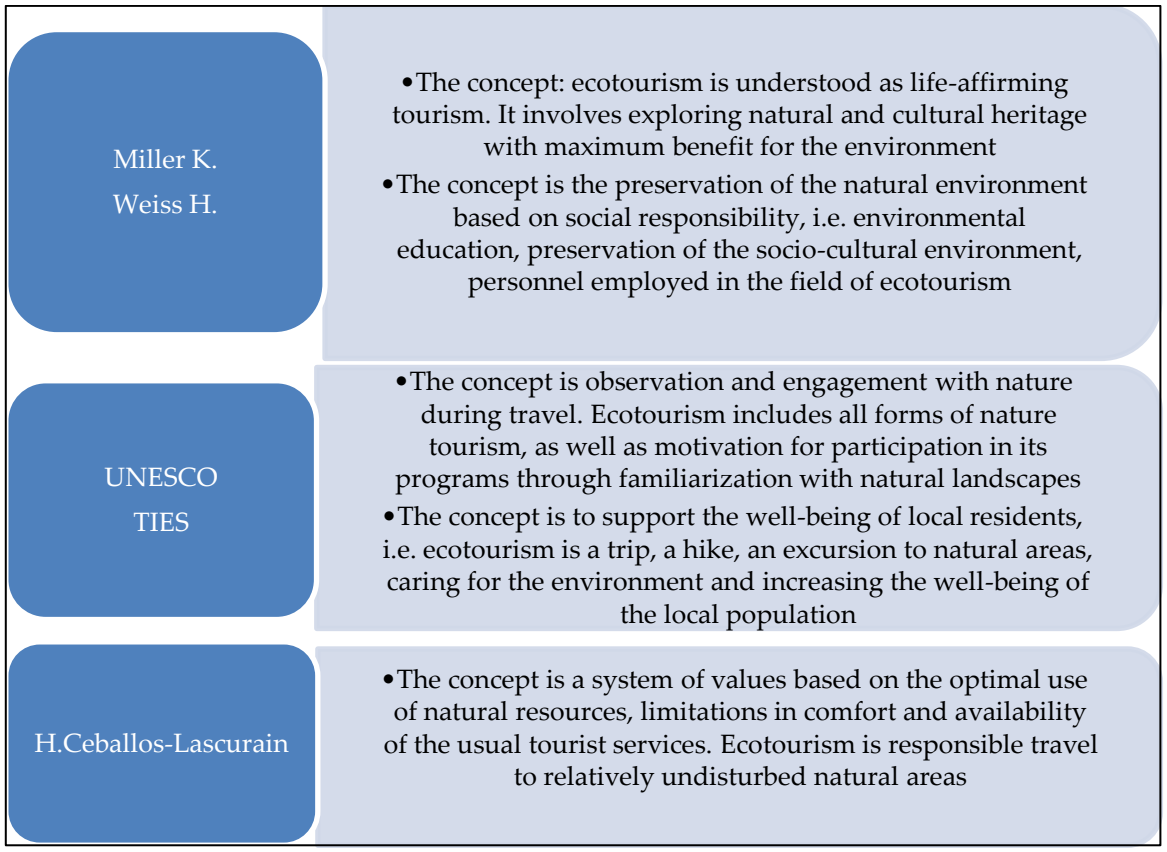


Figure 1: *The concepts of ecological tourism*

In the theory and practice of modern scientific research, the problems of ecotourism, synonymously understood as the development of sustainability of tourist destinations, have received wide coverage by specialists in various fields: economics, biology, geography, philosophy, sociology, etc. Various international organizations involved in research and monitoring of the ecotourism market present their own concepts.

The International Ecotourism Society (TIES). The concept is to support the well-being of local residents, i.e. ecotourism is a trip, a hike, an excursion to natural areas, caring for the environment and raising the standard of living of the local population.

United Nations Educational, Scientific and Cultural Organization (UNESCO). The concept is observation and engagement with nature during travel. Ecotourism includes all forms of nature tourism, as well as motivation for participation in its programs through familiarization with natural landscapes.

International Union for Conservation of Nature (IUCN). The concept is that trips to natural

areas should promote both nature conservation and create the necessary economic conditions, with the interest of the local population.

A significant contribution to the development of ecotourism concepts was made by P. Bjork, P. Wight, D. Fennel, who considered it as an integral part of nature tourism [19, 22].

Ecotourism is sustainable and nature-oriented tourism and recreation.

As an innovative form of tourist activity, ecotourism was formed in the 1980s in the process of searching for solutions to a range of problems caused by rapid industrialization processes, which prompted the search for optimal interaction between man and nature. Summarizing various approaches and assessments to understanding the category of "ecological tourism", we conclude that ecotourism is an environmentally friendly type of tourism, in which special attention is paid to visiting natural regions with the aim of helping the environment and local communities. Its aim is to reduce environmental damage, promote cultural exchange and raise awareness of biodiversity and its conservation. Wildlife watching, hiking and staying in eco-friendly hotels are typical activities that provide travelers with valuable experiences while preserving ecosystems and promoting local economic development.

Over the past decades in the global tourism market there has been a clear trend towards demand for programs and services of specialized tourism, including wellness, gastronomic, industrial and many others. The ecotourism market is divided into such areas as green, nature conservation, ecosphere, noosphere, soft, nature-oriented, eco-biotourism, and tour-realism. In fact, these are similar concepts implemented within various tourist destinations. From this perspective, all types of ecotourism can be classified as specialized tourism, aimed at satisfying the needs of special interests (SIT) of consumers.

Ecotourism programs are gaining popularity due to growing public concern about environmental issues and the growing popularity of the concept of sustainable development. Research in the field of sustainable development shows that responsible tourism principles are increasingly becoming a priority for both travelers and tour operators, which is in line with global principles of environmental and social management. The concept of sustainable development covers a wide range of socio-economic and environmental aspects (Fig. 2). Ecotourism is primarily focused on the long-term sustainable development of natural areas, which is the reason for the interchangeability of terms. In this sense, ecotourism is one of the effective forms of sustainable tourism.

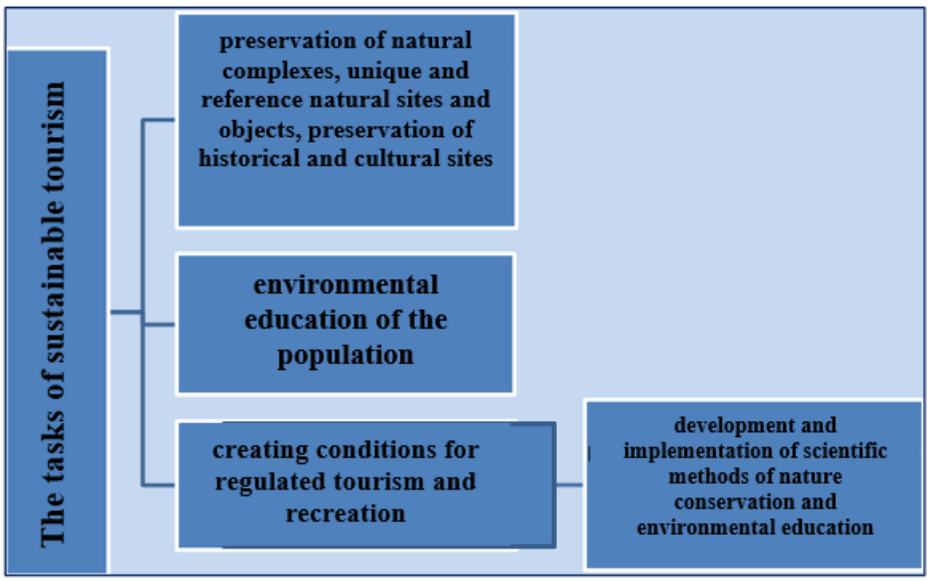


Figure 2: *The tasks of sustainable tourism*

The tasks of sustainable tourism are universal. According to the statistics provided, ecotourism, as one of the main forms of sustainable development, has become widespread. From the perspective of consumer preferences and the degree of impact on the natural environment, researchers make a distinction between "soft", socially responsible tourism, focused on all possible for environment preservation, and "hard" tourism, aimed at extracting maximum profit.

The vast majority of ecotourism programs are implemented in specially protected natural areas (SPNA). Over the period from 1976 to 2024, the number of natural reserves increased from 59 to 759, and the number of participating countries from 8 to 136. Specially protected natural areas usually include national parks, various nature reserves, dendrological parks, and botanical gardens. There are currently more than a thousand national parks and tens of thousands of protected areas in the world. According to the approximate evaluation there are 70 000 of them, and they occupy around 10% of the entire land area. In Russia there are 101 nature reserves and 35 national parks, which together cover an area of 40 million hectares (about 2% of the area of the Russian Federation). Table 2 reflects the features of the ecological tourism market in terms of leading countries.

Table 2: *Countries leading in the development of ecological tourism in specially protected natural areas*

No	Country	Amount of biodiversity (units)	Share of protected areas (of the total area of the country, in%)	Number of protected species	Number of UNESCO natural and cultural heritage sites	Efficiency of nature protection activities	Rating
1.	Brazil	43.205	30.0	91	8	43.6	94.9
2.	Mexico	28.989	14.6	115	8	45.5	86
3.	Australia	26.653	20.4	101	16	60.1	84
4.	Ecuador	22.673	23.4	52	2	46.5	82.1
5.	Costa Rica	13.678	26.6	12	3	46.3	81.2
6.	Bhutan	6.470	49.7	22	0	37.4	70.5
7.	Peru	24.777	22.5	61	4	39.8	81
8.	Indonesia	27.505	12.2	209	4	28.2	80.1
9.	Panama	13.505	31.4	16	3	50.5	79.6
10.	Tanzania	13.854	38.4	38	4	34.2	79.3

More than 30% of the ecotourism market share is in North America, which is facilitated by the developed infrastructure in specially protected natural areas. Table 2 shows the 10 countries in the world with the highest ecotourism ratings. The rating, as a complex indicator, includes such indices as the share of specially protected areas in the total area of the country, the amount of biodiversity of flora and fauna, the number of protected species of flora and fauna in the area, the presence of UNESCO natural and cultural heritage sites, and the degree of efficiency of nature management. The results were interesting. For example, in Brazil the overall ecotourism index was 94.9 out of 100. Brazil is one of the richest countries in the world in terms of biodiversity, with over 43 000 different species of animals and plants. And this is despite the massive deforestation in the Amazon. Currently, about 30% of Brazil's territory is under protection. The country has 8 UNESCO natural heritage sites, one of which is the Central Amazon Conservation Complex, where endangered species such as the Amazon manatee and black caiman are protected.

Mexico also has a high ecotourism index of 86. The country is home to 29 000 species of animals and plants, of which 115 are protected. Endangered species include the Angel Island mouse, the fishing bat, and the Buller's chipmunk. Mexico has an area of 2 million km², which is about four times smaller than Brazil, but it is also home to 8 UNESCO natural heritage sites. One such site – 244 coastal areas, islands and islets in the Gulf of California – is home to 39% of the

world's marine mammals.

Ecotourism is highly valued in Australia, with an ecotourism index of 84. Australia is the only country in the top five outside of America. Its rating was boosted by an environmental performance score of 60 out of 100. The country has 16 UNESCO natural heritage sites, the largest number of all 50 countries surveyed. The UNESCO World Heritage Site, the Great Barrier Reef, is the world's largest collection of coral reefs, home to endangered species such as the sea cow and the green sea turtle. About 20% of Australia's land area is protected, as are 101 of its 27 000 animal and plant species.

Special interest tourism drives growth and implementation of innovation in the global tourism sector by meeting the growing demand for personalized and meaningful travel experiences. Travelers are actively looking for eco-friendly travel options, and destinations like Costa Rica are leading the way. Costa Rica promotes ecotourism through carbon-neutral resorts and protected rainforests, setting an example that encourages the global tourism sector to adopt environmentally responsible practices, which has resulted in a 57% increase in forest cover.

Ecotourism is developing in various forms and consists of a specific set of services, formed into specific programs and offered to potential consumers. One of the tools for determining external factors of ecotourism market development is PEST analysis. Determination of macroenvironment factors of international ecotourism development by PEST analysis is given in Table 3.

Table 3: *Macroenvironmental factors for the development of ecotourism*

Natural and geographical	Political	Socio-economic	Scientific and technological
1. Climatic; 2. Floristic; 3. Faunistic; 4. State of the environment	1. State regulation of the ecotourism market; 2. External threats of geopolitical instability; 3. Internal political stability; 4. Ethical and political standards; 5. State programs and initiatives; 6. Environmental protection laws; 7. Foreign economic activity; 8. Tourism laws and regulations. Compliance with tourism regulations and laws, including licenses and insurance; 9. Responsibility for safety.	1. Availability of financial resources; 2. Tax regime; 3. Income level of the population; 4. Level of infrastructure development; 5. Differentiation of population incomes; 6. Socio-cultural preferences; 7. Development and promotion of ecotourism as an attractive form of recreation; using online channels and traditional media.	1. Improving the information technology infrastructure, as digital technologies help to predict visits to specially protected natural areas to prevent excessive load on them; 2. Creation of digital platforms in the direction of environmental education to obtain information about environmental problems in a specific territory, its biodiversity, and following the rules for behavior there; 3. Creating online marketplaces to help local communities promote their own products; 4. Development of sensor technologies for condition monitoring

Source: compiled by the authors

Political decisions made by governments around the world, including new laws and changes to existing legislation, can have a direct impact on businesses in ecotourism sector. Global conflicts, trade wars or sanctions can have a long-term negative impact on tourism.

Economic factors cover the influence of economic conditions and processes on the development of tourism. Reduced tax rates for companies operating in the ecotourism sector, or tax breaks for those who invest in such projects, significantly stimulate its development. These factors help to understand the macroeconomic environment and its impact on the tourism business. Economic factors contributing to the growth of the ecotourism market are the financial leverages for the development of ecotourism (which include direct investment, grants, tax incentives, loans, as well as various forms of partnership and cooperation) and investments in

hotel infrastructure, transport communications, improvement, repair, restoration of visiting sites, as well as investments in biodiversity conservation and environmental education projects.

According to various evaluations, income from the sale of ecotourism services worldwide ranges from 170 to 300 billion dollars per year. The USA has the highest income – 14 billion dollars from visits to protected areas; in Australia the same indicator is 3 billion dollars per year; in Kenya – 450 million dollars per year. In the Russian Federation, the area of specially protected natural areas is only 2%. The growth in demand for ecotourism programs and services is 20-30%. The most visited SPNA in the Russian Federation are the Kislovodsk National Park – 5.3 million people per year, the Sochi National Park – 1.7 million people, the Krasnoyarsk Pillars National Park – 1.1 million people, and the Curonian Spit National Park – 850 thousand people.

The cost of such programs varies significantly depending on the region, duration, etc. For example, the cost of a program in the largest Russian National Park, the Commander Islands named after S. V. Makarov, starts from 250 000 rubles, where visitors are very attracted by watching whales, killer whales, dolphins, and seal rookeries.

Factors of scientific and technological direction in ecotourism are modern engineering and digital solutions that help to reduce the negative impact on the natural environment and get the expected quality from traveling in a natural area. These factors include the introduction of digital and engineering solutions that help minimize impact on nature and improve the quality of the tourist experience. Digital technologies are being promoted in the form of mobile applications.

1. ECO Trip – an eco-friendly route on hand. A platform for booking green tourist routes in Russia, combining ecological paths, eco-hotels and farms. Travelers can choose eco-friendly routes, book accommodation and participate in educational tours on the topic of ecology. The application helps find eco-hotels and tours that support eco-friendly practices.

2. Green Key – eco-friendly comfort. In 1994, Green Key International was founded in Denmark. Green Key is an international organization that helps find hotels and resorts with green certifications. They all care about reducing the consumption of water, energy and other resources, and also support local initiatives.

3. Green Globe is a similar program that offers a certification process for the hospitality industry.

4. Good Guide – conscious consumption on holiday. Good Guide will help you choose eco-friendly and ethical products, whether they are gourmet delicacies, cosmetics or memorable souvenirs.

Mobile apps for responsible tourism make eco-friendly travels accessible and convenient. The study of the macroenvironmental factors for the development of ecotourism at the state level allows us to determine the optimal course of its development at the national and international levels.

IV. Conclusions

After the COVID-19 pandemic, the demand for ecotourism products and services has been higher than other types of tourism. In the near future, the demand for ecotourism services will experience an upward trend and could reach US $498 billion by 2029. This forecast can be explained by the increase in the number of recovery trips, the expansion of digital platforms for the purpose of awareness of the proposed ecotourism programs, and the growth in the attractiveness of investments and finances for ecotourism. The concept of ecotourism remains controversial. In a broad sense, it is a form of nature tourism focused on responsible interaction with the environment. There is no definition of “ecotourism” at the legislative level, which hinders the development of sustainable practices. Ecological tourism should be based on three main components: 1) a contribution made by visitors to the conservation of nature, through entrance

fees or other instruments that support the ecosystem; 2) ecotourism should have a positive impact on the local economy; 3) the damage from such tourism to the natural area should be minimal.

Ecological tourism has many varieties that are present in almost every country in the world. The most common among them are the following types: tourism in specially protected natural areas (SPNA), rural tourism, agritourism, some types of sports tourism, as well as cultural tourism implemented within SPNA. Ecotourism today is one of the dynamic segments of the international tourism market. Analysts from consulting companies predict that its average annual growth will be 15.2% per year until 2030, while the entire tourism market will grow by only 5.4% annually. The largest share of the ecotourism market today is occupied by Europe due to the diversity of natural landscapes and high-quality environmental policies that allow Europe to maintain a leading position in this area. In the coming years, the main growth drivers will be the regions of Asia, as well as Latin America and Africa, due to rising living standards, development of transport infrastructure and government support for sustainable tourism.

A comprehensive analysis of the external environment, i.e. natural-geographical, political, socio-economic, technical, legal factors, allows for an objective assessment of the comprehensive approach to the prospects and opportunities for ecotourism at the national level. The growth of ecotourism is driven not only by changes in policy and infrastructure, but also by a deeper social and cultural transformation. Mass tourism today has become too unified. It doesn't really matter which country a tourist is visiting – Finland, Germany, the USA, Thailand, Turkey, Mexico – because there are almost the same supermarkets, standard souvenirs from the same factories, clothes from the same brands, i.e. everything is the same everywhere. Much more attractive is the natural environment, the culture of local communities, i.e., unique things and phenomena, and these are what will be the main centers of attraction for tourists.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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GENETIC TUNING OF HIERARCHICAL MODELS BASED ON EXPERIMENTAL DATA

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Abstract

The multidirectional search method is applied to the individual elements of the experimental data, forming and observing potential solution sets. The aim of this study is to genetically tune linguistic models using experimental data based on a fuzzy knowledge base. Experiential knowledge is derived from experience or observation. This process manifests itself in many different situations. It can be observed and predicted using qualitative characteristics. However, the process is not always understandable in terms of fundamental principles. For the purpose of forming primary information, the article establishes a fuzzy model that determines the linguistic values of variables and the formation of their membership functions. A knowledge matrix is drawn up according to the rules connecting the input and output of the identified object, and knowledge is determined based on logical considerations of the form 'IF-THEN-OTHERWISE'. Based on the matrix, the values of the input variables x_i are associated with one of the possible types of solution d_j. This problem is solved using fuzzy logic equations. These equations are based on a knowledge base or a system of logical judgements that is similar to it. It also allowed the membership functions of various solutions to be calculated at fixed input data values for the object. Typically, a solution with a high membership function value is considered the desired solution.

Keywords: formulation of membership functions, fuzzy knowledge base, fuzzy model, linguistic variables, fuzzy knowledge base, linguistic interpretation, genetic algorithm

I. Introduction

The identification of nonlinear dynamic objects based on fuzzy logic relies on generating a fuzzy knowledge base from experimental data that links input and output variables. The method of modifying and processing experimental information in a fuzzy knowledge base is widely applied as an efficient approach for data processing in fields such as medicine, banking, management, and others. In this case, qualitative criteria will be close to the results of linguistic approximation and corresponding experimental data based on certain regularities.

In conditions of uncertainty, the information obtained about an object is incomplete, imprecise, and fuzzy. This makes tuning and managing models based on experimental data more challenging. Therefore, there arises a necessity to create and tune linguistic models based on experimental data, addressing this as an actual problem.

The goal is to find an optimal solution by genetically tuning linguistic models with experimental data, based on a fuzzy knowledge base.

Learning from experimental datasets is a hot topic in machine learning research [3,4]. This problem is characterized by a class distribution where the number of samples in one class is greater than the number of samples in the other class. Medical diagnostics, fraud detection, finance, risk management, network intrusion, etc. including, but not limited to, many real-world problems are dominated by the presence of unbalanced data sets. Furthermore, the positive or minority class is

usually the class of highest interest from a learning point of view, and it is also costly if not well classified [1,5].

There are a number of intrinsic properties of data that reduce the effectiveness of learning. Some of these deficiencies within the data include the presence of small errors [6] and the presence of overlapping samples between classes.

Experimental knowledge obtained from experience or observation can be easily expressed and described in terms of qualitative conditions. The process can be observed and predicted using qualitative characteristics. However, it is not always comprehensible in terms of fundamental principles. The proposed algorithm uses the idea of identifying linguistic terms based on the maximum of the membership function, which is generalized across the entire knowledge matrix. The study of the fuzzy system based on experimental data has shown it to be more effective compared to traditional methods.

II. Problem Statement

Rules for constructing hierarchical models. When there are many input variables x_i constructing a fuzzy knowledge base about the unknown dependency (1) becomes difficult. This is related to the fact that a person can simultaneously retain an understanding of about 7±2 features in their working memory. Therefore, it is advisable to classify the input variables and construct a decision tree based on them.

The hierarchical interrelationship between the input and output variables (integral indicators) corresponding to the system of relations (1-4) is depicted in the tree structure shown in Figure 1.

$$R = f_R(X, Y, \dots, Z) \quad (1)$$
$$X = f_X(x_1, x_2, \dots, x_n) \quad (2)$$
$$Y = f_Y(y_1, y_2, \dots, y_n) \quad (3)$$
$$Z = f_Z(z_1, z_2, \dots, z_n)\,, \quad (4)$$

where, $R -$ represents the output variables (integral indicators); $X, Y, Z -$ represent classes of input variables; $x_i, y_j, z_k (i = \overline{1,l}; j = \overline{1,m}; k = \overline{1,n};) -$ are input variables that belong to the classes X, Y, Z respectively.

Fig. 1 illustrates a tree that reflects the input variables in a two-level hierarchy. However, detailing can be done across various levels: class-subclass, group-subgroup, etc. Let us assume that all variables at the top of the tree are linguistic variables expressed by the following terms:

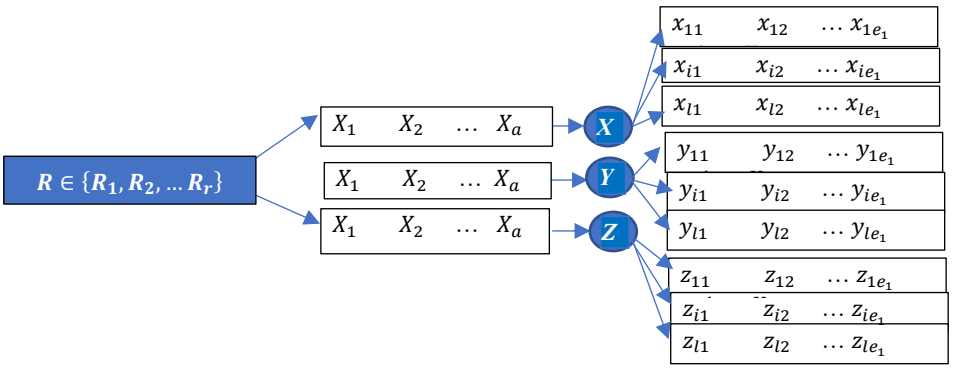


Figure 1: *Generalized Logical Inference Tree*

- $\{R_1, R_2, \dots, R_r\} -$ Set of terms for evaluating the variables R;
- $\{X_1, X_2, \dots, X_a\} -$ A set of terms for evaluating the X variables;
- $\{Y_1, Y_2, \dots, Y_b\} -$ A set of terms for evaluating Y variables;

- $\{Z_1, Z_2, \ldots, Z_c\}$ – A set of terms for evaluating the Z variables;
- $\{x_{i1}, x_{i2}, \ldots, x_{ia_i}\}$ – set of terms for evaluation of variables $x_i, i = \overline{1,l}$;
- $\{y_{j1}, y_{j2}, \ldots, y_{jb_j}\}$ – set of terms for evaluation of variables $y_j, j = \overline{1,m}$;
- $\{z_{k1}, z_{k2}, \ldots, z_{kc_k}\}$ – set of terms for evaluation of variables $z_k, k = \overline{1,n}$

The introduced sets of terms indicate the branches of the tree. Within each set, fuzzy terms are arranged sequentially from bottom to top, following the principle where the strength (i.e., the number of terms) of all sets used for evaluating the linguistic variables involved in the relations (1)-(4) may vary.

Let us describe the terms as fuzzy sets using the concept of universal sets and the membership function.

$$R_i = \int_W \mu_{R_i}(w)/w, i = \overline{1,r}, w \in W; \quad (5)$$

$$X_i = \int_{U_X} \mu_{X_i}(v_X)/v_X, i = \overline{1,a}, v_X \in U_X; \quad (6)$$

$$Y_i = \int_{U_Y} \mu_{Y_i}(v_Y)/v_Y, i = \overline{1,b}, v_Y \in U_Y; \quad (7)$$

$$Z_i = \int_{U_Z} \mu_{Z_i}(v_Z)/v_Z, i = \overline{1,c}, v_Z \in U_Z; \quad (8)$$

$$x_{ij} = \int_{U_{x_i}} \mu_{x_{ij}}(x_i)/x_i, i = \overline{1,l}, j = \overline{1,a_i}, x_i \in U_{x_i}; \quad (9)$$

$$y_{jk} = \int_{U_{y_j}} \mu_{y_{jk}}(y_j)/y_j, j = \overline{1,m}, k = \overline{1,b_j}, y_j \in U_{y_j}; \quad (10)$$

$$z_{kl} = \int_{U_{z_k}} \mu_{z_{kl}}(z_k)/z_k, k = \overline{1,n}, l = \overline{1,c_k}, z_k \in U_{z_k} \quad (11)$$

Here, W- is the universal set of the variables R, more precisely, $R_i \subset W, i = \overline{1,r}$ – is a universal set whose variables are given

$U_X, U_Y, U_Z - X, Y, Z$ are universal sets given variables, i.e., $X_i \subset U_X$,

$Y_i \subset U_Y, Z_i \subset U_Z$; $U_{x_i}, U_{y_j}, U_{z_k} - x_i, y_j, z_k, i = \overline{1,l}; j = \overline{1,m}; k = \overline{1,n}$are universal sets given by variables;

$\mu^{\xi}(\chi)$ – is the membership function of variable X of fuzzy term ξ.

We will describe the information about the relations (1)–(4) in the form of a fuzzy knowledge base that stores logical judgments about the interactions of input and output variables. A fuzzy knowledge base about relation (1) will have the following rule:

IF $(X = x_{j1})$ AND $(Y = y_{j1})$VƏ...VƏ $(Z = z_{j1})$ OR
$(X = x_{j2})$ AND $(Y = y_{j2})$ AND... AND $(Z = z_{j2})$ OR
...
$\left(X = x_{jh_j}\right)$ AND $\left(Y = y_{jh_j}\right)$ AND... AND $\left(Z = z_{jh_j}\right)$

TNEN $R = R_j, j = \overline{1,r}$ (12)

It is possible to describe this rule in the form of M_R knowledge matrix:

$$M_R = \begin{vmatrix} X & Y & \ldots Z & R \\ x_{11}\ldots x_{1h_1} & y_{11}\ldots y_{1h_1} & z_{11}\ldots z_{1h_1} & R_1 \\ \ldots & \ldots & \ldots & \ldots \\ x_{j1}\ldots x_{jh_j} & y_{j1}\ldots y_{jh_j} & z_{j1}\ldots z_{jh_j} & \ldots R_j \\ \ldots & \ldots & \ldots & \ldots \\ x_{r1}\ldots x_{rh_r} & y_{r1}\ldots y_{rh_r} & z_{r1}\ldots z_{rh_r} & R_r \end{vmatrix} \quad (13)$$

Applying the operations of union and intersection of sets (13), let us write the fuzzy knowledge base in the following form:

$$\cup_{j=1}^{h_j}\left[\left(X = x_{jp}\right) \cap \left(Y = y_{jp}\right) \cap \ldots\right] \rightarrow R_j, j = \overline{1,r} \quad (14)$$

The fuzzy knowledge base about relations (2) is defined according to the following rule:
ıf $(x_1 = {x_1}^{j1})$ and $(x_2 = {x_2}^{j1})$ and... and $(x_l = {x_l}^{j1})$ OR
$(x_1 = {x_1}^{j2})$ and $(x_2 = {x_2}^{j2})$ and... and $(x_l = {x_l}^{j2})$ OR
...
$\left(x_1 = {x_1}^{je_j}\right)$ and $\left(x_2 = {x_2}^{je_j}\right)$ and... and $\left(x_l = {x_l}^{je_j}\right)$
then $X = X_J, j = \overline{1,a}$ (15)

M_X matrices are constructed analogously to the knowledge matrix M_R described in (13). Applying the operations of union and intersection of sets (15), let us write the fuzzy knowledge base in the following form:

$$\cup_{p=1}^{e_j}[\cap_{i=1}^{m}(x_i = {x_i}^{jp})] \rightarrow X = X_j, j = \overline{1,a} \quad (16)$$

The fuzzy knowledge base about relations (3) has the following form:

IF $(y_1 = {y_1}^{j1})$ and $(y_2 = {y_2}^{j1})$ and... and $(y_l = {y_l}^{j1})$ OR
$(y_1 = {y_1}^{j2})$ and $(y_2 = {y_2}^{j2})$ and... and $(y_l = {y_l}^{j2})$ OR
...
$\left(y_1 = {y_1}^{jg_j}\right)$ and $\left(y_2 = {y_2}^{jg_j}\right)$ and... and $\left(y_i = {y_i}^{jg_j}\right)$
then $Y = Y_J, j = \overline{1,b}$ (17)

M_Y matrices are constructed analogously to the knowledge matrix M_R described in (13). Applying the operations of union and intersection of sets (18), let us write the fuzzy knowledge base in the following form:

$$\cup_{p=1}^{g_j}\left[\cap_{i=1}^{m}\left(y_j = {y_j}^{jp}\right)\right] \rightarrow Y = XY_j, j = \overline{1,b} \quad (18)$$

The fuzzy knowledge base about relations (4) has the following form:
ıf $(z_1 = {z_1}^{j1})$ and $(z_2 = {z_2}^{j1})$ and... and $(z_n = {z_n}^{j1})$ OR
$(z_1 = {z_1}^{j2})$ and $(z_2 = {z_2}^{j2})$ and... and $(z_l = {z_l}^{j2})$ OR
...
$\left(z_1 = {z_1}^{jt_j}\right)$ and $\left(z_2 = {z_2}^{jt_j}\right)$ and... and $\left(z_n = {z_n}^{jt_j}\right)$
then $Z = Z_J, j = \overline{1,c}$ (19)

M_Z matrices are constructed analogously to the knowledge matrix M_R described in (13). Applying the operations of union and intersection of sets (21), let us write the fuzzy knowledge base in the following form:

$$\cup_{p=1}^{t_j}[\cap_{i=1}^{m}(z_i = {z_i}^{jp})] \rightarrow Z = Z_j, j = \overline{1,c} \quad (20)$$

Thus, a system of fuzzy logical judgments (14), (16), (18), (20) was determined, which describes the expert information about the relations (1–4) corresponding to the generalized tree of interconnected "input - output variables" .

The principle of encoding linguistic variables and their fuzzy terms proposed above for a two-level inference tree remains unchanged for a tree of any size. The structure of the tree, the selection of the terms of the linguistic variables into its branches, as well as the selection of the fuzzy knowledge base at each non-terminal vertex of the tree, are important for the construction of models of non-linear objects.

III. Solving the problem

Extracting knowledge from experimental data. The identification of nonlinear dynamic objects based on fuzzy logic is explained by the presence of IF-THEN rules that depend on the linguistic values of input-output variables. Previously, it seemed to us that IF-THEN rules were generated by experts. What can be done if there is no such expert? In this case, there is an interest in the generation of IF-THEN rules, fuzzy knowledge base generated from experimental data.

The method of changing experimental information in a fuzzy knowledge base can be an efficient method for processing data in medicine, banking, management and other fields. In this case, due to certain regularities, the quality criteria will be close to the results of linguistic approximation and corresponding experimental data.

An object with n inputs and one output (24) is given by the following properties [3,4,9]:

$$y = f(x_1, x_2, \dots, x_n) \tag{21}$$

1. Input and output change interval

$$x_i \in \left[\underline{x}_i, \overline{x}_i\right], i = \overline{1,n}; y \in \left[\underline{y}, \overline{y}\right],$$

2. $d_j (j = \overline{1,m};)$ is a class of solutions in objects with discrete outputs:

$$\left[\underline{y}, \overline{y}\right] = \underbrace{\left[\underline{y}, y_1\right]}_{d_1} \cup \underbrace{[y_1, y_2]}_{d_2} \cup \dots \cup \underbrace{[y_{j-1}, y_j]}_{d_j} \cup \dots \cup \underbrace{[y_{m-1}, \overline{y}]}_{d_m}$$

A training sampling interval in the form of M pairs of experimental "input-output" data:

$\{X_p, y_p\}$– for objects with continuous output,

$\{X_p, d_p\}$– for objects with discrete output,

where $X_p = \{x_1^p, x_2^p, \dots, x_n^p\}$– p is the input vector in the -th pair, $p = \overline{1,M}$

It is required to summarize the information about the object (1) in the form of fuzzy logical judgments:

IF $x_1 = a_1^{j1}$ and $x_2 = a_2^{j1}$ and ... and $x_n = a_n^{j1}$ (w_{j1} by weight)

or ($x_1 = a_1^{j2}$) and ($x_2 = a_2^{j2}$) and ... and ($x_n = a_n^{j2}$) (w_{j2} by weight)

... or [($x_1 = a_1^{jk_j}$) and ($x_2 = a_2^{1kj}$) and … and ($x_n = a_n^{1kj}$)] ($w_{j_{kj}}$ by weight)

Then $$y \in d_j = \left[y_{j-1}, y_j\right], j = \overline{1,m}, \tag{22}$$

$a_i^{jp} - p = \overline{1,k_j}$In the numbered row, x_i are the linguistic terms that evaluate the input variables; $k_j - d_j, j = \overline{1,m}$ is the number of conjunction rows corresponding to the classes; w_{jp}–[0,1] is a number characterizing the weight of the jp -numbered judgments within the range.

The knowledge base (22) corresponds to the object's model (24) in the form of the following computational relations [3-6]:

$$y = \frac{y\mu^{d_1}(y) + y_1\mu^{d_2}(y) + \dots + y_{m-1}\mu^{d_m}(y)}{\mu^{d_1}(y) + \mu^{d_2}(y) + \dots + \mu^{d_m}(y)}, \tag{23}$$

$$\mu^{d_j}(y) = \max_{p=\overline{1,k_j}} \left\{ w_{jp} \min_{i=\overline{1,n}} [\mu^{jp}(x_i)] \right\}, \tag{24}$$

$$\mu^{jp}(x_i) = \frac{1}{1 + \left(\frac{x_i - b_i^{jp}}{c_i^{jp}}\right)}, \quad i = \overline{1,n}, j = \overline{1,m}, p = \overline{1,k_j} \tag{25}$$

Here, $\mu^{d_j}(y) -$ is the membership function of output y for class d_j;

$\mu^{jp}(x_i)$– membership function of input x_i for a_i^{jp} term;

b_i^{jp} and c_i^{jp}– x_i are parameters that debug the membership functions of the input variables. Relations (23),(24),(25) determine the model of the object written as follows [10]:

$y = F(X, W, B, C)$ – for an object with continuous output;

$\mu^{d_j}(y) = \mu^{d_j}(X, W, B, C)$ – for object with discrete output;

$X = (x_1, x_2, \dots, x_n)$ – input vector;

$W = (w_1, w_2, \dots, w_n)$ – (25) vector of weighting rules in the fuzzy knowledge base;

$B = (b_1, b_2, \dots, b_q)$ and $C = (c_1, c_2, \dots, c_q)$ – tuning parameters vector of membership functions of fuzzy terms in (26);

$N -$ total number of lines of rules, q - total number of terms; $F -$ is a vector of input-output relations corresponding to the use of relations (24)–(25).

(3.2) we give the restrictions on the size of the knowledge base by one of the following cases:

a) $N = k_1 + k_2 + \dots + k_m \le \overline{N}$;

b) $k_1 \le \overline{k}_1, k_2 \le \overline{k}_2 \dots, k_m \le \overline{k}_m$

where, $\overline{N}$ is the maximum number of conjugation lines possible in (25); $\overline{k_j} - d_j, j = \overline{1,m}$the maximum number of possible conjunction lines in the j[th] order of the class of decisions, the number of $a_i^{jp}, i = \overline{1,n}, p = \overline{1,k_j}, j = \overline{1,m}$ linguistic terms used in (25); if the composition is not known, then it is possible to interpret them based on the values of the (b_i^{jp}, c_i^{jp}) parameters of the membership function (27). Therefore, the knowledge base synthesis (25) corresponds to obtaining the parameters matrix described in table 1 [5-7].

In mathematical programming, this problem can be formulated as follows. It is necessary to find a matrix (table 1) that satisfies the restrictions on the range of variation of parameters {W,B,C} and the number of rows:

For a facility with continuous output [9-11]

$$\sum_{p=1}^{M}\left[F(X_p, W, B, C) - y_p\right]^2 = \min_{W,B,C} \quad (26)$$

$$\sum_{p=1}^{M}\left\{\sum_{j=1}^{m}\left[\mu^{d_j}(X_p, W, B, C) - \mu_p^{d_j}(y)\right]^2\right\} = \min_{W,B,C} \quad (27)$$

Where, $\mu_p^{d_j} = \begin{cases} 1, d_j = d_p \\ 0, d_j \ne d_p \end{cases}$

It is considered appropriate to use a genetic algorithm to solve this problem.

Experimental data (x∈[0,10], y∈[-0.47,0.79]) about the object $y = f(x) = e^{\frac{-x}{4}} \cdot sin(\frac{\pi}{2}x)$ in picture 2 generates the model described.

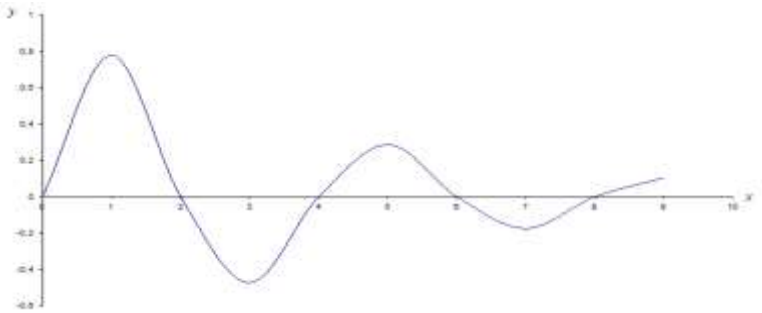


Figure 2: *The transition process of the object*

Object output is divided into seven classes:

$$y \in \underbrace{[-0.47,-0.3]}_{d1} \cup \underbrace{[-0.30,\ -0.05]}_{d2} \cup \underbrace{[-0.05,\ 0.15]}_{d3} \cup \underbrace{[0.15,0.30]}_{d4} \cup$$
$$\cup \underbrace{[0.3\ \ 0.45]}_{d5} \cup \underbrace{[0.45,\ 0.65]}_{d6} \cup \underbrace{[0.65,0.78]}_{d7}$$

The studied problem consists of synthesizing the object described in (1) according to 5 rules. Let us assume that the weights of the rules are equal to 0 or 1.

After linguistic interpretation, this rule will be described as follows:

IF x is close to 2.8 then $y \in d_1$

IF x is close to 6.9 then $y \in d_2$

IF x is close to 0 or x is close to 8.8 or x is close to 10 then $y \in d_3$

IF x is close to 5 then $y \in d_4$
IF x is close to 0.9 then $y \in d_7$

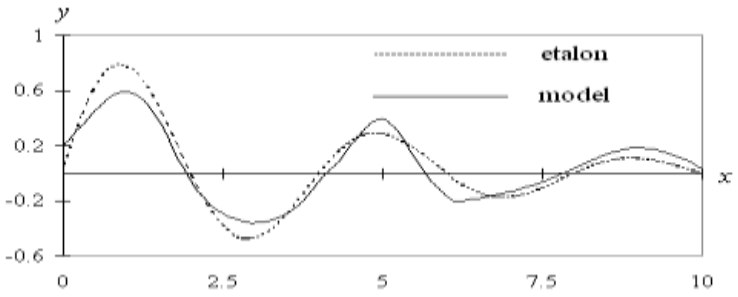


Figure 3. *Comparison of linguistic model and benchmark*

IV. Conclusıon

The approximation algorithm for objects with discrete output is designed in the following order: specify the vector of values of input data, enter the membership function of fuzzy terms used in the fuzzy knowledge base and determine the values of this function for the given values of input data; calculate the multivariate membership function for all solution values of the output variable using logic equations.

The proposed algorithm uses the idea of identifying linguistic terms by the maximum of the membership function. This idea is generalized across the entire knowledge matrix.

Research of the fuzzy system based on experimental data has shown that it is more effective than traditional methods.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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LANDSCAPE AND ECOLOGICAL CONDITIONS OF CARBON SEDIMENTATION IN MOUNTAIN-MEADWAY LANDSCAPES OF THE CHECHEN REPUBLIC

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Abstract

Carbon sequestration and dynamics in mountain meadow landscapes through photosynthesis are crucial for the survival of the biosphere. The role of soil in forest ecosystems is largely determined by its organic compounds. Carbon compounds largely determine soil formation. Soil organic matter is a source of energy for soil organisms, which, in turn, interact with the mineral component of the soil to shape its structure. Soil carbon plays a significant role in nutrient cycling. Consequently, the quantity and quality of soil organic matter reflect and determine its formation and, consequently, the productivity of forest ecosystems. Landscape-ecological conditions for carbon dynamics are examined at the regional level. Phytoclimatic, altitudinal, zonal, and aspect differentiation in terms of carbon dynamics are revealed. A comparative analysis of carbon dynamics conditions in different landscape types is provided, and the effectiveness of various ecosystems in terms of carbon accumulation is assessed. Specifically, carbon dynamics are compared in mountain forest, mountain meadow, and mountain meadow-steppe landscapes. Due to climate warming, mountain meadow landscapes are beginning to expand into areas free of snow and ice. Therefore, they can be considered important carbon sequestration sites.

Keywords: Mortmass, biomass, landscape differentiation, carbon sequestration, mountainous areas, soil types, accumulation, humus.

I. Introduction

The theoretical basis for studying the diversity of carbon balance conditions is the landscape concept, which views mountainous areas as a systemically organized space of ecological-landscape habitats, each representing a relatively homogeneous area in which the components of the carbon balance are approximately equal. The concept of landscape structure underlies the extrapolation of the obtained data on carbon dynamics in a specific natural complex. Three main types of landscape structure are distinguished, corresponding to landscape responses to the impacts and changes in energy fields: vertical, horizontal (morphological), and temporal.

One of the fundamental patterns of landscape spatial organization is altitudinal zonation. Altitude zones are defined by the predominant zonal landscape type, and belts within them are defined by landscape subtype. However, the distribution of landscape types and the ratio of their areas is uneven within the study area of the Chechen Republic. Classical altitudinal belts that uniformly and consistently change with altitude are virtually absent. Their boundaries are uneven due to the complex mountainous terrain and/or anthropogenic impact.

The leading factor in altitudinal differentiation is the change in the heat-to-moisture ratio with altitude. The greatest variation is the change in heat with altitude. Different landscape types are formed at different altitudinal levels: nival-glacial landscapes – above 3000-3500 m above sea level;

mountain-meadow landscapes – the lower boundary varies from 2000 to 2500 m, and the upper boundary coincides with the lower boundary of nival-glacial landscapes, i.e., 3000-3500 m above sea level; mountain-forest landscapes extend to an altitude of 2000 m, and in some areas of warm slopes – up to 2600 m; Mountain forest-meadow, mountain forest-meadow-steppe, and mountain steppe – from 250 to 1800-2400 m.

According to the Intergovernmental Panel on Climate Change (IPCC) (2000), carbon sequestration by terrestrial ecosystems is the net removal of carbon dioxide (CO_2) from the atmosphere or the avoidance of atmospheric carbon dioxide (CO_2) emissions from terrestrial ecosystems. This removal process involves the absorption of CO2 from the atmosphere by all chlorophyll plants through photosynthesis. This carbon is stored as plant biomass (in the stems, branches, leaves, and roots of plants) and organic matter in the soil. Carbon sequestration in landscapes depends on land management practices and various ecosystem conditions that support established vegetation over longer periods of time. Defined carbon sequestration as the adoption of land management practices that increase net primary productivity, reduce heterotrophic respiration, or both, and result in increased ecosystem carbon storage. Planting trees, reducing tillage intensity, or restoring pastures on degraded lands will increase carbon stocks in plants, soils, or both.

II. Methods

Mountainous areas with a mosaic of ecosystem cover and the superposition of different eras of development, a combination of formal and informal practices, can create the impression of anarchy, which should be understood in order to identify patterns of order and dynamics [3,5]. The study region in the Eastern Caucasus covers the territory of the Chechen Republic. It includes both lowland semi-desert and steppe regions, as well as mountainous ones. The spectrum of altitudinal zones includes mountain-forest foothills and low mountains, transitioning with increasing altitude to mountain-steppe basins, mountain-meadow and nival-glacial. Currently, the most developed landscapes in the Chechen Republic are the foothill-steppe landscapes, where approximately 80% of the population lives. Large differences in altitude have created a variety of climatic conditions. With increasing altitude, the amount of precipitation increases (from 300 mm on the plain to 1400-1700 mm in the mountains). In intermountain basins, precipitation decreases to 600-700 mm. Given the interdisciplinary nature of the problem, the study incorporated both qualitative and quantitative methods. Qualitative methods focused on the analysis of historical documents, interviews with decision-makers, including local forest resource users, field observations, and route notes. Quantitative methods included mapping landscape diversity and forest dynamics, followed by geoinformation processing. The research was conducted using the following methods: route landscape surveys for studying mountain meadow landscapes, which allow for the collection of detailed information on vegetation cover, landscape structure, and the physical location of objects, providing a comprehensive understanding of the characteristics of each specific landscape area; the use of modern technology and satellite imagery; and expeditionary research aimed at obtaining high-quality data directly in the field, including surveys of vegetation, soils, and landscape characteristics using qualitative description methods.

III. Results

The concept of landscape structure for calculating carbon sequestration underlies the extrapolation of data obtained on carbon dynamics in a specific natural complex. Three main types of landscape structure are distinguished, corresponding to landscape responses to the impacts and changes in energy fields: vertical, horizontal (morphological), and temporal.

Vertical structure underlies the response of landscape components primarily to vertical flows of matter and energy (sun rays, air masses, precipitation, soil moisture, etc.). A connection between the type of vertical structure and the state of the natural complex has been proven [2, 12].

Horizontal (morphological) structure is formed through the horizontal redistribution of matter and energy flows. Elementary natural complexes (facies) are combined into more complex hierarchically subordinated spatial-morphological units, which underlies classical landscape science [7, 11, 15]. The temporal structure of landscapes is represented by a regular set and alternation of states during daily, seasonal, or multi-year changes in hydrothermal and other processes. By studying patterns in the dynamics of these states and identifying ethological cycles, the basis is laid for interpolating the obtained point-in-time data over longer periods (seasons, years).

Field data and analysis of all three types of landscape structures were used to identify the conditions of carbon dynamics in the Chechen Republic. Field expedition methods were used to study the morphological structure of landscapes, including the establishment of complex profiles in different altitudinal zones and belts, the interpretation of high-resolution satellite images, and the use of geoinformation methods to identify landscape habitats based on a digital elevation model and the creation of derivative layers (aspects, slope angles).

The soil organic carbon pool is the largest among terrestrial pools. The soil carbon pool is more than three times the size of the atmospheric pool (760 Gt) and approximately 4.5 times the size of the biotic pool (560 Gt). The soil carbon pool, or soil pool, is estimated at 2,500 Gt to a depth of 2 m. Of this, the soil organic carbon pool accounts for 1,550 Gt, and soil inorganic carbon and elemental pools account for the remaining 950 Gt. Restoring the soil organic carbon pool on cropland represents a potential sink for atmospheric CO_2. Changes in soil organic carbon (both short-term and long-term) are highly dependent on agricultural activities. A wide range of land use and soil management practices increase the density and distribution of soil organic carbon in the soil. These practices include mulching, conservation tillage, crop rotation with legumes, and the use of cover crops. In addition to plants, carbon dioxide can be captured as a pure byproduct of processes related to oil refining or from flue gases from electricity generation.

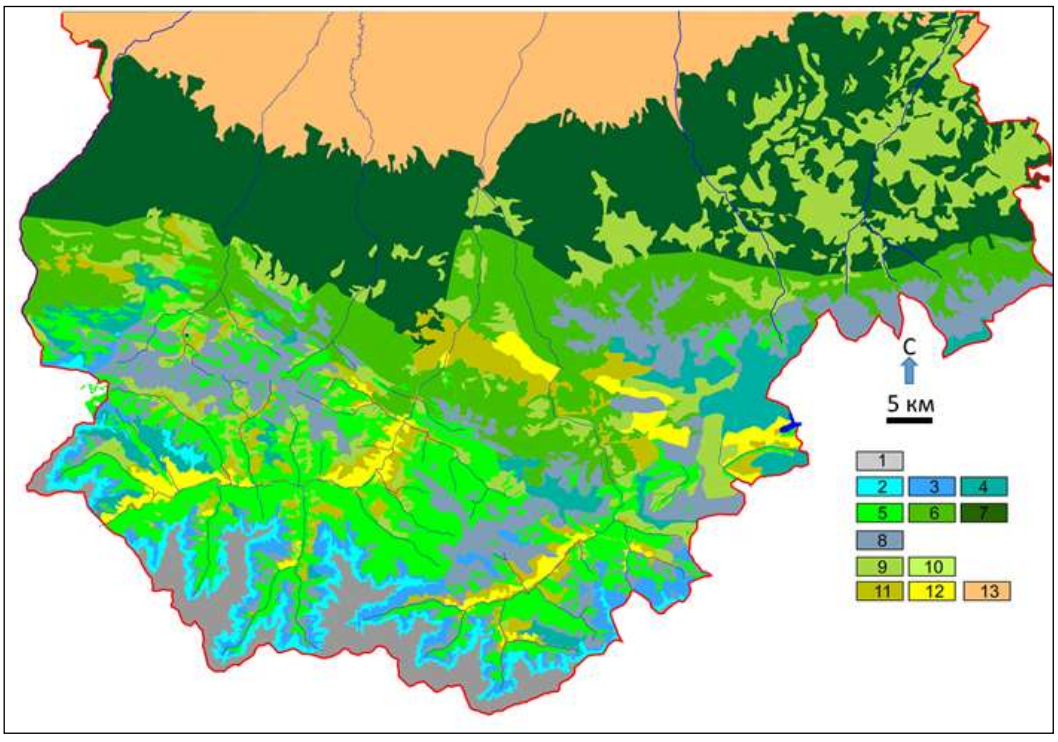
During photosynthesis, plants absorb carbon and return some of it to the atmosphere through respiration. The carbon that remains in plant tissue is then consumed by animals or added to the soil as litter when plants die and decompose. The primary way carbon is stored in the soil is as soil organic matter. Soil organic matter is a complex mixture of carbon compounds consisting of decomposing plant and animal tissue, microbes (protozoa, nematodes, fungi, and bacteria), and carbon bound to soil minerals. Carbon can be stored in the soil for millennia or quickly released back into the atmosphere. Climatic conditions, natural vegetation, soil composition, and drainage influence the amount and duration of carbon stored in the soil.

Along with studying CO_2 emissions from soils, soil catalase activity was determined using the gasometric method. Physicochemical soil parameters, such as humus content, were measured using the Tyurin method, and soil acidity was measured using the potentiometric method.

Natural forests are more resilient to climate change and disturbances than plantations due to their genetic, taxonomic, and functional biodiversity. This resilience includes post-fire recovery, resistance to and recovery from pests and diseases, and adaptation to changes in radiation, temperature, and water availability (including those resulting from global climate change). Although the genetic and taxonomic composition of forest ecosystems changes over time, natural forests will continue to absorb and accumulate carbon as long as there is sufficient water and solar radiation for photosynthesis. Green carbon in natural forests is stored in more reliable reserves than in industrial forests, especially over ecological timescales. Carbon stored in industrial forests is more susceptible to loss than that stored in natural forests. Industrial forests, especially plantations, have reduced genetic diversity and structural complexity, and consequently reduced resilience to pests, diseases, and changing climate conditions. Carbon stocks in forests subject to commercial harvesting, and particularly in monoculture plantations, will, on average, always be significantly lower (~40-60% depending on land use intensity and forest type) than those in natural, undisturbed forests.

Currently, research into the biosphere role of forests, their productivity, and sustainability in the face of global climate change has renewed interest in studying nitrogen cycling in forests. Accounting for nutrient cycling in individual units is still very rough. A systems approach and the construction of conceptual balance models are widely used as a methodological basis for studying nutrient cycling in biogeocenoses. This system of describing a community is used to objectively predict the future of the community, evaluate interventions within the community, and select those that will be beneficial for both the development of the community and its practical functioning [6, 8,12].

Landscapes that represent altitudinal zonation in the mountains of the Chechen Republic are presented by seven main types (altitude zones) and 13 subtypes (belts) (Figure 1). The altitudinal zones form the following landscape types, listed from the highest positions to the lowest: 1) nival-glacial; 2) mountain-meadow (represented by mountain-meadow subnival-alpine, mountain-meadow subalpine, mountain-meadow steppe); 3) mountain-forest (represented by mountain-forest small-leaved and coniferous-small-leaved, mountain-forest mixed broad-leaved and small-leaved, mountain-forest broad-leaved); 4) mountain-forest-meadow; 5) mountain-forest-meadow-steppe (represented by typical mountain-forest-meadow-steppe and mountain-forest-meadow-steppe and forest-steppe); 6) mountain-steppe (represented by mountain-steppe meadow and mountain-dry-steppe shrub); 7) foothill-steppe and forest-steppe.



Legend: nival-glacial – 1; mountain-meadow: 2 – subnival-alpine, 3 – subalpine, 4 – steppe; mountain-forest: 5 – small-leaved and coniferous-small-leaved, 6 – mixed broad-leaved and small-leaved, 7 – broad-leaved; mountain-forest-meadow – 8; mountain-forest-meadow-steppe: 9 – typical, 10 – A38 and forest-steppe; mountain-steppe: 11 – meadow: 12 – mountain-dry-steppe shrub; foothill-steppe and forest-steppe – 13.

Figure 1. Types and subtypes of mountain landscapes of the Chechen Republic

To describe ecosystems, components (plants, animals, soils, etc.) are identified and flows of matter, energy, or informational connections are established between them. Ecosystem connections with external entities—the atmosphere, groundwater, etc.—are also identified. Conceptual balance models represent a graphical or tabular representation of a set of components and the flows linking them with quantitative characteristics. The nitrogen cycle is the most complex of all chemical cycles.

Nitrogen is involved in all processes of organic synthesis and degradation, and also has its own microbiological cycle of entry from the atmosphere into the soil, transformation from organic to mineral forms, and release from the soil into the atmosphere. A detailed diagram of the nitrogen cycle, including the processes of microbiological transformation of its compounds, is highly complex, even at a qualitative level, and its individual components are subject to varying levels of study. The internal nitrogen cycle includes nitrogen uptake from its mineral compounds by vegetation, its conversion to mortmass upon the death of various living organisms, its processing along with soil humus by microorganisms, the mineralization of nitrogen-containing organic compounds to mineral forms, and humification. The external nitrogen cycle represents the combined processes of nitrogen input into the biogeocenosis from the atmosphere via precipitation and dust, nitrogen fixation, and nitrogen loss through leaching into underlying horizons from the root zone and through gaseous release.

The level of soil carbon sequestration is significantly affected by the established ratio of dry organic matter fractions in the total forage biomass. When converting the plant matter of grassland ecosystems to carbon, the conversion factors presented in Table 1 can be used. The data in Table 1 indicate that green phytomass has a higher carbon capacity than other plant matter fractions.

Table 1. Coefficients for converting dry plant matter of grassland ecosystems into carbon

№ п/п	Plant matter fractions	Coefficient
1.	Green phytomass	0,42
2.	Rags + litter	0,40
3.	Living roots	0,38
4.	Aboveground mortmass	0,35
5.	Subterranean mortmass	0,35

As grass stands age, carbon sequestration tends to increase, and the conversion rate may be higher. Equilibrium carbon dioxide levels in forage reservoirs (accumulation equals losses) are reached after 30-70 years of moderate natural resource management. However, meadow soils with low organic matter content can sequester more carbon over a longer period.

The nature of carbon sequestration in pastures is less predictable. In natural pastures, biomass is partially returned with livestock organic matter, resulting in sequestration, on average, not exceeding 4% of net primary production. It is only known for certain that the type of livestock grazed and the intensity of grazing are factors that significantly influence the level of biomass sequestration. Moderate grazing under rotational grazing does not impede the absorption of CO_2 from the atmosphere by pastures, since rotational grazing in different areas potentially stimulates biomass growth. Carbon sequestration rates in different types of forage ecosystems are significantly differentiated.

Intensive and unsystematic grazing, even on mature pastures, leads to the destruction of the stability and strength of the root system, preventing it from acting as active carbon sinks, which is often the dominant factor. Consequently, degradation of the root system, which accounts for 80-90% of the total phytomass, leads to the release of additional CO_2 from the primary carbon storage reservoir.

When harvesting hay, almost all aboveground biomass is removed without excretion, meaning no organic residue remains on the site. If mowing is particularly intensive and occurs intermittently, the amount of plant biomass (carbon) will inevitably decrease. Thus, the amount of accumulated CO_2 varies proportionally to the intensity of biomass removal from the site, depending on the species composition and density of the grass stand. Pastures that are annually overstocked are characterized by a steady accumulation of organic matter, accompanied by increased methane

and nitrous oxide emissions from forage lands. Furthermore, intensive trampling of grassland significantly reduces the biodiversity of the grassland, which threatens to reduce biomass (carbon accumulation) and the forage value of pastures.

The carbon content of natural forages can be somewhat increased by switching to a rotational grazing system. However, this will lead to a certain increase in the labor intensity of pasture livestock farming and the cost of its production. Thus, with targeted management, natural grassland ecosystems can make a significant contribution to carbon dioxide accumulation.

The largest contribution to carbon sequestration, taking into account the area of forage land, comes from croplands abandoned in recent decades. The average CO_2 content in the organic matter of litter and plant associations of overgrown cropland is 46.1%. Within 4-5 years of being withdrawn from cultivation, soil profiles become more capacious reservoirs for the stable removal of CO_2 from the atmosphere. The rate of carbon dioxide accumulation depends primarily on the soil thickness, the length of time it takes for the arable land to become overgrown, and the type of fertile horizon.

The carbon regime of natural meadows can be somewhat adjusted through the use of mineral fertilizers, liming, and other agrochemical techniques. For example, the addition of nitrogen to the soil will increase the biological productivity of hayfields and pastures and enhance the rate of carbon dioxide sequestration. Subsequent bacterial nitrogen fixation will ensure the deepening of the carbon distribution profile in the lower organomineral fractions of the soil, expanding the carbon capacity of the soil reservoir. Furthermore, the active microbial composition of soil fractions significantly suppresses heterotrophic respiration. This method of additionally stimulating carbon accumulation is highly effective, as the soil CO_2 reservoir in virgin lands is relatively stable. The stability of carbon deposits on abandoned lands, in the absence of external influences, is measured in centuries. At the same time, it is important to keep in mind that an overdose of nitrogen at a certain stage will cause increased nitrous oxide emissions, which may outweigh the benefits of carbon dioxide absorption. The effect will be at least neutral or positive.

Biotic and abiotic variability in soil carbon sequestration capacity may change under climate change. Nutrient availability, the composition of soil fauna and microbial communities, and vegetation types depend on climate specificity and its seasonal variability, as well as the nature of the long-term hydrothermal trend. Therefore, the evolutionary adjustment of seasonal hydrothermal parameters across latitudinal and altitudinal natural zones will alter the established pattern of organic matter conversion into subsurface carbon by natural food sources.

A limiting factor for carbon dioxide sequestration may be increasingly frequent, abnormally dry periods, which will affect plant photosynthesis and lead to the evolutionary steppeization of grassland ecosystems, inevitably weakening their role in the decarbonization process.

An earlier spring and a slight shift in the autumn season may have the opposite effect on the carbon balance. If this trend continues, we can predict an extension of the grass growing season, and consequently, an increase in the biotic component of meadows in the carbon cycle. This applies primarily to northern latitudes, where more productive plants will thrive and temporal and spatial peaks will shift.

These assumptions will be valid with an adjustment for the previous cumulative effect of specific hayfields and pastures. This cumulative effect should serve as the starting point for the expected dynamics of carbon sequestration. Given the volatility of global warming, it is extremely difficult to accurately predict the net production of grassland ecosystems. Judging by the dynamics of carbon sequestration over the first two decades of the new century, the average annual sequestration rate is growing at 0.4% per year.

The accumulation of carbon dioxide in hayfields and pastures is characterized by a wider dispersion and depends on the botanical composition of the grassland and its use, the hydrothermal conditions of the area, and soil types. Moreover, the volume of soil carbon dioxide sequestration shows a noticeable downward trend over time, even with traditional land management remaining unchanged for many years.

Grazing natural meadows with moderate land management has a carbon advantage over harvesting hay. Relying on organic livestock feed for carbon sequestration is preferable to the use of agrochemicals.

IV. Conclusion

Observations at a carbon station in low-mountain broadleaf forest landscapes, including gas dynamics, as well as data from other researchers [4, 9], show that a significant portion of the phytomass is converted into mortmass, which, upon decomposition, returns to the atmosphere along with volatile gases. In these phytocenoses, which have reached climax states, carbon emission predominates over runoff.

The mortmass of mountain meadow landscapes consists of slowly decomposing rags and litter. In turf-grass communities, rags can exceed green phytomass and reach 2 t/ha. The underground phytomass of roots is significant, accounting for more than half of the total phytomass. Factors contributing to carbon accumulation in these landscapes include intense solar energy and a relatively short growing season. The prevalence of primitive soils also contributes to low carbon emissions [10, 11, 14]. Aboveground phytomass reserves in subalpine meadows reach 2-3.5 t/ha, with typically higher mortmass values. Under mixed-grass meadows (reed grass, fescue, etc.), particularly in flattened areas, deep and medium-deep soils form, where carbon is deposited. These meadows also have high reserves of belowground phytomass.

On the northern slopes, meadows with rhododendron (*Rhododendron caucasicum Pall.)* thickets are found, where aboveground phytomass increases to 6-10 t/ha, with low herbaceous phytomass values (0.7 t/ha). Soddy-peaty soils, also with active carbon accumulation, develop beneath these meadows.

Observations show that, upon reaching the climax and quasi-climax stages, broadleaf forests, instead of sequestering carbon, begin to actively release it through respiration [1,13,15]. Mortmass mineralization is accompanied by the emission of volatile gases; only a small amount of carbon enters the soil. Furthermore, under the canopy of mature broadleaf forests, the grass cover is sparse, leading to the destruction of the upper soil horizons and their erosion into the lower parts of the slopes. In mountain-steppe landscapes, carbon accumulates primarily in the underground part of the plant community, in the mortmass (primarily underground) and soil humus. Observations show that the ground layers of the mortmass, which transition into the upper soil layers, are critical for understanding carbon dynamics. Carbon accumulation in the main carbon-containing components of mountain landscapes—soils and vegetation—is hampered by climate instability, slope processes, and economic activity.

The opposite is observed in high-altitude landscapes, where phytomass transforms into waste and litter, replenishing the upper soil horizons. The prevalence of subzero temperatures reduces soil respiration and carbon loss. In the mid-altitude zone, due to a lack of moisture, herbaceous phytomass is relatively small, and a certain portion is consumed by livestock. The resulting mortmass enters the soil and is partially returned to the atmosphere through biogenic degradation.

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DEVELOPMENT EFFICIENCY OF THE ORGANIZATION'S HUMAN CAPITAL

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Abstract

This article analyses the formation and efficiency of human capital within an organization. It examines the approaches of scientists to the essence of human capital in foreign and domestic sources. It emphasises that existing deficiencies complicate the management and practical implementation of human capital in companies, which can distort the perception of its value and productivity. Effective human capital management requires the development of a system that considers both current and anticipated organizational needs. This system should cover the development of adaptive competencies, the training and integration of new personnel, and the use of modern technologies in personnel management. The article presents a set of formulas intended for use within the framework of an organization's human capital development management system.

Keywords: human capital, organization, management, efficiency, components, factors, indicators, approaches

I. Introduction

There is an intense interest in human capital in modern economic theories and management practices. This is due to the need to develop and apply effective methods of its management to achieve strategic goals and promptly solve problems at different stages of an organization's development.

This fact makes it necessary to identify the characteristics and productive abilities of employees, as well as to assess the effectiveness and their work efficiency, which are manifested through the formation and implementation of the organization's human capital.

Scientific research defines human capital as a set of knowledge, skills, abilities, talents and other qualities that contribute to personal, social and state well-being. This is a key element that

determines the successful development of an organization's economy under the post-industrial society.

Human capital is the most valuable asset, surpassing all others in importance, including natural resources. It is human capital, and not property or production capacity, that is the basis of economic progress, productivity and competitiveness.

For the majority of the working population, this is the main asset that determines the results of activities, success and social status. Effective human capital management is a key factor in creating a sustainable competitive advantage.

II. Methodology

A lot of time has passed since the beginning of active research on human capital (the 60s of the twentieth century, works by G. Becker, T. Schulz, etc.). Nevertheless, many key methodological and practical questions remain open. They include the vagueness of concepts, the composition of elements, the conditions of formation and implementation, the features of reproduction, the methods of assessing the results and efficiency. Many Russian scientists have pointed this out (M. N. Arnaut, A. A. Bulov, A. I. Dobrynin, Yu. A. Korchagin, etc.).

The theory of human capital is based on the provisions of neo-Keynesian, neoclassical and institutional economic theories, as well as a number of other areas of economic thought. These theories recognize people as the most important resource of society, equal in value to physical capital such as machinery and equipment. According to this theory, regions with a high level of human capital development, i.e., educated and qualified population, have an advantage in attracting and accumulating material and financial resources. At the same time, even a large population will not bring economic prosperity if it does not have a sufficient level of knowledge and skills formed over a long historical period.

In the 20th-21st centuries, foreign researchers began to study the influence of social factors and technologies on human capital. Thus, D. Heckman noted that human capital includes not only formal education, but also social skills that are important for successful work activity [16]. Other authors, such as T. Davenport, have emphasized the role of digital technologies in the transformation of human capital [15].

Modern foreign scientists are interested in various aspects of the influence of human capital on the performance indices of companies, including the influence of capital on the competitive advantages of companies [14], flexible working hours [11], work organization and working efficiency of employee [12; 18].

In Russian science, the study of the essence of human capital has also undergone long stages of evolution. Some authors considered human capital as a set of knowledge, practical skills and certain motivations that determine the results of labor activity [2]. Later, human capital began to be considered as a key resource for increasing the competitiveness of organizations [20].

Modern Russian researchers focus on the role of digitalization in the transformation of human capital [5], ensuring personnel competence [9], connection with information technologies [6], etc.

A critical analysis of foreign and Russian approaches to the definition of human capital has shown both similarities and differences in understanding its content. The common feature is the emphasis on the belonging of knowledge, skills and health as mandatory and attributive components of this concept. At the same time, foreign researchers prefer to focus on issues of economic return on investment in human capital. For Russian scientists, the peculiarities of the mutual influence of human capital and the socio-economic state of society and the economy are of greater interest.

III. Results

Human capital is a key aspect of successful functioning and a factor in ensuring the competitiveness and profitability of an organization, which requires effective management of the processes of its formation and implementation in accordance with the goals and strategic directions of its development.

The uniqueness of human capital lies in the creative potential of employees and their ability to find solutions to complex production problems. This allows the company to adapt more quickly to unfavorable changes in the market and maintain stability in the face of tough competition.

To operationalize and systematize work with human capital in the company's management system, a corresponding subsystem built into its organizational structure must be identified, all documents regulating this area of activity must be compiled and formalized. For management purposes, the composition of human capital can be represented as the sum of the sets of its components, presented as:

$$\mathrm{HC} = \sum_{i=1}^{n} \sum_{j=1}^{m} \mathrm{C}_{ij}, \quad (1)$$

where HC is the human capital of the organization; C is the component of human capital.

Each component of human capital also represents a complex structure, as a set of characteristics and properties of a person in the form of independent groups of knowledge, abilities, skills, professionalism, production experience, motivation, labor potential, etc., considered and reflected in the organization’s management system.

For each component included in the human capital of the organization, indicators must be developed to keep track of the results of their implementation, as well as accounting of costs (expenses) for their provision and development. Without a clearly substantiated system of indicators reflecting the state and movement of elements of human capital, it is impossible to determine its cost, analyze the state and changes over a certain period, determine the effectiveness of investments, and develop measures for further development.

Human capital management should be aimed not only at maintaining its proper condition according to the current goals of the organization's activities. Of no less importance is the management of changes in human capital, which should be synchronized with the existing trends of the external environment and reflect the directions associated, for example, with changes in the requirements for the composition or content of human capital components, leading to their renewal or replacement. Thus, the emergence of new professions or the complication of existing ones requires adjustments to the set of components that determine the knowledge of the organization's personnel. The basic volume of knowledge that employees of a certain specialty currently possess may in the very near future cease to satisfy the needs of the organization, which will require its improvement in individual components or complete replacement.

The introduction of effective innovative technologies, such as digitalization, creates promising opportunities for business development and improving financial performance. However, digitalization requires personnel to have new knowledge and skills, which requires mandatory training or retraining.

Another direction in the development of the human capital of the organization is the development of soft skills, which are not directly related to a particular specialty, but characterize the personal qualities of employees, including communication, intellectual, volitional, and leadership. These skills also directly or indirectly affect the efficiency of the organization's human capital. In this regard, an important direction for the development of human capital is the system of professional training, which guides the organization's personnel to acquire new knowledge and skills.

In the set of measures for the development of human capital, the company should use approaches that allow influencing the efficiency of personnel management. For this purpose, it is necessary to ensure the achievement of planned measurable goals through the formation of a highly qualified and motivated team focused on the final result and trained in line with the relevant human resources (HR) strategy.

In addition, it is necessary to achieve the company's business goals with minimal costs for the formation and development of human capital, ensuring the necessary balance between economic feasibility and efficiency.

In the most general case, the efficiency of using the organization's human capital in a period of time t ($E_{HC}t$) can be determined according to the following traditional scheme:

$$E_{HC} = \frac{R_{HC}t}{C_{HC}t}, \quad (2)$$

where $R_{HC}t$ is the result of the organization's activities obtained through the use of human capital in period t; $C_{HC}t$ is the organization's costs (expenses, investments) for the formation and development of human capital in period t.

However, for planning or detailed analysis purposes, efficiency must be determined for individual components of the organization's human capital. To do this, the organization must establish detailed accounting of results and costs for each element of human capital.

By modifying the approach proposed by O. G. Vaganyan [6], it is possible to determine the value of the coefficient of efficiency of human capital of the organization (CEI_{HC}) for the corresponding period using the following formula:

$$CEI_{HC} = \frac{VHC_2 - VHC_1}{I_2}, \quad (3)$$

where VHC_2 and VHC_1 denote the value (or assessment) of human capital, respectively, for the periods under study: previous (1) and subsequent (2); I_2 is the amount of investment in human capital in period 2.

When $CEI_{HC} > 1$, the investment efficiency in period 2 is positive (growing).

When $CEI_{HC} < 1$, the investment efficiency in period 2 is downward (growing), which requires appropriate measures from the company's management system.

In a similar way, it is possible to determine the amount of capital return from the implementation of investments in the human capital of an organization based on the return on capital (ROC) indicator for the corresponding period using the following formula:

$$ROC = \frac{\Delta NP}{C}, \quad (4)$$

where ΔNP is the increase in net profit (or net income); C is the amount of capital investments (or capital expenditures) that caused the increase in net profit.

At the same time,

$$\Delta NP = NP_2 - NP_1, \quad (5)$$

where NP_1 and NP_2 are the amount of net profit of the organization at the beginning and end of the period under study, respectively.

The organization must establish a system for selecting and applying the most effective methods and tools for personnel management that can take the effectiveness of work processes to a new level, ensuring synergy between strategy and execution.

The result of the company's human capital management is aimed at maximizing the efficiency of personnel activities based on a specific strategic perspective.

$$HCM = ECP \rightarrow max, \quad (6)$$

where HCM is the result of the company's human capital management; ECP is the efficiency of the company's personnel.

Investments directed into the formation and development of human capital should become an indispensable condition for ensuring the future state of the organization, determining the goals

and results of its functioning. Management of the effectiveness of investment in human capital should be carried out through the implementation of appropriate policies within the framework of achieving the goals of the organization's activities [4].

In addition to labor costs, in the course of determining the indicators of economic efficiency of investment in improving the management of the company's personnel, it is important to consider the overall result of such an investment. The improvement of human capital of both the entire team and individual employees, as well as the result of implementing management decisions, must be taken into account and serve as a supplement to the indicators and results of the production activities of the entire company.

The result of investing in improving the company's human resources management system should reflect the state of its human capital in dynamics, which requires the use of an appropriate system of indicators and metrics. The effectiveness of the organization's human capital management should be demonstrated in all priority areas, including:

– growth in production and sales volumes due to increased productivity, quality of labor and products, improvement of the organization, including marketing, innovation, etc.;

– increasing the level of employee motivation, attractiveness and prestige of the company, which contributes to increasing the stability of the workforce, reducing the loss of working time, etc.;

– reducing financial costs for training personnel by reducing the duration of their training and the correct selection of qualified specialists, which will increase the overall level of the company's labor capital;

– improving corporate culture and strengthening team spirit, which contributes to the creation of a favorable working atmosphere. This, in turn, increases employee engagement, their loyalty to the company and readiness for innovation. Management focused on the development of corporate values, helps to form stable connections between employees and management, which minimizes conflicts and improves communication;

– optimization of the adaptation processes for new employees, which allows them to be integrated into the work process more quickly and reduce the period of time it takes for them to achieve full productivity. An effective adaptation system includes not only professional training, but also familiarization with corporate standards, which helps reduce errors and improve the quality of work;

– development of an assessment and feedback system which allows timely identification of weaknesses in management and their prompt elimination. Regular assessment of the results of work and professional growth of employees helps to maintain a high level of motivation and stimulates them to continuous improvement;

–the introduction of modern technologies in human resources management, such as the automation of HR processes and the use of analytical tools, which increases the accuracy of decision-making and reduces the administrative burden on management.

The overall final result of the company's activities is usually presented in its reporting documents as a set of all its results (revenue, profit from sales, etc.). It can also be reflected through the sum of individual effects arising from the implementation of specific measures carried out, for example, by the HR department and affecting the state of human capital.

IV. Conclusions

Modern attention to human capital in management and economic theory is due to the need for effective management of this resource to achieve the strategic goals of organizations. Human capital includes a number of components, including the knowledge, skills and talents of

employees, that contribute to the well-being of both individuals and society as a whole. In the conditions of post-industrial society, human capital becomes a key factor determining the competitiveness and economic progress of organizations.

Currently, there are many approaches to the concept of human capital. The multifunctionality of understanding the essence of human capital complicates its operationalization in companies, which can lead to difficulties in managing development processes and distortion of the assessment of its value and effectiveness. It is important to develop clear indicators for recording and analyzing the state of human capital.

Effective human capital management requires the creation of a system that takes into account both the current and future needs of the organization. This includes developing soft skills, training and onboarding new employees, and introducing modern technologies into HR management. Investments in human capital should be aimed at maximizing its effectiveness, which in turn contributes to increased productivity, improved corporate culture and reduced training costs.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ASSESSMENT OF INFRASTRUCTURAL CHANGES IN THE TERRITORIES OF TSKHINVALI REGION OF GEORGIA (2007–2023) USING GEOINFORMATION SYSTEMS

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Abstract

This study examines the spatial and quantitative changes to infrastructure and settlements in the Tskhinvali region of Georgia between 2007 and 2023, caused by armed conflict and prolonged occupation. Using high-resolution aerial imagery, satellite data and geographic information systems (GIS), the research identifies and quantifies infrastructural losses across four municipalities: Tskhinvali, Java, Znauri and Akhalgori. Multi-temporal image analysis and digitization were performed using Google Earth Pro and ArcMap software. The results reveal a significant decrease in the number and area of infrastructure objects. Tskhinvali municipality experienced the most pronounced decline, with a 13.4% decrease in building areas and an 18.0% reduction in the number of infrastructure objects. The municipalities of Java and Znauri recorded infrastructure losses of 12.8% and 6.6%, respectively, while Akhalgori showed a modest 1.2% reduction. The spatial analysis also revealed patterns of degradation in specific settlements. These findings emphasize the long-lasting effects of conflict on built environments and highlight the importance of geospatial tools in post-conflict assessments. The study provides a detailed geodatabase to support future reconstruction, regional planning and peacebuilding initiatives. Furthermore, the methodology demonstrates the value of integrating temporal satellite imagery with GIS for monitoring changes in conflict-affected territories.

Keywords: geospatial analysis, GIS, infrastructure degradation, Tskhinvali region, Georgia

I. Introduction

Armed conflicts and occupations leave enduring physical and socio-economic impacts. Beyond immediate casualties, they damage or transform essential infrastructure—roads, bridges, power grids, settlements, and public facilities—reducing economic activity and quality of life [1,2].

Assessing these impacts is vital not only to document destruction but also to inform reconstruction planning, peacebuilding, and long-term regional development strategies [3].

Modern geospatial technologies—particularly high-resolution aerial imagery, satellite data, and geographic information systems (GIS)—provide powerful means to analyze territorial changes in conflict, occupied zones. Unlike ground surveys, which often rely on indirect or secondhand evidence, satellite imagery offers direct, verifiable information about spatial patterns and their evolution over time. The consistent temporal coverage of satellite archives also enables comparative studies of past and present conditions. These capabilities are crucial for understanding conflict dynamics, planning humanitarian interventions, and supporting reconstruction [4–7. Following the 2008 Russia–Georgia war, the Russian Federation recognized the independence of the self-proclaimed "Republic of South Ossetia," a move later followed by Nicaragua, Venezuela, and Nauru. However, the vast majority of the international community—including the European Union, NATO, the United Nations, and most UN member states—continues to regard these territories (Tskhinvali region) as part of Georgia's sovereign territory. While this issue has complex geopolitical, legal, and humanitarian dimensions [8–10], the present study addresses exclusively the infrastructural aspects of the changes observed in the occupied territories. Under the influence of hostilities and after the occupation of the Tskhinvali region in 2008, infrastructural facilities and settlements in the territories have changed. This article studies and analyzes these changes based on orthophotos derived from processing satellite and aerial images.

Knowing what infrastructural changes are taking place in the occupied territories of the Tskhinvali region after the occupation, what infrastructural facilities were destroyed and where they are being developed, where new settlements are being formed, etc., will help us to develop plans for the peaceful resolution of the conflict; also, when restoring territorial integrity, we will be ready to see how the existing infrastructure should be developed in the future.

This study uses multi-temporal, high-resolution aerial imagery and GIS-based digitization techniques to analyze settlement changes in the occupied territories of the Tskhinvali region between 2007 and 2023. Its objectives are to:

1. Quantify the scale and spatial distribution of infrastructure losses.
2. Identify the areas most affected by conflict and occupation.
3. Build an information database to support future reconstruction planning and conflict resolution initiatives.

II. Study area

The Tskhinvali region is located on the southern slopes of the Greater Caucasus range. Its northern border runs along the main watershed range of the Caucasus, and the eastern border runs along the Alevi range; the western border of the region crosses the Likhi, Racha, and Shoda-Kedela ranges, the valleys of the Dzirula, Kvirila, Jejora, and Gharula rivers, and ends directly at Mamisoni Pass; the southern border follows the northern periphery of the Shida Kartli plain. In the north, the Tskhinvali region borders the Republic of North Ossetia of the Russian Federation - Alania, and on the other three sides - the administrative units of Georgia: in the east - Kazbegi and Dusheti municipalities, in the south - Kaspi, Gori, Kareli, and Khashuri municipalities, and in the west - Sachkhere and Oni municipalities (see Fig. 1) [11].

The territory of the Tskhinvali region occupies 3,800 km². In the Tskhinvali region, Tskhinvali city, 4 townships - Akhalgori (former Leningori), Kornisi (former Znauri), Kvaisa, and Java, and about 300 villages are located [12].

The so-called Tskhinvali region (formerly South Ossetia Autonomous Region until 1991). The northernmost point of the region is the Caucasus Range, Mount Chanchakhi, at 4,461 m above sea level; the southernmost point is the valley of the river Tortla (a tributary of Mejuda), north of

Tbilisi-Senaki-Leselidze highway, south of Orchosani village at 725 m above sea level; the westernmost point is the gorge of the Gharula River (the left tributary of Rioni), northeast of Oni's village of Kvedi, 3 km, 1,300 m above sea level; and the easternmost point is the Lomisa-Alevi range, the area of Kartolisi, 4 km east of the village of Monasteri, at 1,839 m above sea level.

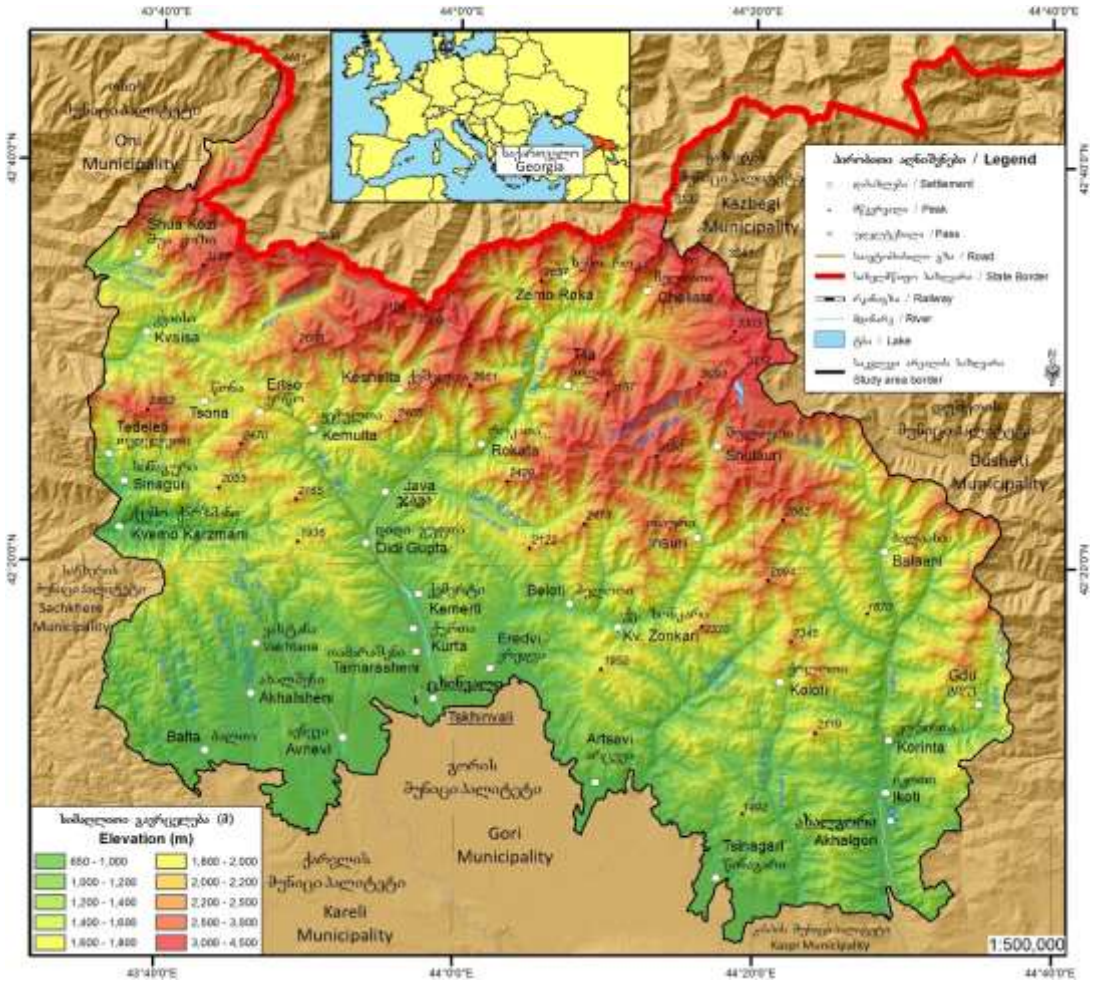


Figure 1: *A map of the study area*

Java Municipality (former South Ossetia Autonomous District until 1991). The northernmost point of the municipality is Mount Chanchakhi, the Caucasus Range, at 4,461 m above sea level; The southernmost point is the area of Nacherala, the watershed of Kekhura and Itrapuli (Didi Liakhvi river basin), at 1,751 m above sea level; The westernmost point is the gorge of the Gharula River (a left tributary of the Rioni river), 3 km northeast of the Oni village of Kvedi, at 1,300 m above sea level, and the easternmost point is the Keli volcanic mountain range, south of Kelitsadi Lake, at 3,409 m above sea level [12,13].

The so-called Znauri Municipality (within the former South Ossetia Autonomous District until 1991). The northernmost point of the municipality is the Likhi range, Mount Rustavi, the watershed of the Aghmosavletis Prone and Patsa rivers, at 1,936 m above sea level; the southernmost point is the gorge of the Ghaghuri River (the left tributary of the Dasavletis Prone River), south of Shua Kvatetri village, at 760 m above sea level; the westernmost point is the Likhi range, Mt. Kaprebi hill, at 1,183 m above sea level; and the easternmost point is the basin of the Aghmosavletis Prone River, the Saltani channel, 3 km east of the village of Didmukha, at 845 m above sea level [12,13].

Akhalgori region (former South Ossetia Autonomous District until 1991 - Leningori Region). The northernmost point of the municipality is the Keli highland, west of the Archvebi

Lake, at 3,310 m above sea level. The southernmost point is the gorge of the river of Tortla (a tributary of Mejuda), north of the Tbilisi-Senaki-Leselidze highway, south of the village of Orchosani, at 725 m above sea level; the westernmost point is the Shida Kartli plain, 4 km southwest of Tsinagari village, at 728 m above sea level. The easternmost point is the Lomisa-Alevi range, an area of Kartolisi, 4 km to the east of the village of Monasteri, at 1,839 m above sea level [12,13].

III. Methods and materials

The following activities were carried out within the study area: historical data collection, generalization, and analysis. The main information of the research was analyzed in geoinformation systems, where images of different resolutions and areas were processed based on aerial imagery and satellite data of different periods.

Aerial images of different periods and Google Earth Pro software were used as the main base data, where photos of different periods were collected within the study area. The main part included information from the year 2007 and 2023. Digitization of infrastructural objects was carried out using ArcMap software. In the first stage, the photos of 2023 were converted into digital format and grouped according to municipalities. In the next stage, similar activities were conducted based on the data from 2007 [4,14]. In the final stage of the research, the analysis of existing infrastructural objects in the first and second stages in different periods and the preparation of the relevant database were carried out (see Fig. 2).



Figure 2: *Study area database*

III. Results and discussion

The results obtained based on the analysis of infrastructural objects using the mentioned methodology are presented below, according to municipalities (see Fig. 3).



2007 2023

Figure 3: *Distribution of infrastructural objects by municipalities (2007-2023)*

Tskhinvali municipality

Based on the data of 2023 within the study area, it was determined that 11,098 different types of infrastructural objects were quantitatively fixed within the municipality in the mentioned year. Particularly large number of infrastructural facilities are located in the territories of the Tskhinvali city and nearby settlements, such as villages of Tamarasheni, Kurta, Kekhvi, Kemerti, and Eredvi. Regarding the 2007 data, an analysis of aerial imagery from different areas revealed that 13,546 distinct types of infrastructural objects were recorded in the temporarily occupied territory of the municipality. From 2007 to 2023, the number of infrastructure facilities decreased by 18.0% (see Fig. 4).

The change in the spatial distribution of buildings was also analyzed for the territory of the Tskhinvali municipality. As a result, it was identified that in the period from 2007 to 2023, the areas of buildings in the occupied territory of the municipality decreased by 13.4% (see Fig. 5).

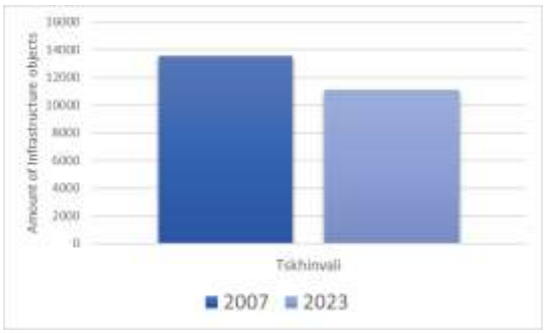


Figure 4: *Change in the quantity of infrastructural objects in the occupied territory of the Tskhinvali municipality (2007-2023)*

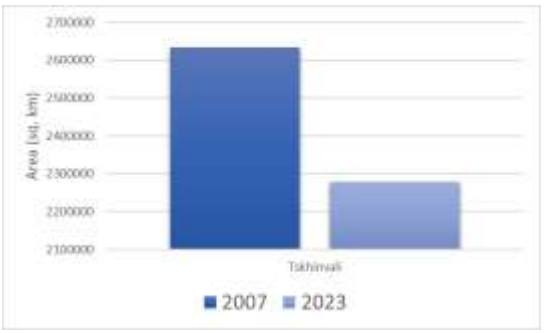


Figure 5: *Change of buildings by area in the occupied territory of the Tskhinvali municipality (2007-2023)*

Changes in the quantity and area of some settlements within the Tskhinvali municipality are demonstrated below (see Fig. 6).



Tamarasheni village (2007-2023)



Zemo Achabeti village (2007-2023)



Kekhvi village (2007-2023)



Kemerti village (2007-2023)

Figure 6. *Changes in the quantity and area of several settlements within the Tskhinvali municipality (2007-2023)*

Java municipality

Based on the data of 2023, within the study area, it was determined that 4,353 different types of infrastructural objects were quantitatively recorded within the municipality in the mentioned year. Particularly, a large number of infrastructural facilities are located in the territories of the Java township and nearby settlements - the village of Didi Gupta, Sakire, Mskhlebi, and Buzala. As for the data of 2007, based on the analysis of aerial imagery data of different areas, it was identified that according to the 2007 data, 4,991 different types of infrastructural objects were recorded in the temporarily occupied territory of the municipality. From 2007 to 2023, the number of infrastructure facilities decreased by 12.8% (see Fig. 7).

The change in the spatial distribution of buildings was also analyzed for the territory of the Java municipality. As a result, it was identified that in the period from 2007 to 2023, the areas of buildings in the occupied territory of the municipality decreased by 7.8% (see Fig. 8).

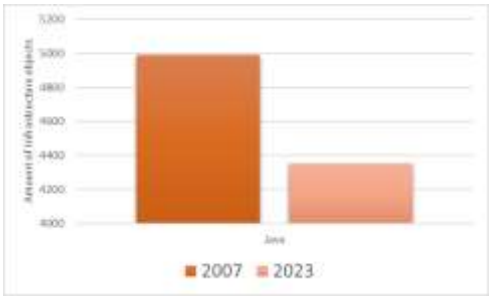


Figure 7: *Quantitative change of infrastructural objects in the occupied territory of the Java municipality (2007-2023)*

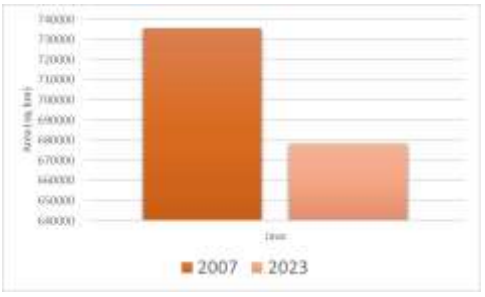


Figure 8: *Change of buildings by area in the occupied territory of the Java municipality (2007-2023)*

Changes in the quantity and area of several settlements within the Java municipality are demonstrated below (see Fig. 9).



Java township (2007-2023)



Chetari village (2007-2023)



Biteta village (2007-2023)



Tsru village (2007-2023)

Figure 9: *Changes in the quantity and area of several settlements within the Java municipality (2007-2023)*

Znauri municipality

Based on the data of 2023 within the study area, it was determined that 4,600 different types of infrastructural objects were quantitatively fixed within the municipality in that year. Particularly large number of infrastructural objects are located in the villages of Kornisi, Avnevi, Didi Tsikhiata, and Akhalsheni. As for the data of 2007, based on the analysis of aerial imagery data of different areas, it was determined that according to the 2007 data, 4,926 different types of infrastructural objects were recorded in the temporarily occupied territory of the municipality. From 2007 to 2023, the number of infrastructure facilities decreased by 6.6% (see Fig. 10).

The change in the spatial distribution of buildings was also analyzed for the territory of the Znauri municipality. As a result, it was established that in the period from 2007 to 2023, the areas of buildings in the occupied territory of the municipality decreased by 8.7% (see Fig. 11).

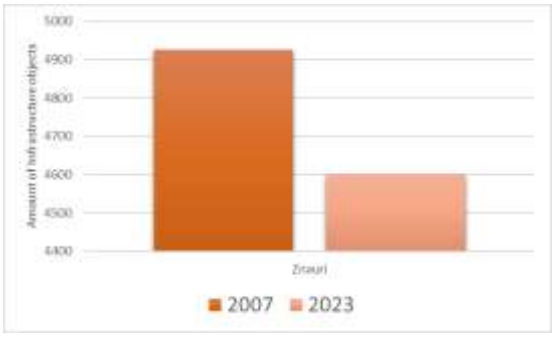


Figure 10: *Quantitative change of infrastructural objects in the occupied territory of the Znauri municipality (2007-2023)*

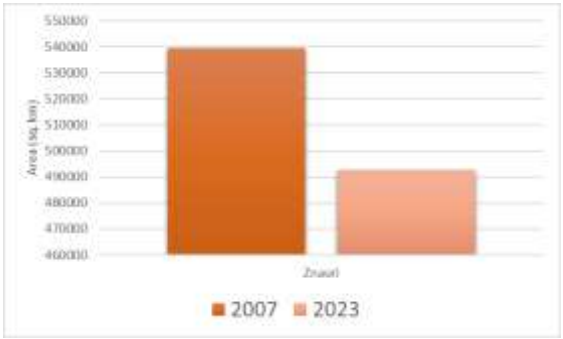
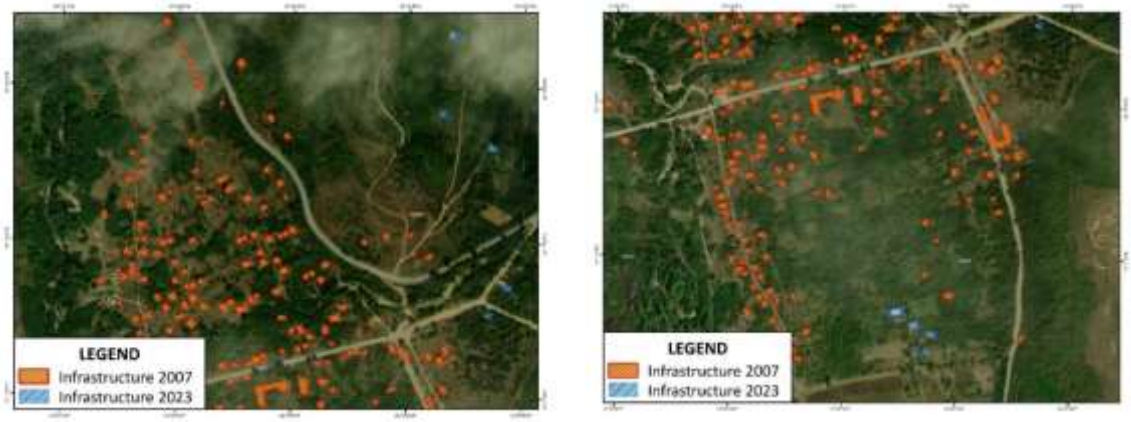


Figure 11: *Change of buildings by area in the occupied territory of the Znauri municipality (2007-2023)*

Changes in the quantity and area of several settlements within the Znauri municipality are demonstrated below (see Fig. 12).



Avnevi village (2007-2023) Avnevi village (2007-2023)

Figure 12: *Changes in the quantity and area of several settlements within the Znauri municipality (2007-2023)*

Akhalgori municipality

Based on the data of 2023 within the study area, it was determined that 5,508 different types of infrastructural objects were quantitatively recorded within the municipality in the mentioned year. A particularly large number of infrastructural facilities are located in the territory of the Akhalgori city. Regarding the 2007 data, an analysis of aerial imagery from different areas revealed that 5,575 distinct types of infrastructural objects were recorded in the temporarily

occupied territory of the municipality. From 2007 to 2023, the number of infrastructure facilities decreased by 1.2% (see Fig. 13).

The change in the spatial distribution of buildings was also analyzed for the territory of the Akhalgori municipality. As a result, it was determined that the areas of buildings in the occupied territory of the municipality decreased by 1.3% in the period from 2007 to 2023 (see Fig. 14).

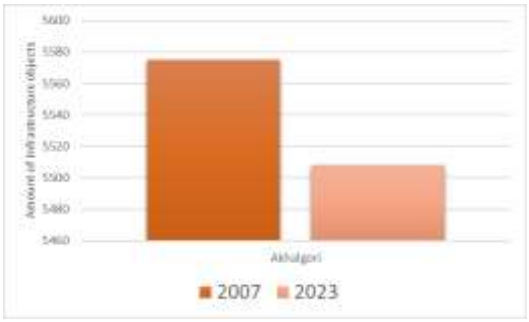


Figure 13: *Quantitative change of infrastructural objects in the occupied territory of the Akhalgori municipality (2007-2023)*

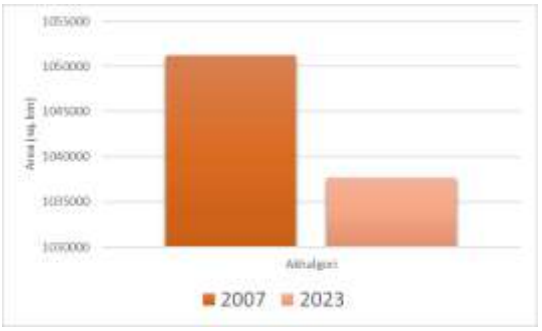
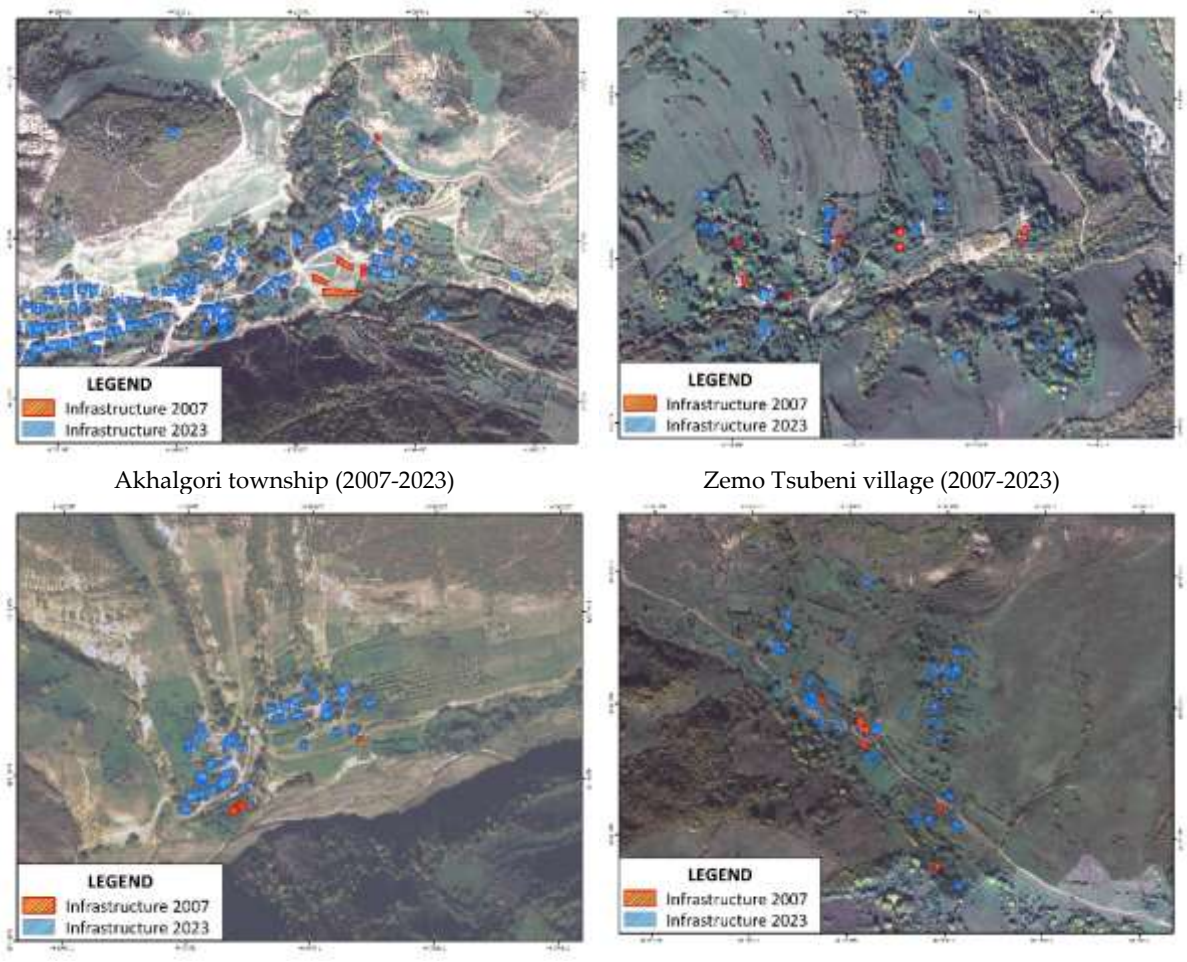


Figure 14: *Change of buildings by area in the occupied territory of the Akhalgori municipality (2007-2023)*

Changes in the quantity and area of several settlements within the Akhalgori municipality are demonstrated below (see Fig. 15).



Akhalgori township (2007-2023)

Zemo Tsubeni village (2007-2023)

Kvemo Alevi village (2007-2023)

Tsoldi village (2007-2023)

Figure 15: *Changes in the quantity and area of several settlements within the Akhalgori municipality (2007-2023)*

IV. Conclusion

This study provides a detailed geospatial analysis of the infrastructural and settlement changes in the Tskhinvali region of Georgia between 2007 and 2023. Aerial imagery, satellite data, and geographic information system (GIS) tools were utilized to digitize and measure changes in the number and spatial extent of infrastructural facilities across the territories of the four municipalities of Tskhinvali Region: Tskhinvali, Java, Znauri, and Akhalgori.

The findings indicate a significant decline in infrastructural assets and settlement areas, with the largest reductions marked in Tskhinvali municipality (18% decrease in infrastructure objects and 13.4% reduction in building areas) and smaller but measurable losses in other municipalities: Java – 12.8%, Znauri – 6.6%, Akhalgori – 1.2%. The spatial analysis also identified certain villages where infrastructural destruction or degradation was noticeable.

The conclusions reveal the enduring effects of hostilities and occupation on the infrastructure objects and settlements of the area. By creating this geodatabase, they provide a useful basis for planning reconstruction projects, territorial reintegration efforts, and settling disputes. In addition, the method used to incorporate multi-temporal imagery in GIS digitization can serve as a model for similar investigations conducted on other areas affected by conflict.

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CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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PROSPECTS FOR GREEN FINANCING OF CONSTRUCTION IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT

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Abstract

The 'green' agenda is becoming an increasingly urgent issue for countries to address, and since the construction industry causes significant damage, it is important to focus on 'greening' it. Effective financing is necessary for 'green' construction, since the initial costs are higher than standard. At the same time, the successful experience of other countries demonstrates the wide range of opportunities available to market participants. The article concluded that foreign countries, particularly China, have successfully introduced 'green' financing instruments that could be utilized in a similar way in Russia. The study identified prospects for developing 'green' financing and analyzed the possibilities for implementing it in Russia. The existing practice of issuing 'green' bonds was evaluated and it was concluded that this practice should be expanded by encouraging financial institutions and developers to issue bonds. The necessity for banks, financial institutions, and developers to introduce 'green' lending has been proven. This would facilitate the growth of green financing in Russia. The study revealed that creating an ecosystem offering tax benefits, reduced loan rates, and government subsidies for market participants implementing green construction projects would be advisable. This would enable processes in the housing market to be structured and systematized, as well as increasing the effectiveness of interaction between participants. All processes involving participants in the housing market, including financing procedures and instruments, should be clearly defined within this system.

Keywords: ecosystem, housing market, financing, financial instruments, "green" construction; ESG rating

I. Introduction

The construction industry is an industry that causes one of the most significant damages to the ecological state of the country and the world as a whole. Currently, countries have increasingly begun to focus on the need and importance of implementing the "green" agenda. And of course, changes are also taking place in other industries and spheres, and many states include achieving carbon neutrality by 2050-2060 in their development strategies.

We would like to emphasize that, in particular, the BRICS countries and especially in Russia, the importance of the "green" agenda is increasing every year. China is one of the leaders in the introduction of "green" technologies and the use of "green" financial mechanisms in construction. Moreover, China was the country that began to introduce them in construction, and continues to spread it.

At the same time, Russia has been closely involved in the implementation of this agenda for several years, and in particular, companies in construction are advised to act based on the need to

reduce their carbon footprint. The government and financial institutions are taking steps to involve companies in the implementation of the principles of the "green" agenda. In particular, the extent to which the company acts within the framework of the agenda and implements the principles of the "green" agenda depends on what kind of financing and under what conditions the company can receive.

The introduction of "green" technologies and "green" financial instruments makes it possible to bring Russia closer to achieving a "green" economy and reducing the negative impact of industries on the environment, which indicates the relevance of this topic.

The purpose of the study is to determine the prospects for the development of "green" financing of construction in Russia in modern conditions, which is especially important in the context of the need to achieve carbon neutrality by 2060.

II. Methods and Materials

Mortgage lending occupies a fundamental place in financing the purchase of housing and, in fact, for the construction of real estate. For many years, the population has been using this tool to buy housing, and developers are building real estate using, among other things, the money they receive from buyers. It is important to note that according to the results of 2024, mortgage lending accounted for about 4.8 trillion rubles. Despite the fact that this is almost 39% less than in 2023, it is still practically the main source through which the population buys real estate.

Analyzing the financing of construction, it is worth noting that it is mainly conducted through shared-equity construction, mortgage funds and funds held in escrow accounts.

In 2024, there was an increase in the key interest rate, and as a result, loans for developers became quite expensive. This led to the fact that it was difficult to maintain the processes as intensively as it was before. As a result, difficulties arose in implementing the Strategy for the Development of the construction industry and Housing and Communal Services of the Russian Federation for the period up to 2030 with a forecast up to 2035, which was not a very good prerequisite for the growth of the industry and the country's economy as a whole.

In addition to the fact that in 2024 there were already more significant financing problems, developers needed to pay more attention to the implementation of the principles of the "green" economy and environmental protection. After all, as previously noted, the construction industry causes serious harm to the environment, both at the stage of production of any materials, and in the housing construction processes themselves. And only those companies that already use "green" technologies help to reduce this damage. It is also important to note the presence of an old housing stock. If, for example, a program for demolishing dilapidated and dilapidated housing is actively being implemented in Moscow, then this has become a real problem in the regions and a significant proportion of such real estate still remains.

The issue of greening industries is on the international agenda, and Russia is no exception and is actively moving in this direction. It should be emphasized that the economic development of any country can no longer be achieved without countries implementing ESG principles in industries and implementing the principles of the "green" agenda in the activities of business entities.

Experts in the field of "green" construction and "green" financing speak about the importance and necessity of preparing a concept [1] that allows achieving the goals that are specified both in the framework of sustainable development and in the development strategies of countries.

In foreign countries and in Russia, there is a trend where financing conditions directly depend on how well a developer implements ESG principles in their activities, and how actively the volume of "green" technologies used in construction is increasing.

It is important to note that back in 2017, the Environmental Safety Strategy of the Russian Federation for the period up to 2025 pointed out the need to use environmentally friendly materials and develop environmentally friendly industries. And more than once at the St. Petersburg Economic Forum, at the government level, emphasis was placed on the development

of the ESG agenda in Russia.

The list of national interests and strategic priorities of the Russian Federation includes interrelated items: human capital development; environmental protection and adaptation to climate change; sustainable development of the Russian economy [2].

All this confirms that Russia is paying quite significant attention to the "greening of the economy" and in the future this agenda will only grow.

In the course of the work, a list of research methods was used that allowed us to draw reasonable conclusions about the prospects for the development of "green" financing and "green" technologies in Russia. These include deduction, induction, comparative analysis, data analysis, and situation modeling. It was an integrated approach to the use of research methods that allowed us to obtain a systematic vision of the development of the situation on the housing market in Russia.

III. Results

During the analysis of the available materials, it was revealed that in modern conditions, with a high key interest rate and certain restrictions on lending, it is important for companies to have such tools that will allow them to continue their activities effectively. And it is the implementation of ESG principles in their activities that will help developers use profitable "green" financial instruments [3].

However, an assessment of the current situation has led to the conclusion that developers themselves often do not want to move towards higher performance and are ready to build energy-efficient housing because they believe it is expensive. At the same time, the demand for such housing is not high enough, due to the higher price compared to ordinary housing.

The ESG transformation in construction in Russia is at an early stage and it is necessary to form not only the concept of "green" construction itself, but also a list of financial instruments that will make it possible to more effectively implement ESG principles, improve the quality of construction and move towards the country's global goal of achieving carbon neutrality by 2060.

There are only a limited number of Russian developers who implement ESG principles and are included in the domestic ESG rating. However, when formulating the results, the implementation of ERP in construction is complicated by the lack of specific strategies, as well as by the fact that ESG principles for construction are not specifically disclosed.

If we decompose ESG into components and analyze which of them companies devote more time to, then the environmental component is not so developed and companies pay more attention to social and corporate governance. However, it is the implementation of the environmental component that is more relevant for investors.

Currently, only four Russian developers are included in the ESG ranking of Russian companies by the end of 2024: LSR Group (40th place), Airplane Group (54th place), A101 Group (70th place), Etalon Group (77th place) (Table 1).

Table 1: *Construction companies in the ESG ranking by the end of 2024*

Company name	E-rank	S- rank	G- rank
LSR Group	39	77	20
The Airplane Group	57	63	52
GC "A101"	71	61	82
The Etalon Group	113	73	45

Source: [4].

The low number of developers in the rating indicates a lack of dissemination of the ideas of the "green" agenda in the industry. In this case, it is necessary to actively spread the principles of the "green" economy in industries and provide them with appropriate "green" financial instruments.

As a result of the analysis of the practice of the BRICS countries, and especially China [5], it is precisely the active implementation of the principles of the "green" economy in construction that allows not only to increase the efficiency of the industry, but also to influence the macroeconomic indicators of the country and increase the growth rate of the country's economy [6]. After all, it must be emphasized that construction is a driver of economic growth. Currently, it is also important to ensure continuous economic growth in Russia, including through the construction industry, despite the rising cost of lending, although we are already seeing certain trends towards a reduction in the key interest rate.

In Russia, a regulatory legal framework is being formed that regulates "green" construction, "green" standards [7-15].

Since August 2024, GOST R 71392-2024 "green" standard for individual housing construction began to operate, which includes 45 criteria by which a house can be considered environmentally friendly [8].

Another significant step in Russia was the creation of the Clover system. This system is implemented using a Methodology for evaluating and certifying buildings for new construction projects[1] [9].

In addition to all these, there are certain environmental certifications, but almost all of them are voluntary and do not oblige companies to perform them.

Gradually, you can see the formation of the necessary base. However, financing the construction of such housing is extremely important. And a sufficient number of mechanisms and tools have not yet been formed in this direction.

When assessing the financial effectiveness of projects, they are often rejected by calculating only the initial high costs from their point of view, without analyzing the prospects, including the possibility of obtaining government support. The payback period for "green" projects averages about 6 years, which is, in principle, a fairly good indicator [10].

According to the World Bank, "green" construction requires additional costs. However, I would like to note here that the cumulative positive effect that should be achieved through the implementation of such projects should significantly exceed the costs and bring Russia closer to achieving carbon neutrality.

Depending on the industries, additional costs can range from 1-5% (Fig.1), which generally makes it possible to calculate how to increase the profitability of projects in order to recoup these costs.

The results of the analysis showed that an important area for ensuring the recoupment of additional costs and reducing the payback period is the development and implementation of a list of effective financial instruments and mechanisms. At the same time, such tools can already be found in the BRICS countries. In Russia, it is still at the stage of formation.

For developers, it is necessary to understand that these mechanisms will speed up the payback period, reduce costs and increase public demand for eco-friendly housing options.

When developing options for "green" financing, it is important to take into account their alignment with the standards of the "green" taxonomy developed by VEB.RF. Moreover, individual mechanisms can be linked to absolutely "green" projects, as well as to those that partially perform this function.

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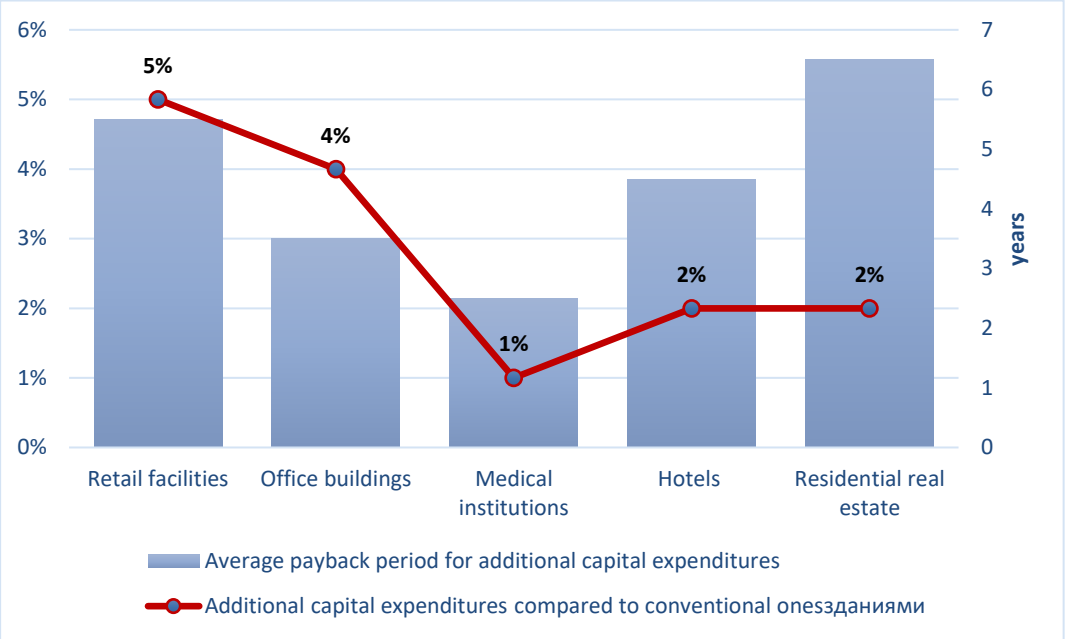


Figure 1: *Additional costs of "green" construction and their average payback period in emerging markets*
Source: The International Finance Corporation (World Bank Group) [11]

IV. Discussion

Currently, one of the financing options is "green" financing, which involves a range of methods for financing the green economy. One of the forms is a "green" loan. A loan that fully or partially finances projects that meet "green" standards. Usually, "green" loans are provided to legal entities. A "green" mortgage is usually issued to a borrower for the purchase of housing that meets "green" standards, that is, aimed at protecting the environment [12].

The difference between a "green" mortgage and a "green" loan is what the financing will be used for. In the first case, for a specific housing facility. In the second case, different options are possible. Also, the recipients in the first case are individuals, and in the second – legal entities.

Currently, in Russia, the tools for the "green" agenda are quite scattered, and it is important to provide a common system that will allow achieving the goals of the "green" agenda.

The "green" bonds available on the market, which have already become widespread, can become a source of funding. The mechanism for issuing and distributing bonds as a whole has already been worked out and this will accelerate the achievement of common goals.

Russia has already issued "green" bonds. The first issue took place in 2018 by the KhMAO Resource Conservation company. Later, the bonds were issued by the Moscow Government, and it was the first Russian region to carry out such a procedure.

It is essential to involve banks in the issue of "green" bonds, as well as the spread of such a process for the construction sector, where such a practice is just being formed [13]. In 2023, the Legend company together with the Dom Bank. The Russian Federation has issued green bonds in the amount of 3 billion rubles with a maturity of 4 years. In 2024, the same company has already signed an agreement with Sberbank on the "green" project financing of the first Moscow project of the company.

VEB.RF issued 40 billion rubles worth of "green" bonds in November 2023.

If we talk about the issue of "green" bonds by banks, then this process is only in its infancy. In the process of "green" securitization, the underlying assets can be, for example, mortgage loans or consumer loans that are used to purchase housing.

Currently, various strategies for the development of "green" financing are being discussed,

however, from our point of view, it is important to thoroughly work out the project of issuing "green" bonds by different entities so that they are of interest to investors and there is a steady demand for them [12 - 39].

To increase the interest of investors and developers in the construction of "green" facilities, it is important to show the advantages that each entity can receive.

This may be a reduced loan rate. This practice has already been introduced by Dom.rf, when the rate could be lowered by 1-2%, depending on how well the "green" standards are met.

It is important to consider options for tax incentives and government support for "green" projects. In foreign practice, investment funds are actively involved in the development of such projects. This is still a new direction in Russia, but it is extremely promising.

However, for developers, both tax optimization and obtaining land at a lower-than-market value, as well as various government support options, are important.

This can be beneficial for the state, since, in this way, it will be possible to step up the implementation of the "green" agenda, which is extremely relevant at the present time.

It is essential to create an investment-attractive market for "green" bonds, so that an increasing number of investors can participate in it.

In order to increase the number of companies that will be included further in the ESG rating, it is important to consider options for issuing "green" bonds and increasing the number of "green" projects.

For private investors, it is necessary to understand the advantages of "green" bonds. This includes not only obtaining a fixed income, but also improving the infrastructure of cities and improving the quality of life of the population. Subsequently, this will lead to the formation of a holistic, effective ecosystem of green finance in Russia.

For a "green" mortgage, only a reduction in the rate for the borrower is not enough to achieve a multiple increase in the volume of its issuance and, accordingly, an understanding for developers of the need to build "green" housing. A set of measures is important to encourage all market participants to be interested in the development of "green" financing.

V. Conclusion

"Green" financing of construction in Russia is at the stage of formation. There are a number of tools and mechanisms that are already being implemented. However, so far this is not enough to accelerate the process of implementing the "green" agenda and achieving carbon neutrality by 2060. The main problem is the lack of an ecosystem that allows you to involve all market participants and create a list of tools and mechanisms that will achieve your goals.

Individual actions of market participants do not lead to scaling of processes, make them one-time and do not show uninvolved participants the advantages they can get.

It is necessary to form an ecosystem, work out the processes of distributing the issue of "green" bonds, link them with different issuing entities and ensure that certain advantages are obtained for those participants who participate in the process. It is essential to consider options for tax incentives for developers involved in the issuance of "green" bonds, as well as the provision of various benefits and subsidies.

It is necessary to form a regulatory legal framework, which is lacking. Accounting and assessment of risks that may be borne by market participants, as well as the development of measures that can minimize them. It seems that the direction of "green" financing within the framework of the "green" agenda is extremely relevant and market participants can help solve some of the problems that currently exist and are associated with expensive lendin.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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MODERN METHODS AND BIG DATA TO STUDY DANGEROUS HYDROMETEOROLOGICAL EVENTS

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Abstract

The article discusses the atmospheric processes that cause dangerous hydrometeorological events. Georgia is a mountainous country with complex topography and a variety of climatic zones. It is prone to all kinds of dangerous hydrometeorological disasters, including heavy rain, hail, thunderstorms, flooding and landslides. It is especially important to investigate the processes that cause these catastrophic events using new data. This has become possible since the launch of the Earth Observing System programme, which provides a wealth of new satellite data that allows us to reanalyze these physical processes. Many methods have been employed to study their spatiotemporal characteristics, including numerical modelling, statistical analysis, analytical solutions, big data and machine learning. NASA THEMIS satellite data makes it possible to apply quantum physics to explain atmospheric processes. These results could be used in future studies and incorporated into early warning systems.

Keywords: Big Data, natural hydrometeorological disasters, Earth Observing System, weather numerical modeling, geo-magnetic index, photon exchange

I. Introduction

Meteorological and hydrological hazards are those resulting from the state and behavior of the Earth's atmosphere, its interaction with the land and oceans, the weather and climate it produces, and the resulting distribution of water resources. According to EM-DAT, from 1979 to 2019, 50% of all recorded disasters (including technological and 'complex' disasters), 56% of deaths and 75% of economic losses are attributed to weather, climate and water-related hazards. Some of the most devastating hazards include tropical cyclones, drought, reverie floods, and heatwaves. These hazards are observed, monitored, and forecasted by the national meteorological and hydrological services of each country [1].

Understanding of the natural environment is increasingly important to respond to the climate change negative impacts and anthropogenic pressures on finite natural resources, and their impacts on water, energy and food security, infrastructure, human health, natural hazards. This is also a major cross-disciplinary challenge involving almost all scientific fields

In 2013, the UK government announced large-scale investment in Big Data infrastructure for science, particularly in the environmental sector starting funding for a program called CEMS (Climate and Environmental Monitoring from Space). This allowed for the creation of larger databases to cope with the upcoming Big Data revolution and to allow research partner organizations to work with more data and produce more results. With a specific focus on climate change and planetary monitoring, CEMS storage removed the need to download enormous data sets while reducing the cost of access. Along with Cloud data, this is now the standard globally for some of the world's top research institutes

II. Study area, material and methods

Environmental data comes from a wide variety of sources and this is increasingly rapidly with new innovations in data capture:

1. Large volumes of data are collected via remote sensing, typically from satellite sensing or aircraft-borne sensing devices, including an increasing use of drones. This includes passive sensing, such as photography or infrared imagery, and active sensing, e.g., RADAR/LIDAR. The increasing availability of open satellite data is a major trend in earth and environmental sciences. For example, the EU Copernicus program and the associated Sentinel missions, or NASA's Earth Observing System satellites, LandSat archive are regularly mined for data for a variety of applications [4].

2. Other data are collected via earth monitoring systems, which consist of a range of sensor technologies measuring various physical entities. Namely weather stations and monitoring systems

3. Model output is also a significant generator of environmental data with results from previous model runs often stored for subsequent analysis

The local circulation systems developed on the background of synoptical processes play significant role in the spatial-temporal distribution of weather determining parameters. The study of all those phenomena includes both the mathematical modeling and separate analysis of microphysical processes, important for precipitation formation, temperature and wind field distribution, also the processing of long-term observation series of those climatic parameters.

One of most important precipitation formation microphysical process – coagulation described by the integral-differential equations has been analytically solved considering income of cloud particles. The results evidently showed redistribution of ice crystals and rain drops in cloud dispersive medium. To investigate solid and liquid precipitation formation following analytical model has been created using the kinetic coalescence equation system for spatial heterogeneous Coachy type task that has the following type [5,6,11]

$$\frac{\partial n1(v,t)}{\partial t} = -n_1(V,t)\int_0^{\infty}\sigma_{11}(V,U)n_1(U,t)dU - n_1(V,t)\int_0^{\infty}\sigma_{12}(V,U)n_2(U,t)dU + \\ + \frac{1}{2}\int_0^{V}\sigma_{11}(V-U,U)n_1(V-U,t)n_1(U,t)dU + \frac{M}{1-LN2(0)t}n_1(V,t) \quad (1)$$

$$\frac{\partial n2(V,t)}{\partial t} = -n_2(V,t)\int_0^{\infty}\sigma_{21}(V,U)n_1(U,t)dU + \int_0^{V}\sigma_{21}(V-U,U)n_2(V-U,t)n_1(U,t)dU + \\ + LN_2(t)n_2(V,t) \quad (2)$$

With following initial conditions: $n_1(V,t)=n_1(V,0)$; $n_2(V,t)=n_2(V,0)$ when t=0, n_1 refers to water drops (rain) and n_2-ice crystals (hail) and the distribution function has following type

$$n_i(V,t) = \frac{4N_i^3(0)}{W_i^2(0)}V\exp(-\frac{2N_i(0)}{W_i(0)}V), i = 1,2$$

The solution gives expressions for rain and hail concentrations, water and ice content and is able to identify dangerous size hail grains spectrum.

The results evidently showed redistribution of ice crystals and rain drops in cloud dispersive medium

The mathematical modeling contain several local weather nonstationary mesoscale model to describe atmospheric processes [9] operational thermohydrodynamical convective cloud model [8,9,10], global forecasting model (WRF) [6], analytical model for microphysical processes (coalescence) [10], the newly proposed study of variation character of meteorological parameters [8,9] (temperature, precipitation, pressure) depending on the geo-magnetic short-time disturbances [16]. Numerical forecasting models based on complete hydrothermodynamical equations give possibility to detail involve physical factors describing atmospheric phenomena that greatly influenced or sometimes define atmospheric circulation processes

For short-term operational forecasting the use of confined area models became available in several national meteorological services. The range of those models is quite diverse from which special attention deserve regional mesoscale models also atmosphere dynamical models with artificial boundaries where model variables are defined from coarse value grid from global model outputs. Such models can describe real weather conditions invisible for global models that form in atmosphere small-scale processes [7].

Numerical forecasting models based on complete hydrothermodynamical equations give possibility detail involve physical factors describing atmospheric phenomena that greatly influenced or sometimes define atmospheric circulation processes. The consideration of those factors in numerical models provides improvement forecasting quality. Realization of weather forecasting issue on confined area is characterized by definite difficulties. Such is the formulation of boundary conditions on the borders of forecasting area. The lack of meteorological data on region borders influenced researches to seek problem solution different ways. By using telescopization or embedded grid method became one of the most effective mean for this [6, 7]. Except boundary conditions telescopization method gives possibility to solve those main issues that are essential for weather forecasting on confined area. Specifically reducing spatial grid step on target area in such way that didn't increase model realization time, also detail describe region orographic features, realize interconnection between largescale, regional and mesoscale meteorological processes using bilateral and unilateral interaction of solutions from different grids.

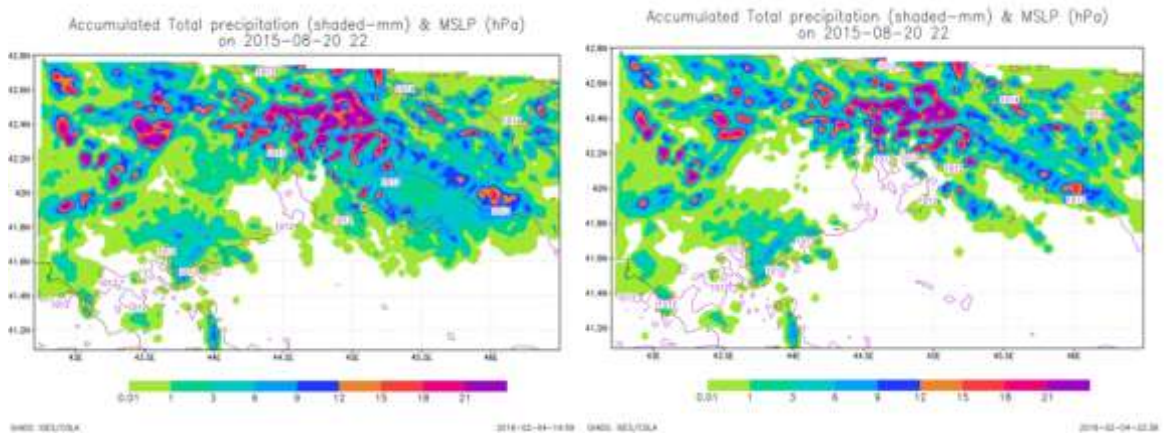


Figure 1: *Forecasted 2.2km resolution gridded precipitation on August 20, 2015 [11].*

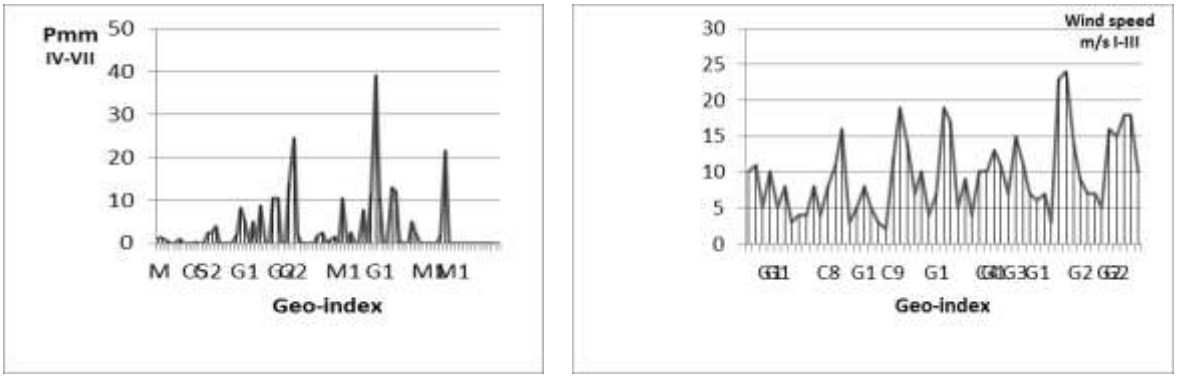
Another one is the operational one-dimensional thermohydrodynamical convective cloud model created for research of natural and artificial precipitation formation and can be used in weather modification [7]. In model for crystallization and melting processes have been introduced new parameterization schemes. The model inputs are radio probe data and outputs vertical development of meteorological parameters till cloud dissipation.

Weather research and forecasting model (WRF) is weather numerical forecasting and atmosphere simulation system created as for research as operational application. The model is elaborated USA National Center for Atmosphere Research (NCAR), Mesoscale and Microscale Meteorological Division (MMM), NOAA, NCEP, ESRL, AFWA, Naval Research Laboratory, CAPS, and etc. It is used in following fields: real-time numerical forecasting, data assimilation, physical parameterization research, regional climatic simulations and etc [3, 6,7,11]. ARW provides introduction of higher spatial-temporal resolution horizontal grid that focuses on target sub-region and significantly increases model resolution (from 15km to 2km) [7.11].

III. Results and discussion

Despite all above listed approaches the origin and nature of most of atmospheric phenomena are still unknown. The climatic observations often show quasi periodic variations similar to solar activity cycles over a wide range of time scale. However, the detailed mechanism and the extent of the influence of solar activity on climate change have not been clearly understood, several possible mechanisms are proposed; such as the forcing through total and spectral irradiance, solar wind and the galactic cosmic rays [2, 15]. The Earth Observation System (EOS) program is designed to examine the role of Earth-Sun connection in wide-scale global processes in order to determine the function of the Earth as a single system. The one of natural reason of global climate change are the Sun's insulation (light and heat), its magnetic flux, and the relative position and orientation of the Earth to the Sun. Geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth. These storms result from variations in the solar wind that produces major changes in the currents, plasmas, and fields in Earth's magnetosphere. The largest storms that result from these conditions are associated with solar coronal mass ejections (CMEs) where a billion tons or so of plasma from the sun, with its embedded magnetic field, arrives at Earth. CMEs typically take several days to arrive at Earth.

The correlation between geomagnetic storms and 2014-19-year period meteorological elements (wind, pressure, temperature, precipitation) for Georgian region using meteorological observation and NASA's Solar Dynamics Observatory and NOAA Space Weather Prediction Center data [13, 14] has been conducted [2, 15,16]. The results show that there exist dependence between weather parameters and income radiation. Especially important is wind parameter variability investigation. Such research hasn't been carried out yet in Georgia and is important for space weather researches.



(a) (b)

Figure 2: *Precipitation and geo-index correlation in 2017 (IV-VII months) (a)and wind speed and geo-index correlation in 2017 (I-III) (b)for Tbilisi.*

The analysis has been conducted for current, pre and aftershock 3 and 5 days. For meteorological parameters current day is crucial and 3, 5-day time lapse is reliable for circulation processes. It is ascertained that during all magnetic storms south-west or south-east wave processes have been formed and strong storms create high pressure areas. Depending on the synoptic situation wave processes leads the formation of thunderstorm and heavy showers

IV. Conclusion

The Vere River tragedy on 13 June, 2015 is clear evidence of how meteorological disaster triggered geo-hazard. On this day, flash-flood on Vere River flooded part of Tbilisi city, destroyed buildings, infrastructure, Zoo, many Zoo habitats and 18 humans were dead. After analyzing satellite data and synoptical situation it became clear what happened. During several days from 9 to 14 June 2 MEV high energy electrons penetrate atmosphere [12, 15]. The abundant amounts of electrons create stable clusters in lower atmosphere resisting precipitation infall. After they became so massive that couldn't resist gravitation the great amount of rain water has been fallen out from clouds, causing flooding.

It is not fully clear the physical mechanism of this correlation and the issue needs further investigation applying quantum filed theory that is more suitable for description of photon-photon or photon-charged particle interaction as during geomagnetic activity great amount of charged particles and photons penetrate atmosphere.

The most of water properties are preconditioned by the fact that three component atoms aren't placed on one line. Negative charge prevailed on oxygen atoms part and positive on hydrogen. Thus water molecule is electrically polarized. Among atoms and molecules acts force that always has attractive character. It is intermolecular dispersive or Van-Deer-Vaalse force [6,12]. It is only one of the expressions of electromagnetic force. It acts among electrically neutral systems such as dipole or quadruple. In dipoles force reduces by r^4 inverse proportional and in quadruple by r^{-6}. It is not temperature dependent and it s nature is quantum. By increasing dipole number their interaction increases.

$$U(r) = -\frac{2}{3c^2}\sum_n r_n^{-1}\left|d_n\right|^2 \omega_n^2 \exp\left(\frac{\Gamma_n r}{c}\right)\cos\frac{\omega_n r}{c} \qquad (3)$$

During cristalization and condensation the some portion of latent heat may be trasformed in characterized radiation. The transformation energy is distributed between existed and new energetic levels. They are called as phase radiation and is depended on medium optical properties. The cloud medium may be imagined as unity of clusters that are on different energetic levels, interacting through energy emition-absorbtion. According to this Earth surrounding environment is one of possible renewable energy source [16], the use of which gives chanse on transition into new energy transportation means.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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NEW TECHNOLOGY FOR OBTAINING FLAVONOIDS FROM MANDARIN PROCESSING WASTE

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Abstract

The mandarin (C. unshiu) is widely distributed in Georgia. Natural juices and concentrates are mainly made from this fruit. During processing, more than 60% of mandarin pomace (MP) is obtained as production waste and released into the environment, causing harm to nature. However, waste is also a source of functional ingredients, including important flavonoids that impact human health. In this study, we examined the technological parameters of mandarin flavonoid pomace (PEF). An extractor model was created and the influence of the mixing intensity of a mandarin pomace and extractant mixture (water and calcium oxide) on the flavonoid extraction rate and yield was determined. Optimal extraction parameters were found to be a speed of 500 rpm for 2 hours, increasing the yield by 12%. The quantitative content of flavonoids was determined using a mixture of the extractant dimethyl sulfoxide (DMSO) and ethanol (10:2) by the spectral method (286 nm). To assess the flavonoids qualitatively, a purification method was developed using a mixture of 10% NaOH and 96% C_2H_5OH in a 1:1 ratio, followed by further processing in the CO_2 zone. The quantitative content of hesperidin in the resulting preparation is greater than 90%. Based on the research results, a rational technological scheme has been developed for enterprises producing flavonoid extracts.

Keywords: industrial mandarin waste, UPLC-MS analysis, flavanoid extract pomace (FEP), Hesperidin

I.Introduction

It is known that citrus fruits (Rutaceae), which include oranges, tangerines, limes, lemons, sour oranges (Bigaradia), and grapefruits, contain many substances useful for the human body [1]. To date, citrus fruits are distributed in 140 countries of the world, namely in both belts of the earth's equator, covering the tropical and subtropical regions of the world between 35 ° south latitude and 35 ° north latitude. Most of the harvest and production is concentrated in the Southern Hemisphere [2]. World cultivation of citrus fruits has grown significantly in recent years, and their annual production has reached 110 million tons [3]. In Georgia, which is practically the extreme north of citrus distribution, mandarin (C. Unshiu) is predominant. Its average annual yield is 100 thousand tons.

Citrus fruits are characterized by flavonoid glycosides: hesperidin, naringin, neoheperidin. Although more than 5000 flavonoids are known [10], only a limited number of them have been

determined by their effect on the appearance, taste and nutritional value of the product. For example, an excess of hespedin in citrus juice causes puffiness [11], and naringin causes a feeling of bitterness [12].

In citrus juices, we have identified and quantified flavonoid compounds, in the core of which the hydroxyl is located mainly in positions C-5 and C-7 [13].

Flavanones are characterized by a wide range of biological and pharmacological activity (antioxidant, anticarcinogenic, anti-inflammatory), they play an important role in the prevention of bone loss, cancer and atherosclerosis [6,7].

The high content of biologically valuable compounds in citrus residues has led to great interest in waste valorization. Researchers use citrus waste in a variety of beneficial ways to minimize environmental damage. Citrus residues are rich in phytochemicals [8]. Therefore, it is advisable to use citrus residues for functional nutrition and food preparation [9].

To date, the most common and effective method for the study of phenolic compounds is the HPLC method. In most cases, their detection and quantitative study is possible without prior derivatization and concentration. Reverse phase chromatography is widely used to separate flavonoids on C8 or C18 columns (using a gradient of polar solvent mixtures). Gradient chromatography is also often used to separate flavonoids [14,15,16,17].

The main product of industrial processing of mandarin fruits in Georgia is juice and its concentrate. Juice production wastes (peel, part of the pulp, seeds), despite the fact that they contain a wide range of secondary components such as polyphenols, carotenoids, vitamins, dietary fiber, etc., unfortunately, are thrown away and remain unused [2,3, 4, 5]. It should be noted that the biologically active substances of mandarin grown in Georgia and the possibility of their use using modern research methods have not been fully studied.

II. Materials and Methods

2.1. Reagents and Samples

Hesperedin (standard), Chemical reagents Acetonitrile, Formic acid, were purchased from Sigma–Aldrich (Germany; Tbilisi, Georgia)

Mandarin extract - produced from raw mandarin fruits grown in Western Georgia, Unshiu variety (Citrus unshiu L), harvest 2020-2021. The industrial technological process of juice preparation provides for the selection and checking of fruits, washing, obtaining juice on a roller press (the fruit is cut in half, held on a perforated surface), then the residue is additionally squeezed out on a screw press. The juice preparation process was carried out on the technological line of the Italian production "FENCO". The production process was carried out at a citrus processing plant (Sakrtvelo, Kobuleti), owned by Georgian Industrial Asset Management Group LLC. For research, there has been used an extract, obtained from the press.

Preparation of FEP samples.

Pre-washed mandarin juice, crushed to particles 0.5-1.0 mm in size, was placed in an extractor equipped with a weeder (rotation speed 50-1000 rpm) and a temperature controller (0-1000C), drinking water was added (1 part of the juice and 2 parts of water), calcium oxide was added until the pH of the mixture reached 11. The test mixture thus prepared was divided into four samples of equal weight. Exposure of sample No. 1 (control) for 24 hours with periodic stirring (4-5 times); A mixture of the remaining samples (No. 2, No. 3, No. 4) was loaded into the extractor, intensively mixed at a speed of 355, 500 and 710 rpm, respectively; Samples were processed at a temperature of +350C. In addition to the control, the test samples were processed for different durations at hourly intervals from 1 to 5 hours. For all samples after the extraction process, the suspension was removed, filtered and 20% hydrochloric acid was added until the pH value of the region was 5. The acidified extract was kept at a temperature of +6-(+8) ° C for 24 hours until the flavonoid complex was completely precipitated. At the end of the process, the supernatant was drained with a siphon, and

the remaining mass was centrifuged at 3000 rpm at a temperature of +8^{0}C. There has been formed a pale precipitate, which was dried at 60-65^{0}C and then crushed; dry PFE has been obtained.

2.2.Methods

Standard methods of analysis

Determination of dry matter - by thermogravimetric method (AOAC Official Method); **Quantitative determination of water-soluble dry substances** - by means of a digital refractometer (Carl Zeiss, Germany) (AOAC Official Method, **920.151 (37.1.12)(AOAC, 2000).**

Determination of total titration acidity and pH value - on an automatic titrometer (Mettler-Toledo AG, Analytical www.mt.com/education-line CH-8603 Schwerzenbach, Switzerland) **920.151 (37.1.12)(AOAC, 2000)**;

determination of carotenoids - by HPLC method ~~(19)~~;

determination of total pectin by carbazole - spectral method (26);

Quantitative determination of vitamin C - using the iodometric method of titration (AOAC Official Method, 1999, Gaithersburg, MD, method 939.13 and 966.18)and HPLC (25);

Fiber - by AOAC method (AOAC, 2000);

Quantification of carbohydrates – by HPLC Method;

2.2.1. Hesperidin separation and identification of substances by Ultra High-Performance Liquid Chromatography (UPLC)-PDA,MS methods; **(**Waters, Ultra-high pressure liquid chromatography system, Waters PDA Deteqtor, Acquity UPLC H-Class Core System, Acquity QDa Single Quadupole Mass-Detector, USA) analysis by column BEN HSS, 1.7 μm, Eluent Water+0.1 % F.A. (A) and ACN+0.1% F.A. (B), (gradient 0 min-2% B; 0-3 min 25% B, 3-6 min 26% B, 6-10 min 35% B, 10-12.5min 99% B, 12.5-13min 99% B, 13-13.5 min 2% B, 13.5-15 min 2 % B), Flow 0.3 ml/min, column tem. 40°C, MS scan 100-1200 da, Probe 600°C, Positive (ESI-MS)+ ცხრ negative (ESI-MS)-, capillary 0.8 kV, CV -15.

Qualitative and quantitative study of vitamin C by high pressure liquid chromatography method. Instrument - Waters Binary HPLC Pump 1525; Breeze 2489, detector - ultraviolet and visible lights, column - C18 Bridge (150 mm x 4.8 mm), eluent - water: methanol (50:50), detection at 270 nm (25).

Determination of carbohydrate by High performance liquid chromatography (HPLC RI) - Waters (Waters HPLC Pump 1525), chromatographic column with amide (250 mm x 4.5 mm); column temperature 40°C, eluent 80% acetonitrile detected by refractometry (Waters RI detector 2414).

Quantification of hesperidin

For the quantitative determination of hespedin, we have used a spectrophotometric method. The quantitative study is based on the determination of the optical density of flavanones, hesperidin has been used as a standard sample. Flavonoids have been extracted with a mixture of ethyl alcohol and dimethyl sulfoxide (DMSO) (10:2). Using this extractant, hesperidin was extracted from the samples and spectrophotometry was performed at 286 nm [20].

An analytical sample of the raw material was crushed to a particle size passing through a 2 mm sieve. A sample weighing about 1.0 g (exact weight) was placed in a 100 ml flask.

To build a calibration curve, we transferred 0.01 g of standard hesperidin into a 50 ml volumetric flask, added 40 ml of a mixture of solvents, dissolved hesperidin by shaking, and filled the flask to the mark.

The following volumes of the standard solution were transferred into flasks with a capacity of 25 ml: 0.6; 1.0; 1.4; 1.8; 2.2; 2.6; 3.0; 3.4; 3.8 ml, the flasks were filled to the mark with a mixture of solvents, the concentration of hesperidin were: 0.48; 0.80, 1.12; 1296; 1.76; 2.08; 2.40; 2.72; 3.04*10-5 g/ml. An analytical solution was poured into the working cuvette, and a mixture of solvents was

poured into the comparative cuvette. The calibration graph of standard solutions, built depending on the optical density of the solutions (D) and the quantitative indicators of various concentrations of hesperidin (C), had the form of a straight line.

The mass fraction of flavonoids in the studied extracts in terms of hesperidin has been calculated by the following formula:

$$X= \frac{c*100*25*100}{a*1*(100-w)}*100\%;$$

where:
c - concentration of the analyzed solution, corresponding to the measured optical density on the calibration curve - 10^{-5} g/ml.
a - mass of raw materials, g;
w - loss of raw materials during drying, %.

Qualitative assessment of FEP

The extraction of hesperidin from the flavonoid extract has been carried out according to the following method: 5 g of the dry preparation was dissolved in an equal mixture of 10% sodium alkali solution and 96% ethyl alcohol. Dissolution occured within 15 minutes with constant shaking. It was then filtered under vacuum. The resulting filtrate was subjected to a flow of carbon dioxide for 1.5 hours, whereby hesperidin was abundantly precipitated. It was then filtered under vacuum; the precipitate remaining on the filter was first treated with a weak solution of hydrochloric acid and then washed with hot water. The resulting hesperidin was a colorless microscopic needle.

Statistical Analysis – Standard error was calculated for each data using Excel software. Confidence coefficient $p \leq 0.05$.

III. Results and discussion

Mandarin, like other citrus fruits, is characterized by a high biological value due to its special chemical composition (21,22). Hesperidin has been found mainly in the peel of citrus fruits and is considered to be the main functional component. Hesperidin dominates among the flavonones in the peel of mandarin fruits (23), whit has also been confirmed by the results of our studies on the example of mandarin grown in Georgia.

At the initial stage of the research, the main chemical parameters of the mandarin extract were determined. The data obtained are shown in table No. 1:

Table 1: *Physical-chemical parameters of mandarin residue*

№	The name of the indicator	Method	unit	Result
1	Soluble dry matter (TSS)	Refractometry	%	5,3±0,12
2	dry substance, by drying	by drying	%	19,5±1,75
3	Titrate acidity in terms of citric acid (pH 8.1)	titration	%	0,26±0,14
4	Vitamin C	HPLC	mg/%	38,80 ±0,2
5	Quantitative determination of flavonoids	spectral	%	2,24±0,4
6	total sugars, including:	HPLC	%	3,54±0,4
	glucose	HPLC	%	1,65±1,05
	fructose	HPLC	%	1, 73±0,34
	Sucrose	HPLC	%	0,16±0,0015
	Pectin substances, including:	spectral		
	total pectin	spectral	%	4,21±0,13

7	Hydropectin	spectral	%	1,60±0,036
	Protopectin	spectral	%	2,61±0,066
8	essential oils	titration	%	0,46±0,08
9	fiber	weight method	%	3,51±0,05
10	Quantitative determination of carotins	HPLC	mg/%	17,8±0,20

Table 1 shows that MP is characterized by a high content of biologically active substances: total flavonoids, carotenoids, vitamin C. MP contains much more antioxidant substances than pulp and juice. Among them, flavonoids are of great importance.

The data of the experiment conducted in order to intensify the process of extracting flavonoids from MP (acceleration of the process, increase in yield) are shown in Table 2:

Table 2: *The influence of the intensity of stirring of the extractant on the rate and yield of flavonoids in the extractant*

weed speed RPM	control	Duration of exposure, h				
		1	2	3	4	5
		Total amount of flavonoids,%				
355	3,92	2,16±0,07	3,41±0,12	4,47±0,17	4,48±0,13	4,4±0,15
500		2,64±0,08	4,47±0,15	4,47±0,17	4,48±0,14	4,42±0,17
710		2,59±0,07	4,48±0,16	4,48±0,18	4,46±0,17	4,39±0,18

The data of Table 2 show that in the control experiment - without the use of weeds, after the end of the process, the maximum concentration of the flavonoid complex is 3.92% based on dry weight. In the case of trial variants of the experiment, the maximum yield of flavonoids is 2.16-4.48%, which is achieved with various combinations of time and speed. Although the extraction yield at 710 rpm for 2 hours is high, foaming and disintegration of the crushed mandarin particles are observed, which ultimately degrades the quality of the flavonoids and subsequent processing. According to the results of the experiment, the speed of the weed was 500 rpm, and the time was 2 hours. The experiment shows that the use of an extractor equipped with a weed reduces the extraction time of the flavonoid substance from 24 hours to 2 hours and at the same time increases the yield by 12%. Based on the results of the research, a recommended technological scheme for the industrial production of flavonoids from mandarin juice production waste has been developed.

Identification and quantification of hesperidin

The study of flavonoids using a mass spectrometer - Hesperidin MW 610 Da, m / z (M-H-) 609, a fragment of the hesperidin 301 aglycone was identified in the mandarin extract and the preparation obtained from it, the results are presented on chromatograms (Fig. 1-4).

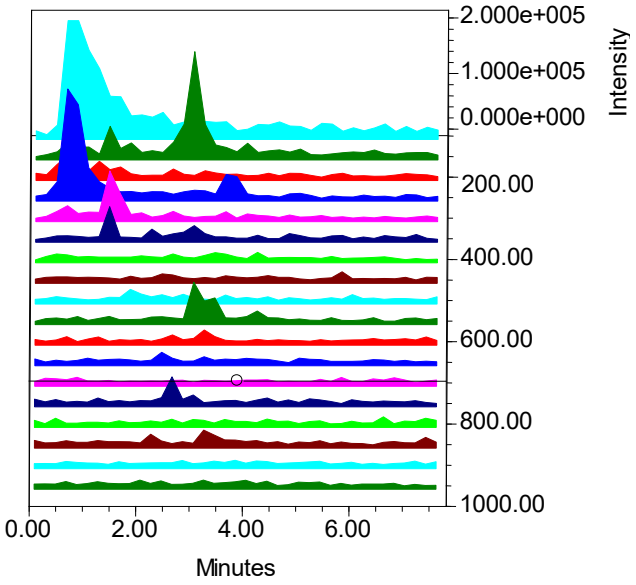


Figure 1: *Hesperidin in Mandarin Unshio residues UPLC-MS Chromatogram*

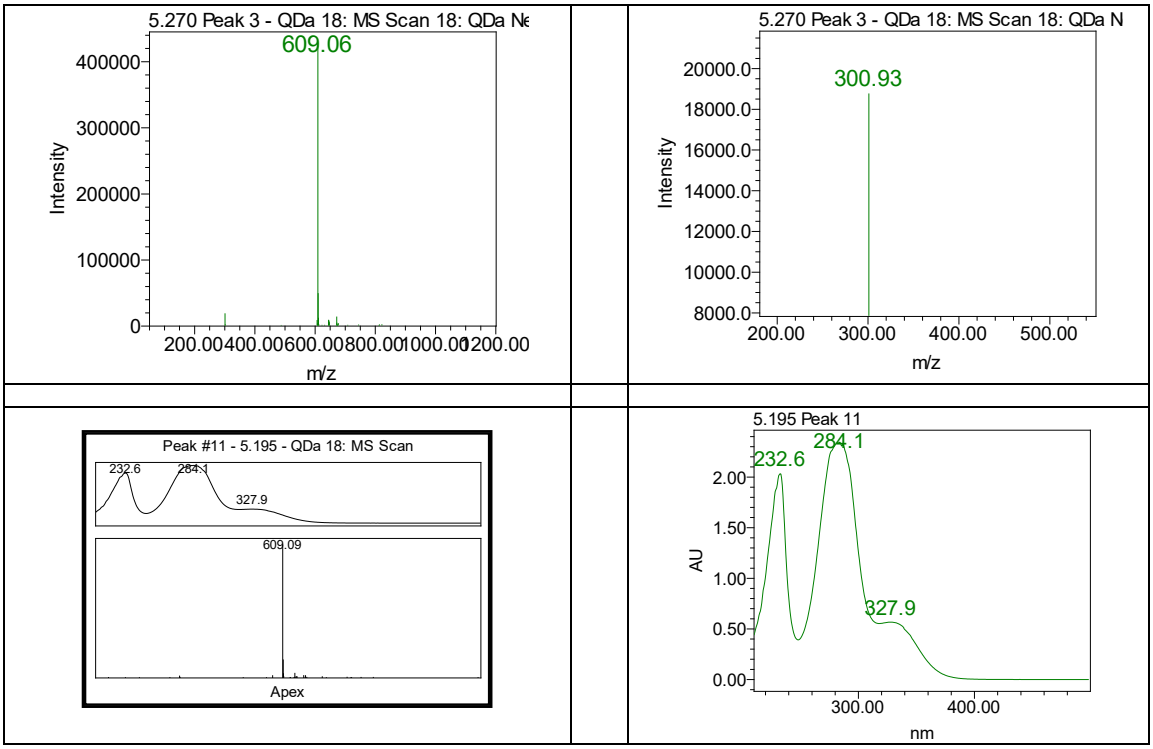


Figure 2: *Hesperidin obtained from PFE by recrystallization (ethanol + 20% DMSO), UPLC-MS spectrum SIR 609.09 Da, absorption max 284.1 nm.*

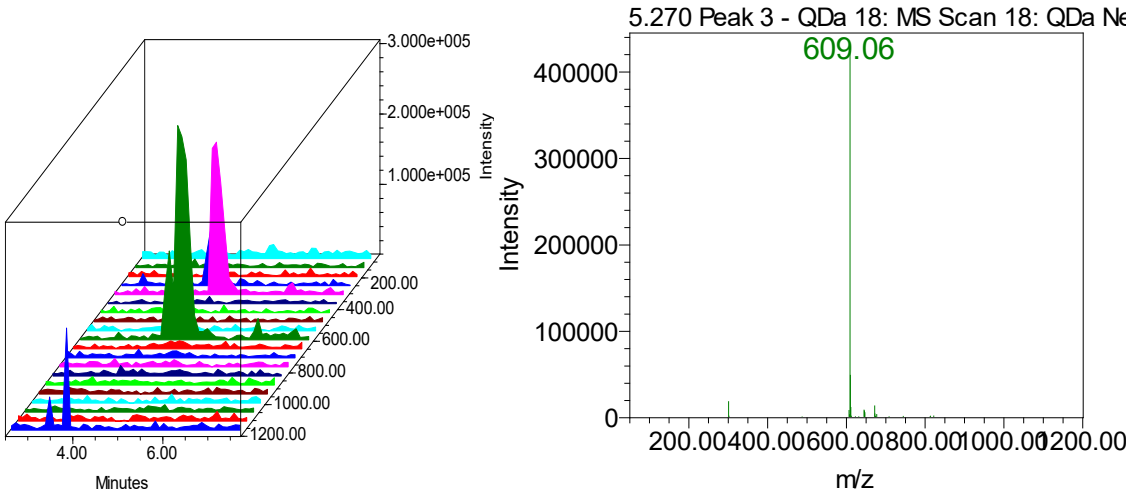


Figure 3: *Hesperidin obtained from PFE by recrystallization (NaOH+C2H5OH) UPLC-MS chromatogram, in 3D format, UPLC-MS spectrum SIR 609.09 Da*

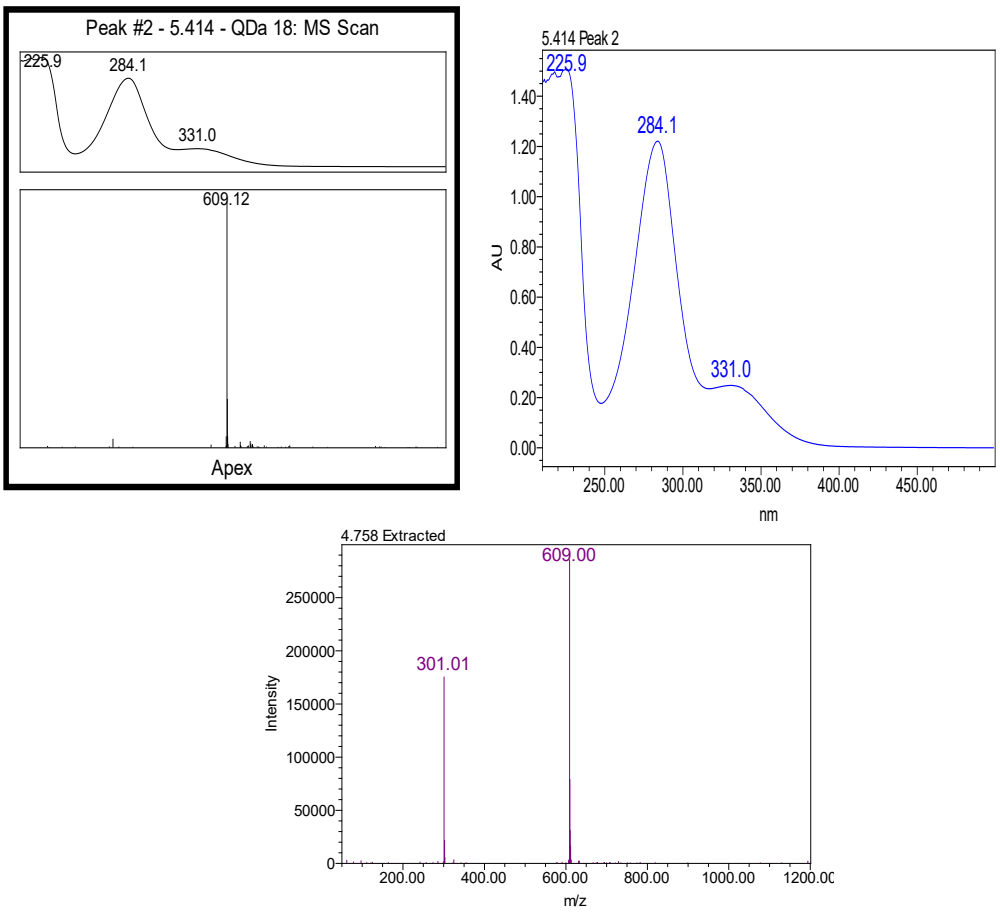


Figure 4: *UPLC-MS spectrum of standard hesperidin SIR 609.09 Da,absorption max 284.1 nm.*

Substances were identified using standard compounds (Fig. 4.) and mass of substances https://metlin.scripps.edu free database, as well as comparing the data of peer-reviewed literary publications.

To maximize the recovery of hesperidin, the samples have been eluted with different solvents, but extraction with a DMSO solution is optimal. The content of recrystallized hesperidin from the extract of unshiu flavonoids is 996 mg/g and with chromatographic extraction of 20% DMSO, a lower content of impurities is observed, the quantitative index of hesperidin in the resulting preparation is 90%.

Table 3: *Quantitative content of hesperidin in mandarin and preparations derived from it*

Sample name	mg/g
Hesperidin Standard	1,000.0
Hesperidin obtained from PFE, (ethanol + 20% DMSO)	983.0±39,32
Hesperidin obtained from PFE, ($NaOH+C_2H_5OH$)	996.0±39,84

The content of hesperidin in the mandarin peel is almost 1.5 times higher (0.750 mg/g) than in the whole cake; (0.496 mg/g). Recrystallization of hesperidin from PFE is effectively possible with NaOH+C2H5OH and ethanol + 20% DMSO. The results obtained are almost identical and allow them to be used for the recrystallization of hesperidin in an individual form from PFE.

IV. Conclusion

The chemical composition of oilcake, which remains during the processing of mandarin fruits (C. Unshiu), common in Georgia, has been studied, and it was found that it contains biologically active substances: flavonoids, carotenoids, vitamin C, pectin substances. The use of mandarin pomace to obtain PFE with a high content of hesperidin has been substantiated theoretically and experimentally. The kinetics of extraction of flavonoids and the factors, influencing it, have been determined; the optimal conditions for extraction and mixing were determined. Flavonoid content, hesperidin identification and quantitative content were determined by HPLC. Hesperidin was found to be the dominant flavonoid. There has been developed the method for the qualitative assessment of flavonoid extract, which makes it possible to achieve 90% hesperidin content in PFE.

Based on the results of the research, there has been developed a recommended rational technological scheme for the industrial production of flavonoids (hesperidin) from mandarin pomace, which ensures high yield and quality.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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INFLUENCE OF NON-NEWTONIAN FLUID RHEOLOGY ON PIPE AND ANNULAR FLOW DYNAMICS IN RESERVOIR DEVELOPMENT

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Abstract

During reservoir development, efficient fluid transport is very important for the optimization of production and minimization of operational costs. This study investigates the influence of non-Newtonian fluid properties on the flow behavior in pipes and in annuli. Unlike Newtonian fluids, the non-Newtonian fluids have much more complex rheological characteristics which include yield stress and power-law index, and those properties affect the overall fluid dynamics during production from the well and further fluid transport in the pipelines. Lack of consideration of non-Newtonian parameters during engineering calculations leads to different technical, economic and ecological risks. A full mathematical derivation of velocity distribution in pipes and in annuli for non-Newtonian fluids was presented. Based on the velocity distributions the formulas for flow rates have also been derived and the flow conditions for yield stress fluids have been shown. It has been demonstrated that yield stress fluids form a certain region in the middle of the flow that flows with maximum velocity but individual fluid layers within this region do not move relative to each other, so the velocity gradient is zero here. This region is referred to as core of the flow. The analysis has shown that in pipes the decrease of yield stress strongly increases velocity and decreases the radius of the core. The decrease of the consistency index significantly increases velocity. One of the most interesting observations is that the relationship between velocity and the power-law index depends on the pressure gradient. At low pressure gradients the increase of the power-law index increases the velocity, but at high pressure gradients the increase of the power-law index decreases the velocity. For annular flow the effect of those parameters is the same, however, the velocity for annular flow is much more sensitive to the pressure gradient and the yield stress.

Keywords: non-Newtonian fluids, Herschel-Bulkley model, Bingham model, fluid flow in pipes, fluid flow in annulus

I. Introduction

Non-Newtonian fluids are widely used in the oil and gas industry. Most of the oil reserves in the world today can be characterized as unconventional reserves a significant portion of which is made up of non-Newtonian fluids [1], [2]. The relevance of studying the behavior of non-Newtonian oils is growing nowadays as many experts believe that in the future most of the demand for oil will be fulfilled by non-Newtonian reserves [3]. Non-Newtonian fluids are also very common in drilling, as most of the drilling muds have non-Newtonian behavior [4].

The simplest definition of non-Newtonian fluids is that any fluid the flow of which cannot be described by the Newtonian law [5] is considered non-Newtonian. There is a certain set of parameters that are unique to non-Newtonian fluids which are:

- Yield stress. Fluids that have yield stress do not flow until the shear stress that occurs in them exceeds a certain value which is known as the yield stress [6].
- Power-law index. For some fluids the relationship between shear stress and velocity gradient is not linear and this nonlinearity is taken into account by a parameter known as the power-law index [7]
- Consistency index. For non-Newtonian fluids that have a power-law index that is not equal to 1, dynamic viscosity is replaced with the consistency index, the dimension of which is dependent on the power-law index [8].

A complete analysis of fluid flow is not possible without taking into account the boundary conditions. Some examples of practically encountered boundary conditions are upward flow of oil through the production tubing, horizontal flow of oil through long pipelines used for transport of hydrocarbons to large distances, downward flow of drilling mud through the drill pipe, upward flow of drilling mud through the annulus between the borehole wall and the drill pipe and etc.

Lack of consideration of non-Newtonian parameters during engineering calculations related to pipeline systems design means ignoring the influence of those parameters on the flow [9]. Obviously, this introduces several risks. Such risks might be technical (actual flow rate too far from the predicted one, the velocity profile in pipe is different from the predicted profile, etc.), economical (the necessary volume of fluids is not delivered through the transport pipeline) and ecological (failure of fluid transport facilities leading to ecological harm). The best mitigation of those risks is consideration of as many flow parameters as possible (the ones that have impact on the flow) during engineering calculations.

Several authors have experimentally studied the relationship between shear stress and shear rate for non-Newtonian fluids [10], [11], [12]. The authors of [13] have presented the flow rate in pipe formula for Herschel-Bulkley fluids, however, the full derivation has not been provided, and the impact of non-Newtonian parameters has not been analyzed in detail. In the work [14], an analytical formula has been derived that determines the velocity distribution for Bingham fluids in annulus for flow in curved (angular) direction. The purpose of this work is to:

- Present a full mathematical derivation of the velocity distribution for Herschel-Bulkley fluids flowing in a pipe
- Present a full mathematical derivation of the velocity distribution for Bingham fluids flowing in annulus
- Based on the velocity distributions derive a formula that calculates the fluid flow rate
- Analyze the influence of various non-Newtonian parameters on the velocity distribution

II. Velocity distribution derivation and analysis

The balance of forces acting on a cylindrical element in z-direction (along the pipe) can be expressed as follows [15]:

$$\frac{\sigma_{rz}}{r}+\frac{\partial\sigma_{rz}}{\partial r}+\frac{1}{r}\frac{\partial\sigma_{\theta z}}{\partial\theta}+\frac{\partial\sigma_{zz}}{\partial z}+\rho Z=\rho\frac{dv_z}{dt}. \quad (1)$$

Here θ, r, z – are cylindrical coordinates, t is time, σ_{rz} is the shear stress that is perpendicular to the r-direction and directed in the z-direction, $\sigma_{\theta z}$ is the shear stress that is perpendicular to the θ-direction and directed in the z-direction, σ_{zz} is the normal stress in z-direction, ρ is fluid density, Z is the acceleration in the z-direction, and v_z is the velocity in z-direction. The well-known Navier-Stokes equations [16] for Newtonian fluids are derived from the balance of forces formula given above.

In this work, we consider steady-state laminar flow of incompressible non-Newtonian fluids in a pipe. We assume that flow exists only in the z-direction, and the velocity is not dependent on θ. Due to the steady state, $\frac{dv_z}{dt}$ becomes 0, and $\frac{\partial\sigma_{\theta z}}{\partial\theta}$ becomes 0 due the symmetrical flow. $\frac{\partial v_z}{\partial z}$ is also equal to 0 since the fluid is assumed to be incompressible. We also express the normal stress in z-direction as σ_{zz} = -P, where P is fluid pressure. According to the Herschel-Bulkley model, the shear

stress σ_{rz} can be expressed as [17]:

$$\sigma_{rz} = -\tau_0 + K\left(\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r}\right)^n. \quad (2)$$

As there is no flow in r-direction, the term $\frac{\partial v_r}{\partial z}$ is neglected and as a result we get:

$$\sigma_{rz} = -\tau_0 + K\left(\frac{\partial v_z}{\partial r}\right)^n. \quad (3)$$

Firstly, we need to determine the relationship between the shear stress σ_{rz} and the pressure gradient. Considering everything written above, equation (1) is transformed into the following ordinary differential equation:

$$\frac{\sigma_{rz}}{r} + \frac{d\sigma_{rz}}{dr} - \frac{dP}{dz} + \rho Z = 0. \quad (4)$$

The following assumptions are made in equation (4):

- σ_{rz} is considered to be only a function of r and it is not dependent on coordinates z and θ.
- The pressure gradient $\frac{dP}{dz}$ only dependents on the coordinate z and it is not dependent on r and θ.

Then the solution of the equation (4) would look as follows:

$$\sigma_{rz} = \frac{c_1}{r} + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right). \quad (5)$$

Further solution of this equation depends on the chosen boundary conditions. Firstly, we will consider flow in a pipe of radius R. In case of a pipe, r = 0 is a valid coordinate, however, it leads to an infinite σ_{rz} in equation (5) which is not possible. For this reason, c_1 must be taken as 0, and as a result we get:

$$\sigma_{rz} = \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right). \quad (6)$$

From this equation, we can conclude that the shear stress is equal to 0 in the center of the pipe, and it has the maximum value at the pipe radius R.

The next goal is to determine the relationship between fluid velocity and r. For this, we insert equation (3) into equation (4), and as a result we get the following:

$$-\frac{\tau_0}{r} + \frac{K}{r}\left(\frac{dv}{dr}\right)^n + Kn\left(\frac{dv}{dr}\right)^{n-1}\frac{d^2v}{dr^2} = \frac{dP}{dz} - \rho Z. \quad (7)$$

Now let's assume that $\frac{dv}{dr} = w$, $\frac{d^2v}{dr^2} = \frac{dw}{dr}$, add the term $\frac{\tau_0}{r}$ to left and right side and divide both sides by K:

$$n\frac{dw}{dr}w^{n-1} + \frac{w^n}{r} = \frac{\tau_0 + r\left(\frac{dP}{dz} - \rho Z\right)}{Kr}. \quad (8)$$

Let's assume that $w^n = u$, $nw^{n-1}\frac{dw}{dr} = \frac{du}{dr}$. Then we get:

$$\frac{du}{dr} + \frac{u}{r} = \frac{\tau_0 + r\left(\frac{dP}{dz} - \rho Z\right)}{Kr}. \quad (9)$$

Equation (9) can be transformed as follows:

$$d(ru) = \frac{\tau_0 + r\left(\frac{dP}{dz} - \rho Z\right)}{K}dr. \quad (10)$$

By integrating both sides of this equation we get:

$$ru = \frac{\tau_0 r + \frac{r^2}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K} + c_1. \quad (11)$$

By solving for u, we get:

$$u = \frac{\tau_0 + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K} + \frac{c_1}{r}. \quad (12)$$

Then u is transformed back into w:

$$w = \sqrt[n]{\frac{\tau_0 + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K} + \frac{c_1}{r}}. \quad (13)$$

Then w is transformed back to v:

$$\frac{dv}{dr} = \sqrt[n]{\frac{\tau_0 + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K}} + \frac{c_1}{r}. \tag{14}$$

Since r = 0 leads to an infinite $\frac{dv}{dr}$, the constant c_1 needs to be made equal to 0:

$$\frac{dv}{dr} = \sqrt[n]{\frac{\tau_0 + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K}}. \tag{15}$$

Considering that $\frac{dP}{dz}$ always has a negative value, and that the term $\tau_0 + \frac{r}{2}\frac{dP}{dz}$ has to always be positive, in order for $\frac{dv}{dr}$ to remain a real number, we rewrite the equation (15) as follows:

$$\frac{dv}{dr} = -\sqrt[n]{\frac{-\frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right) - \tau_0}{K}}. \tag{16}$$

From equation (6), we can conclude that in order for a fluid layer located at coordinate r to move relative to neighboring layers, the following condition has to be satisfied:

$$\left|\frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right)\right| > \tau_0. \tag{17}$$

The solution of differential equation (16) is as follows:

$$v = c_2 - \frac{n}{n+1}\sqrt[n]{\frac{-\frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right) - \tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz} - \rho Z} + r\right). \tag{18}$$

As indicated previously, the shear stress has a minimum value in the center of the pipe, and it increases with the increase of radius. Since we are considering a fluid that has a yield stress τ_0, there has to be a certain radius r_c in the pipe until which the shear stress that occurs in the fluid does not exceed the yield stress. Therefore, a certain flow region from r=0 to r=r_c is formed where the shear stress is less than τ_0. This region can be called the core of the flow, and it is moving through the pipe as a whole, meaning that the layers within this core do not move relative to each other. The core of the flow has a certain velocity v_c which is the maximum velocity in the pipe. In the flow region from r=r_c to r=R the velocity gradually decreases and becomes equal to 0 at r=R and we can refer to this region as out-of-core region. All of this can be summarized in the following equations:

$$r_c = \left|\frac{2\tau_0}{\frac{dP}{dz} - \rho Z}\right|, \tag{19}$$

$$\left|\frac{2\tau_0}{\frac{dP}{dz} - \rho Z}\right| < R. \tag{20}$$

Equation (19) shows the formula for determination of the radius of the core. We can see that the core radius increases with the increase of yield stress and decreases with the increase of the pressure gradient. Equation (20) shows the condition of flow in a pipe in general. In other words, in order for flow to occur in the pipe, the radius of the core needs to be smaller than the radius of the pipe.

Next, we shall determine the constant c_2 in equation (18) by using the conditions described above. Due to the fact that the velocity is equal to 0 at r = R, we get:

$$0 = c_2 - \frac{n}{n+1}\sqrt[n]{\frac{-\frac{R}{2}\left(\frac{dP}{dz} - \rho Z\right) - \tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz} - \rho Z} + R\right). \tag{21}$$

From here we get that the constant c_2 is determined as:

$$c_2 = \frac{n}{n+1}\sqrt[n]{\frac{-\frac{R}{2}\left(\frac{dP}{dz} - \rho Z\right) - \tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz} - \rho Z} + R\right). \tag{22}$$

Finally, we derive the equation that describes the velocity distribution in a pipe for Herschel-Bulkley fluids:

$$v = \frac{n}{n+1}\sqrt[n]{\frac{-\frac{R}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz}-\rho Z}+R\right)-\frac{n}{n+1}\sqrt[n]{\frac{-\frac{r}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz}-\rho Z}+r\right). \quad (23)$$

If we insert r=r_c into the equation above and use the definition of r_c from equation (19), we will get the following formula for finding the velocity of the core of the flow:

$$v_c = \frac{n}{n+1}\sqrt[n]{\frac{-\frac{R}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz}-\rho Z}+R\right). \quad (24)$$

By knowing the velocity distribution, we can determine the flow rate in the pipe using the formula below:

$$Q = Q_c + Q_{oc}, \quad (25)$$

where Q_c is the flow rate of the core region and Q_{oc} is the flow rate of out-of-core region. Q_c is determined as:

$$Q_c = \pi r_c^2 v_c = \pi\left(-\frac{2\tau_0}{\frac{dP}{dz}-\rho Z}\right)^2 \frac{n}{n+1}\sqrt[n]{\frac{-\frac{R}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0}{K}}\left(\frac{2\tau_0}{\frac{dP}{dz}-\rho Z}+R\right). \quad (26)$$

On the other hand, Q_{oc} is determined as:

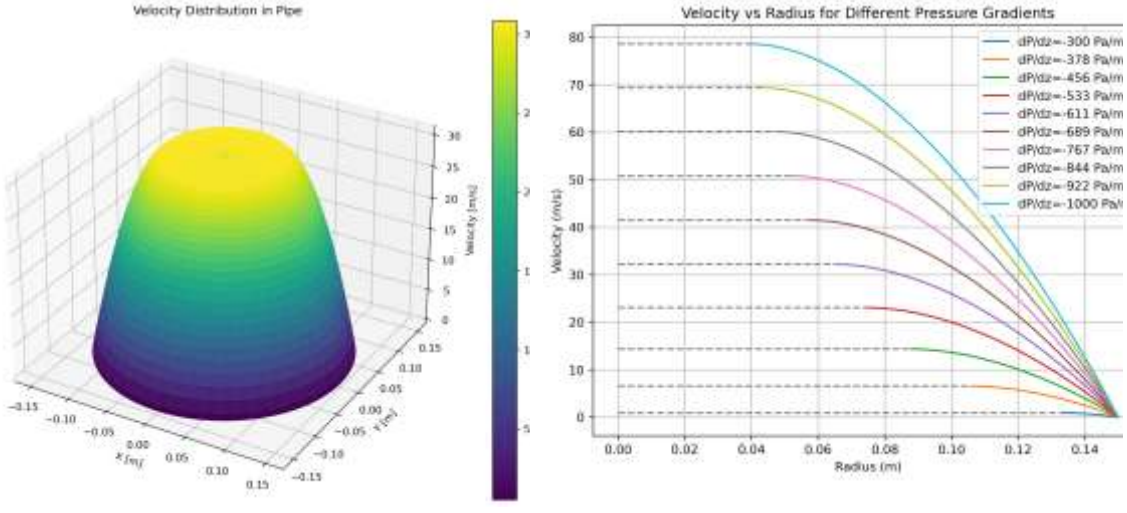
$$Q_{oc} = \int_{r_c}^{R} v d(\pi r^2) = \int_{r_c}^{R} 2\pi v r dr. \quad (27)$$

By calculating this integral and summing up Q_c and Q_{oc}, we get the following final formula for flow rate in pipe:

$$Q = \frac{\pi n}{K^{\frac{1}{n}}}\frac{\left(-\frac{R}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0\right)^{1+\frac{1}{n}}}{\left(-\frac{1}{2}\left(\frac{dP}{dz}-\rho Z\right)\right)^3}\left(\frac{\left(-\frac{R}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0\right)^2}{3n+1}+\frac{2\tau_0\left(-\frac{R}{2}\left(\frac{dP}{dz}-\rho Z\right)-\tau_0\right)}{2n+1}+\frac{\tau_0^2}{n+1}\right). \quad (28)$$

Figure 1 (a) shows the velocity distribution in pipe in 3D built based on equation (23) for Herschel-Bulkley fluids (τ_0=20 Pa, n=1.2). Due the presence of yield stress, a core region of radius r_c is formed in the center of the pipe which has maximum velocity.

Figure 1 (b) shows various distributions of fluid velocity in pipe for different values of pressure gradient. It can be seen that the increase of pressure gradient leads to the increase of velocity in every coordinate, and it decreases the radius r_c of the core.



(a) (b)

Figure 1: *Velocity distribution in pipe in 3D (a); Velocity distributions in pipe for different pressure gradients (b)*

Figure 2 (a) shows various distributions of fluid velocity in pipe for different values of consistency index. It can be seen that the decrease of the consistency index increases velocity at every point, however, it does not affect the core radius. Moreover, the increase of velocity with the decrease of the consistency index is higher for lower consistency indexes.

Figure 2 (b) shows various distributions of fluid velocity in pipe for different values of yield stress. The decrease of yield stress increases velocity at every point and decreases the radius of the core region. The increase of velocity with the decrease of yield stress is higher for lower yield stresses.

Figure 2 (c) shows the relationship between core velocity, pressure gradient and power-law index n. The key observation here is that the relationship between core velocity and power-law index depends on the pressure gradient. At low pressure gradients the velocity increases with the increase of n, while at high pressure gradients the velocity increases with the decrease of n.

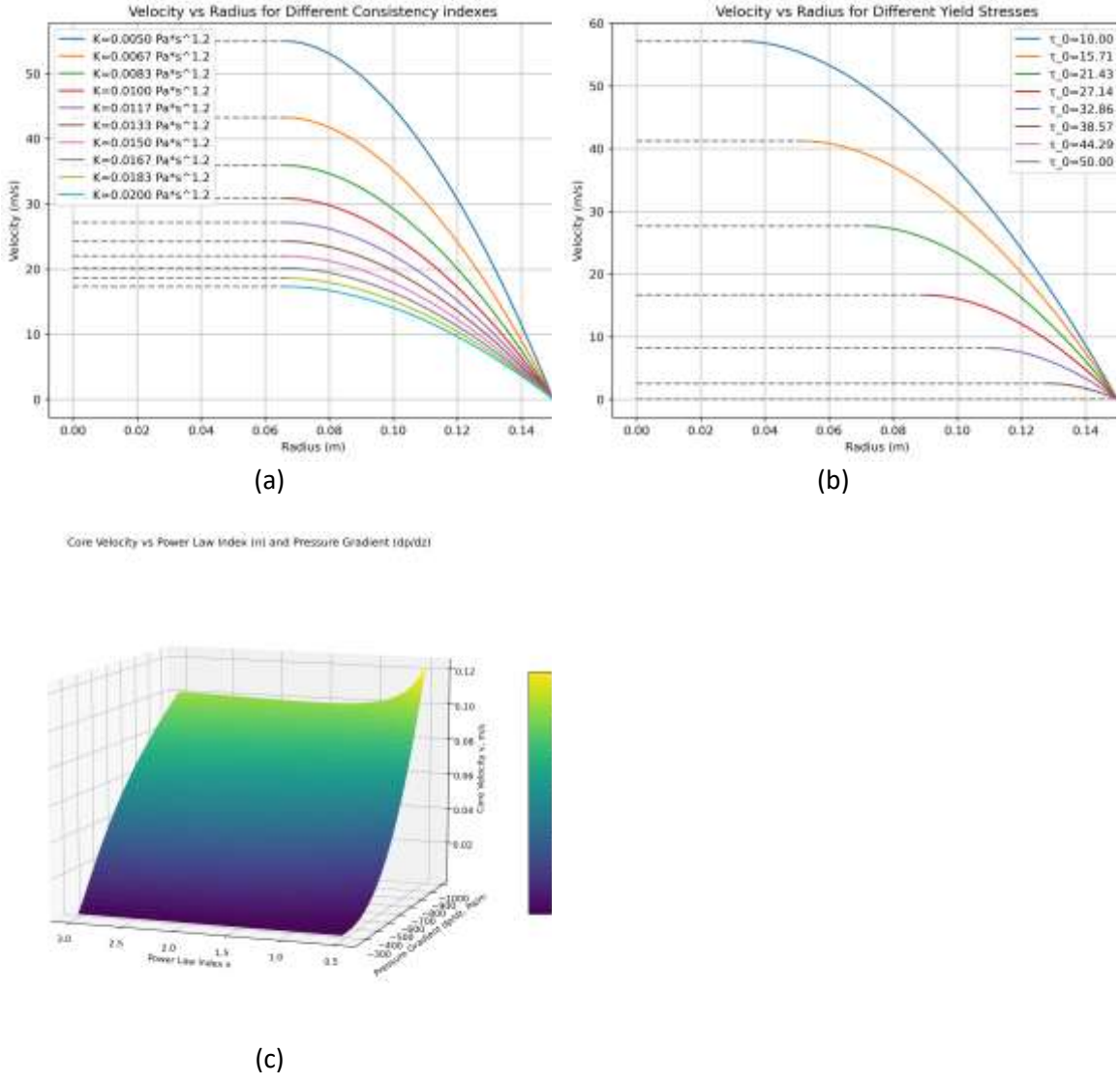


Figure 2: *Velocity distributions in pipe for different consistency indexes (a); Velocity distributions in pipe for different yield stresses (b); Relationship between velocity, pressure gradient and power-law index in 3D (c)*

Next, we shall analyze the flow of non-Newtonian fluids in annulus. No analytical solution for Herschel-Bulkley fluids in annulus was found, however, we derived an analytical solution for Bingham fluids in annulus.

In annulus, the flow occurs between the inner radius R_1 and the outer radius R_2. The core region of the flow should be located between the radiuses r_{c1} and r_{c2}. Those radiuses correspond to the conditions $R_1 < r_{c1} < r_{c2} < R_2$. As in previous case, here we start with the analysis of the shear stress formula:

$$\sigma_{rz} = \frac{c_1}{r} + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right) \tag{29}$$

When r=r_{c1} the shear stress becomes equal to -τ_0, so we get the following:

$$-\tau_0 = \frac{c_1}{r_{c1}} + \frac{r_{c1}}{2}\left(\frac{dP}{dz} - \rho Z\right) \tag{30}$$

From here we find that the constant c_1 is equal to:

$$c_1 = -\tau_0 r_{c1} - \frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz} - \rho Z\right) \tag{31}$$

So, we get the following equation for the shear stress:

$$\sigma_{rz} = \frac{-\tau_0 r_{c1} - \frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz} - \rho Z\right)}{r} + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right) \tag{32}$$

Next, we can insert r=r_{c2} to the shear stress equation and it should also lead to σ_{rz}=$-\tau_0$:

$$-\tau_0 = \frac{-\tau_0 r_{c1} - \frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz} - \rho Z\right)}{r_{c2}} + \frac{r_{c2}}{2}\left(\frac{dP}{dz} - \rho Z\right) \tag{33}$$

From here we get the following relationship between r_{c2} and r_{c1}:

$$r_{c2} = \frac{-\tau_0 - \sqrt{{\tau_0}^2 + 2\left(\tau_0 r_{c1} + \frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz} - \rho Z\right)\right)\left(\frac{dP}{dz} - \rho Z\right)}}{\frac{dP}{dz} - \rho Z} \tag{34}$$

Next, we use the formula for velocity gradient derived earlier to proceed further (we set n=1):

$$\frac{dv}{dr} = \frac{\tau_0 + \frac{r}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K} + \frac{c_1}{r} \tag{35}$$

We should have 2 independent solutions for the flow region between R_1&r_{c1} and between R_2&r_{c2}. Let's first consider the first region. In this case, the velocity gradient at r_{c1} will be equal to 0, so we get:

$$0 = \frac{\tau_0 + \frac{r_{c1}}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K} + \frac{c_1}{r_{c1}} \tag{36}$$

From here we get that c_1 is equal to:

$$c_1 = -\frac{\tau_0 r_{c1} + \frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K} \tag{37}$$

The integration of the velocity gradient equation gives the following result:

$$v = \frac{\frac{r^2}{2}\left(\frac{dP}{dz} - \rho Z\right) + 2c_1 K ln(r) + 2r\tau_0}{2K} + c_2 \tag{38}$$

Since at r=R_1 the velocity becomes equal to 0, then we get:

$$0 = \frac{\frac{{R_1}^2}{2}\left(\frac{dP}{dz} - \rho Z\right) + 2c_1 K ln(R_1) + 2R_1\tau_0}{2K} + c_2 \tag{39}$$

So, the constant c_2 is equal to:

$$c_2 = -\frac{\frac{{R_1}^2}{2}\left(\frac{dP}{dz} - \rho Z\right) + 2c_1 K ln(R_1) + 2R_1\tau_0}{2K} \tag{40}$$

So, the final velocity distribution equation after simplification would look as follows (minus is added to account for the fact that the velocity gradient is positive in the region from R_1 to r_{c1}):

$$v = -\frac{\frac{\left(r^2 - {R_1}^2\right)}{2}\left(\frac{dP}{dz} - \rho Z\right) - 2\left(\frac{\tau_0 r_{c1} + \frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz} - \rho Z\right)}{K}\right) K ln\left(\frac{r}{R_1}\right) + 2\tau_0(r - R_1)}{2K} \tag{41}$$

Similarly, for the second out-of-core region we would get:

$$v=\frac{\frac{\left(r^2-{R_2}^2\right)}{2}\left(\frac{dP}{dz}-\rho Z\right)-2\left(\frac{\tau_0 r_{c2}+\frac{{r_{c2}}^2}{2}\left(\frac{dP}{dz}-\rho Z\right)}{K}\right)Kln\left(\frac{r}{R_2}\right)+2\tau_0(r-R_2)}{2K} \quad (42)$$

At this point we have 1 unknown, which is the r_{c1} (because the relationship between r_{c1} and r_{c2} is already known). To find r_{c1} we use the boundary condition that the velocity in the first region at r=r_{c1} should be equal to the velocity in the second region at r=r_{c2}. Then we express r_{c2} in terms of r_{c1} and solve the equation for r_{c1}. However, mathematically this is very complex, and we suggest using numerical approaches to find the value of r_{c1}.

For annular flow, the condition for a certain layer to move relative to neighboring layers is:

$$\left|\frac{-\tau_0 r_{c1}-\frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz}-\rho Z\right)}{r}+\frac{r}{2}\left(\frac{dP}{dz}-\rho Z\right)\right|>\tau_0 \quad (43)$$

The general flow condition in annulus is:

$$R_1<r_{c1}<r_{c2}<R_2 \quad (44)$$

Obviously, the values of r_{c1} and r_{c2} depend on the value of the pressure gradient. When the pressure gradient increases then the values of r_{c1} and r_{c2} become closer.

The flow rate in annulus is determined using the formula:

$$Q=\ Q_c+Q_{oc1}+Q_{oc2} \quad (45)$$

where Q_c is the flow rate of the core region, and Q_{oc1}&Q_{oc2} are flow rates of out-of-core regions. Q_c is determined using the formula:

$$Q_c=\pi(r_{c2}^2-r_{c1}^2)v_c \quad (46)$$

Here v_c can be found by inserting either r_{c1} in the first velocity distribution equation or r_{c2} in the second velocity distribution equation.

On the other hand, Q_{oc1} is determined using the formula below:

$$Q_{oc1}=2\pi\int_{R_1}^{r_{c1}}vrdr \quad (47)$$

Integration results in the following:

$$Q_{oc1}=-\frac{\pi r^2\left(6\left(\tau_0 r_{c1}+\frac{{r_{c1}}^2}{2}\left(\frac{dP}{dz}-\rho Z\right)\right)\left(1-2ln\left(\frac{r}{R_1}\right)\right)-3{R_1}^2\left(\frac{dP}{dz}-\rho Z\right)-12R_1\tau_0+\frac{3}{2}\left(\frac{dP}{dz}-\rho Z\right)r^2+8r\tau_0\right)}{12K}\Big|_{R_1}^{r_{c1}} \quad (48)$$

Similarly, for Q_{oc2} we have:

$$Q_{oc2}=2\pi\int_{r_{c2}}^{R_2}vrdr \quad (49)$$

And integration gives the following result:

$$Q_{oc2}=\frac{\pi r^2\left(6\left(\tau_0 r_{c2}+\frac{{r_{c2}}^2}{2}\left(\frac{dP}{dz}-\rho Z\right)\right)\left(1-2ln\left(\frac{r}{R_2}\right)\right)-3{R_2}^2\left(\frac{dP}{dz}-\rho Z\right)-12R_2\tau_0+\frac{3}{2}\left(\frac{dP}{dz}-\rho Z\right)r^2+8r\tau_0\right)}{12K}\Big|_{r_{c2}}^{R_2} \quad (50)$$

Figure 3 (a) shows the velocity distribution in annulus in 3D for Bingham fluids (τ_0=300 Pa, n=1). It can be seen that the velocity is equal to 0 at the inner and outer boundaries of the annulus and it quite abruptly increases to the maximum value which corresponds to the core of the flow.

Figure 3 (b) shows various distributions of fluid velocity in annulus for different values of pressure gradient. Despite the fact that the pressure gradient varies in a small interval, it significantly affects the velocity profile. At pressure gradient equal to -520 Pa/m flow is absent while at -625 Pa/m the velocity is very high, and the radius of the core is very small. Another observation is that the velocity increases more abruptly in the inner part of the annulus (between the annulus inner radius and the core inner radius) than in the outer part of the annulus (between the core outer radius and the annulus outer radius).

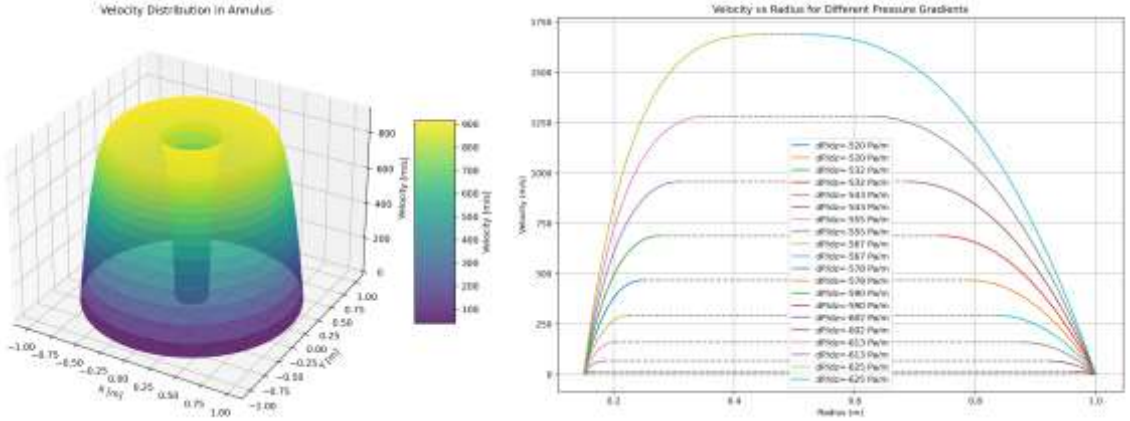


Figure 3: *Velocity distribution in annulus in 3D (a); Velocity distributions in annulus for different pressure gradients (b)*

Fig.4 (a) shows various distributions of fluid velocity in annulus for different values of consistency index. It can be seen that decrease of the consistency index significantly increases velocity but does not affect the inner and outer radiuses of the core.

Fig.4 (b) shows various distributions of fluid velocity in annulus for different values of yield stress. The yield stress changes in a very small interval (from 250 to 300 Pa), however, the sensitivity of the velocity profile to yield stress is very high, as it increases from 0 at τ_0=300 Pa to a very high value at τ_0=250 Pa, at which the size of the core becomes very small.

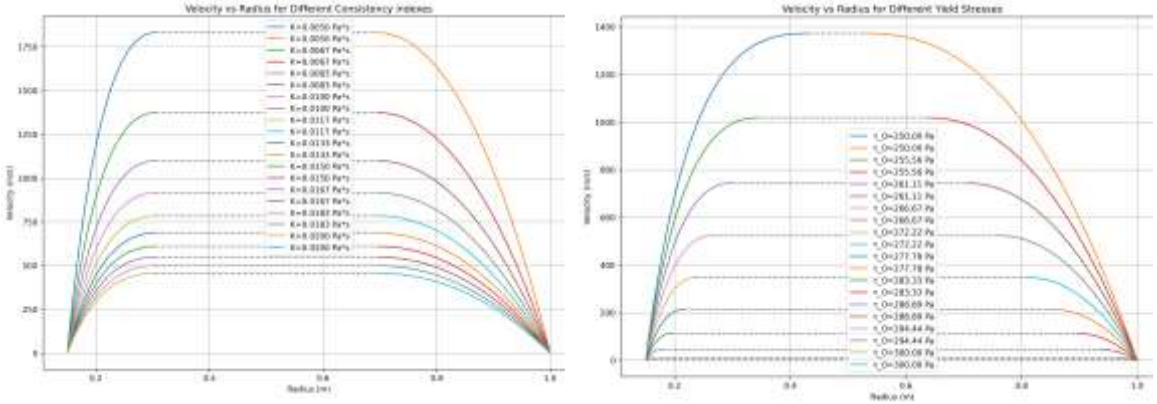


Fig.4: *Velocity distributions in annulus for different consistency indexes (a); Velocity distributions in annulus for different yield stresses (b)*

III. Conclusion

The purpose of this work was to study the flow of non-Newtonian fluids in pipe and annulus and analyze the impact of non-Newtonian parameters on the flow. Firstly, the velocity distribution in pipes for Herschel-Bulkley fluids has been derived based on the balance of forces equation. It has been shown that the flow of yield stress fluids is characterized by presence of a certain region (core of the flow) that moves as a whole (layers do not move relative to each other) which has the maximum velocity. Moreover, the flow condition for such fluids in a pipe has been presented and the formula to determine the overall flow rate in the pipe has been derived.

Next, the impact of non-Newtonian parameters on the velocity distribution in a pipe was graphically analyzed. The conclusion was that the decrease of the consistency index significantly increases the velocity, however, it does not affect the size of the core. On the other hand, the decrease

of the yield stress strongly increases velocity and decreases the size of the core. The most interesting finding of this work is that the relationship between the velocity and the power-law index depends on the pressure gradient. At low pressure gradients the increase of power-law index increases velocity, while at high pressure gradients it is the opposite.

No analytical solution for velocity distribution was found for Herschel-Bulkley fluids in annulus, however, a solution has been derived for Bingham fluids. It has been shown that similar to the case with the pipe, in annulus a core region is present as well and it is characterized by 2 radiuses – inner and outer radius of the core that are located between the inner and outer radius of the annulus. It has been concluded that the velocity is very sensitive to even small changes in yield stress and pressure gradient. Another conclusion is that the velocity increases more abruptly between the inner radius of the annulus and the core compared with the velocity in the region between the core and the outer radius of the annulus.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE HUMAN FACTOR IN THE PARADIGM OF SUSTAINABLE DEVELOPMENT OF THE CHECHEN REPUBLIC

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Abstract

This article examines the role of human capital as a key element in the sustainable development strategy of the Chechen Republic. It analyses the formation of human capital in the region, including demographic processes, educational policy, labor resources, and socio-cultural aspects of human potential development in regional economic development, including innovative activities, entrepreneurship, and the social activity of the population. It presents recommendations for improving regional policy in the field of human resources development, taking into account the specifics of the socio-economic development of the Chechen Republic.

Keywords: human factor, sustainable development, the Chechen Republic, human capital, regional policy, socio-economic development, labor resources

I. Introduction

The relevance of the study of the human factor in the paradigm of sustainable development of the Chechen Republic is due to the need for scientific understanding of the specific mechanisms of transformation of socio-economic systems in the context of post-conflict reconstruction and modernization of the region. In the context of the implementation of national projects and the Strategy of Spatial Development of Russia until 2030 with a forecast until 2036 [14], the analysis of the role of human capital as a a key driver of sustainable development, taking into account the unique socio-cultural characteristics of the North Caucasus region. Insufficient knowledge of the relationship between the traditional institutions of Chechen society and modern challenges of sustainable development creates a scientific gap in understanding the mechanisms of effective integration of cultural heritage into the processes of regional modernization.

The purpose of the study is to identify and analyze the features of the formation and implementation of the human factor in the system of sustainable development of the Chechen Republic, taking into account the socio-cultural specifics of the region. The problems of the study are focused on the contradiction between the need to accelerate the modernization of the socio-economic system of the region in accordance with the principles of sustainable development and the need to preserve traditional social institutions and cultural values that determine the identity and social stability of the Chechen society.

II. Methods

The theoretical and methodological basis for the study of the human factor in the paradigm of sustainable development is made up of interdisciplinary approaches that integrate the concepts of socio-economic geography, regional economics, sociology of development and environmental anthropology. The methodological foundation is based on a systematic approach to the analysis of the interaction of social, economic and environmental components of sustainable development, using the concept of human capital by G. Becker [12] and T. Schultz [13], the theory of social capital by P. Bourdieu [4] and J. Coleman [7], as well as the modernization theory of S. Huntington [11].

III. Results

The study is based on the paradigm of sustainable development formulated in UN documents and concretized in the Sustainable Development Goals until 2030 [17], with adaptation to regional specifics through the prism of the concept of "green economy" and the theory of endogenous development of territories. The methodological apparatus includes a structural and functional analysis of social institutions, a comparative approach to compare regional development models, as well as qualitative and quantitative methods sociological research to assess human potential. Particular importance is attached to the application of the cultural-historical approach of A.G. Asmolov [1] to analyze the role of traditional values and institutions in the processes of social development, which allows taking into account the specifics of the socio-cultural context in the formation of strategies for sustainable development of the region.

The modern paradigm of sustainable development, based on the principles of balanced economic growth, social justice and environmental safety, involves the recognition of the human factor as the central element of all transformation processes taking place in society. In the context of regional development policy, the human factor is an integral characteristic of the totality of individual and collective abilities of the population to create material and spiritual benefits, including demographic potential, educational level, professional qualifications, cultural traditions and value orientations, which in their entirety determine the quality of human capital as the main driver of sustainable development of the territory [5].

The specificity of regional approaches to the formation of human capital is due to the need to take into account local socio-economic conditions, historical traditions and cultural characteristics of a particular territory, which requires the development of differentiated development strategies adapted to regional realities and needs. The Chechen Republic as a constituent entity of the Russian Federation is a unique object of scientific research in the context of the interaction of the human factor and sustainable development, since this region is characterized by a synthesis of traditional socio-cultural institutions, high demographic potential and a pronounced orientation towards the technological modernization of economic and social structures in accordance with the imperatives of innovative development of modern society.

The demographic situation in the Chechen Republic is characterized by a number of features that have a significant impact on the formation of the region's human potential and determine its prospects in the context of sustainable development. The population of the republic is more than 1.5 million people [16], while there is a positive dynamics of natural increase, which is due to traditionally high birth rates and relatively low mortality, especially in younger age groups. The age structure of the population of the Chechen Republic is distinguished by a significant proportion of young people, which creates favorable prerequisites for the formation of labor potential and the development of human capital, but at the same time requires the creation of appropriate conditions for education, vocational training and employment of the younger generation. The predominant ethnic group is the Chechens, who make up 96.4% of the republic's population.

Migration processes play an important role in the demographic development of the region, while there is both intraregional migration associated with urbanization and resettlement of the population from rural areas to urban centers, and interregional migration, including both the departure of young specialists to other regions of Russia for education and employment, and the return of representatives of the Chechen diaspora to their historical homeland. An analysis of migration flows shows that in order to ensure the sustainable development of the region, it is necessary to create conditions for the consolidation of young personnel in the territory of the republic, which requires the development of a modern economy, the creation of high-tech jobs and the formation of an attractive social environment for life and professional activity.

The Strategy for the Socio-Economic Development of the Chechen Republic until 2035 [15] defines a comprehensive system of measures aimed at optimizing the demographic situation and improving the standard of living of the region's population. In the field of demographic policy, the priority tasks are to maintain favorable demographic trends through the implementation of a program to stimulate the birth rate, which provides for subsidizing the education of the third and subsequent children from the republican budget, strengthening the institution of the family through the promotion of traditional family values, as well as the development of programs to reduce the working day for parents of large families and subsidize housing construction.

Improving the level and quality of life of the population involves the implementation of two main goals: increasing labor productivity and outstripping job growth to increase incomes of the population, as well as the development of small and medium-sized businesses with an emphasis on the innovative component. The first goal is achieved by increasing labor productivity, supporting employment and reducing the scale of the informal economy, while the second goal is implemented by increasing the availability of financial resources for entrepreneurs, developing their competencies, expanding access to public procurement, reducing administrative barriers and creating a favorable competitive environment. This strategy reflects a systematic approach to the formation of the human potential of the region and creates the basis for sustainable socio-economic development of the Chechen Republic in the long term [2].

The education system of the Chechen Republic is a key institution for the formation of human capital, which, in the face of modern challenges, requires constant improvement and adaptation to the changing needs of the economy and society. The current state of the education system in the republic is characterized by significant investments in the development of the material and technical base of educational institutions, advanced training of teaching staff and the introduction of modern educational technologies, which creates the basis for high-quality education and training of highly qualified specialists. Particular attention is paid to the creation of a barrier-free educational environment that provides equal opportunities for quality education for all categories of students, including children with special educational needs.

Professional training of personnel in the Chechen Republic is carried out taking into account the needs of the regional economy, while priority is given to the development of technical and engineering specialties necessary for the modernization of industry and the development of innovative sectors of the economy. The system of secondary vocational education is actively developing in the direction of training specialists for the service sector, tourism, agriculture and other industries of strategic importance for the economic development of the region. Modernization of secondary vocational education programs involves the introduction of elements of project-based learning, the development of practice-oriented forms of training and the creation of conditions for the formation of students' skills of independent professional activity. An important aspect is the development of network interaction between educational organizations and employers, which makes it possible to ensure the compliance of the content of education with the current requirements of production.

Particular attention is paid to the development of higher education. At present, the Chechen State University named after A.A. Kadyrov, the Grozny State Petroleum Technological University named after Academician M.D. Millionshchikov, the Chechen State Pedagogical University, the

Russian Islamic University named after Kunta-Khadzhi, the Branch of the Moscow State University named after M.V. Lomonosov in the city of Grozny operate on the territory of the Chechen Republic. Research teams implement fundamental and applied research projects supported by federal grants and regional programs for the development of science. The training of scientific personnel through postgraduate studies is actively developing, dissertation councils in various specialties are functioning. Universities participate in interregional and international scientific cooperation, publish research results in peer-reviewed journals and organize scientific conferences, contributing to the formation of the scientific potential of the republic and the preservation of the cultural and historical heritage of the region.

IV. Discussion

The structure of employment in the Chechen Republic reflects current trends in the development of the regional economy and is characterized by the predominance of the service sector, public administration and the social sphere, while there is a gradual development of industry, agriculture and the tourism sector. According to Chechenstat, the officially registered unemployment rate in the republic is 8% [16]. The region's labor market is characterized by a high level of economic activity of the population, especially among young people, which creates both opportunities for economic growth and challenges associated with the need to create a sufficient number of jobs and ensure quality employment. A feature of the labor resources of the Chechen Republic is a high level of motivation for work and entrepreneurship, which is due to cultural traditions and value orientations of the population [9].

The development of entrepreneurship and small business is one of the priorities of the republic's economic policy, since small and medium-sized enterprises are an important source of job creation, innovation and economic growth [6]. State support for entrepreneurship includes the creation of a favorable legal and tax environment, the provision of preferential loans and subsidies, the development of business support infrastructure, including business incubators, technology parks and entrepreneurship development centers. Particular attention is paid to the development of women's entrepreneurship and youth business, which contributes to a fuller use of the human potential of the region and ensures the social integration of various groups of the population in economic activities.

Socio-cultural factors play a fundamental role in the formation of the human factor in the sustainable development of the Chechen Republic, since the traditional values and institutions of Chechen society have a significant impact on the motivation, behavior and life strategies of the population. These social institutions form a specific model of decision-making based on collective responsibility and intergenerational solidarity, which creates unique opportunities for the implementation of long-term development strategies through a system of traditional social control and moral and ethical imperatives. At the same time, the need to adapt traditional norms to the modern challenges of globalization and technological development requires the development of innovative approaches to the integration of cultural heritage into the processes of modernization of the economy and social sphere of the republic.

State policy in the field of human development of the Chechen Republic is based on an integrated approach, which provides for the coordination of the efforts of various authorities, public organizations and the private sector to create conditions conducive to the maximum disclosure of the abilities and talents of the population. Regional programs for the development of human resources include measures to modernize the system of education, health care, social protection, culture and sports, which in their entirety ensure the formation of a favorable environment for the development of human capital [8]. Particular attention is paid to youth support programs, which include the creation of youth centers, the organization of educational and professional programs, support for youth entrepreneurship and social activity.

Investments in social infrastructure and human capital are one of the priorities of the budget policy of the Chechen Republic, which is reflected in significant expenditures on education, health care, culture and social protection of the population. The development of modern social infrastructure, including the construction of new schools, hospitals, sports complexes, cultural centers and other social facilities, creates a material basis for improving the quality of life of the population and developing human potential. An important area of investment policy is the creation of a modern information and communication infrastructure that provides access to modern technologies, educational resources and opportunities for professional development [10].

The proposed conceptual model of the human factor in the paradigm of sustainable development is an integrated system of interrelated elements that reflects the multi-level structure of regional development processes. The model is based on a systems approach that considers the human factor as a central element that accumulates human, social, cultural and institutional capital and at the same time acts as a catalyst for sustainable development through three complementary components: economic, social and environmental sustainability (Fig. 1).

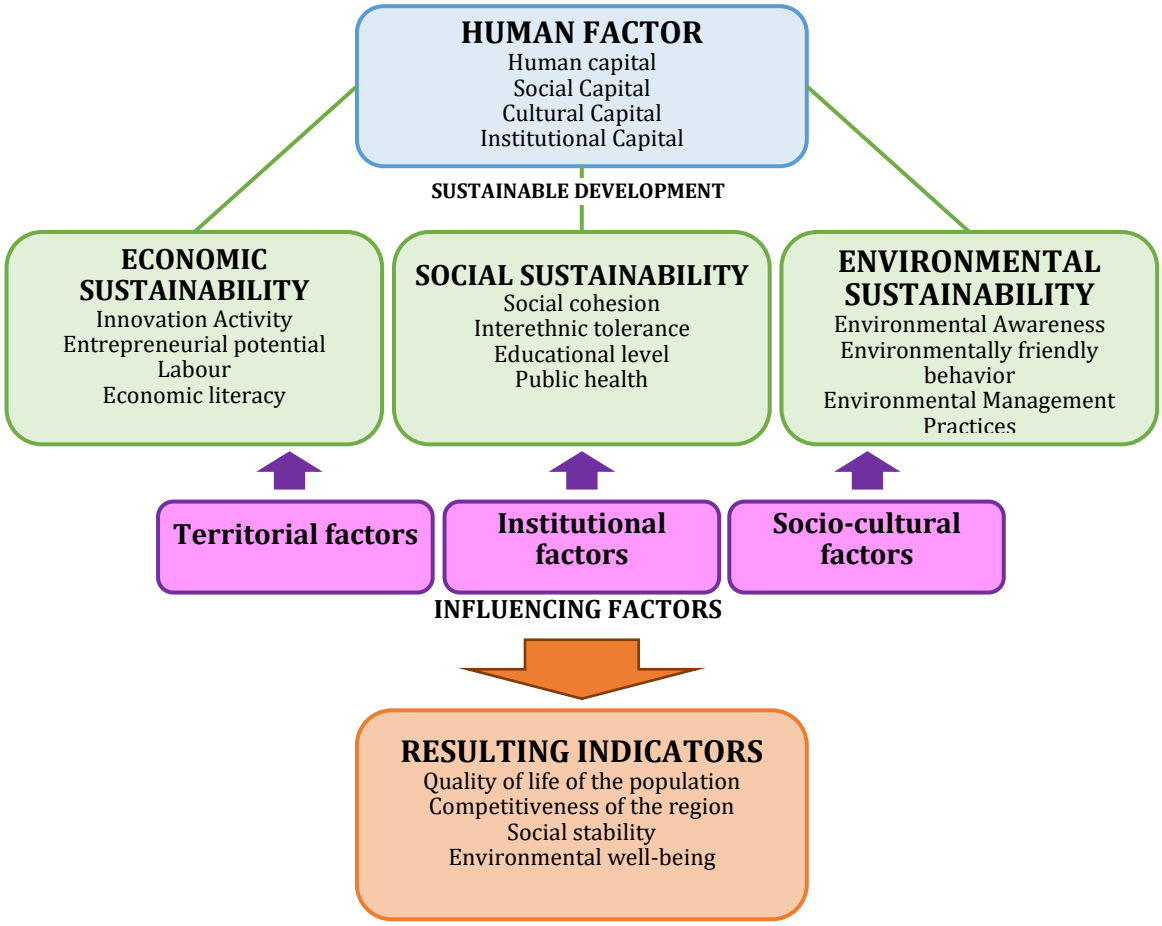


Figure 1: *Conceptual model of the human factor in the paradigm of sustainable development of the Chechen Republic*

The model takes into account the specifics of the regional context through a system of external factors – socio-cultural (traditional institutions, religious values, ethnic identity), institutional (state policy, legal environment, educational system) and territorial (geographical location, resource potential, infrastructural development), which form unique conditions for the realization of human potential.

The resulting indicators of the model's effectiveness are the quality of life of the population, the competitiveness of the region, social stability and environmental well-being, which makes it possible to assess the degree of achievement of sustainable development goals, taking into account the regional specifics of the Chechen Republic.

The study of the role of the human factor in the Chechen Republic allows us to conclude that the region has a significant human potential, which is characterized by a favorable demographic situation, high motivation of the population for education and work, rich cultural traditions and active state support for the development of human resources. The paradigm of sustainable development based on the principles of economic efficiency, social justice and environmental responsibility, involves an integrated approach to the use of human potential, in which economic growth is achieved not at the expense of the depletion of natural and human resources, but through their rational use and reproduction. In the context of the regional policy of the Chechen Republic, this paradigm is implemented through the creation of conditions for a harmonious combination of economic development with the preservation of cultural identity and environmental security, which requires the formation of a new type of human capital capable of adapting to the challenges of globalization and technological modernization without losing traditional values and cultural roots.

However, in order to fully unleash this potential, further work is needed to improve the education system, create modern jobs, develop entrepreneurship and integrate traditional values into the region's modernization strategies. The implementation of the sustainable development paradigm in the Chechen Republic requires the creation of an innovation ecosystem that provides synergy between education, science, production and culture, contributing to the formation of a knowledge economy based on creativity, innovation and high technology. A special role in this process is played by the development of social capital, which is formed on the basis of trust, mutual respect and solidarity between different social groups, which creates a favorable environment for collective actions aimed at achieving the goals of sustainable development. Effective integration of the human factor into the paradigm of sustainable development involves not only investments in education and healthcare, but also the creation of institutional conditions for citizens' participation in decision-making, the development of civil society and the formation of a culture of responsible consumption and production.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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CHALLENGES IN DETERMINING CLAY CONTENT AND POROSITY OF CLAY RESERVOIRS USING NUCLEAR PHYSICS METHODS

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Abstract

The study examines the key factors influencing the intensity of secondary gamma radiation and the gamma activity of geological formations. It is found that the quantitative assessment of the pelitic fraction content is significantly influenced by the mineral composition of both the rock framework and the clay cement, as well as the spatial distribution and concentration of naturally occurring radioactive elements within different lithological rock types and weight fractions. A comprehensive methodology and algorithm has been developed to improve the accuracy of clay content and porosity determination in clayey reservoirs based on nuclear physics methods. These methods involve analyzing variations in gamma ray intensity and their correlation with mineralogical and geochemical properties of the subsurface formations. The proposed approach has been rigorously tested on real geological data from several hydrocarbon fields in Azerbaijan. The validation process included a comparative analysis with conventional petrophysical methods to assess the reliability and accuracy of the results. The effectiveness of the methodology is demonstrated through a practical case study, demonstrating its applicability in improving reservoir characterization and facilitating more informed decision making in hydrocarbon exploration and production.

Keywords: clayey reservoir, porosity, well, hydrogen content, clay content, radioactivity, natural radioactive elements

I. Introduction

The targeted application of a set of nuclear physics methods (NPM) in long-term developed fields enables the acquisition of essential data on the current characteristics of reservoir systems, the identification of additional reserves for enhanced oil recovery, and the establishment of a modern information framework for effective reservoir management. At present, there is no viable alternative to nuclear physics methods for solving these challenges in cased wells.

Among geophysical well-logging methods (GWL) used to determine the reservoir's capacity and filtration properties, gamma logging (GL) and neutron gamma logging (NGL) are considered the most effective. However, quantitative interpretation in cased wells becomes even more complicated due to the influence of various factors on NPM readings, particularly NGL, such as variations in casing eccentricity along the borehole. This effect is especially pronounced in wells with large diameters and in formations with low hydrogen content, such as low-porosity or gas-bearing intervals. Consequently, the ability of NGL to provide reliable quantitative data on porosity in low-porosity reservoirs and gas saturation in cased wells is significantly limited.

On the other hand, NGL is employed (including as part of GWL) not only for porosity determination but also for monitoring changes in oil and gas saturation coefficients of reservoirs and for addressing other reservoir evaluation challenges [4]. The expansion of the range of problems

addressed through NPM is driven by the ability to derive a greater number of informative parameters from radioactive fields, many of which can be reliably determined only using modern mathematical methods. However, with large data volumes, processing NGL results, especially under complex geological and technical conditions, becomes a labor-intensive task.

Efforts to improve NGL methodology and interpretation have been focused on overcoming these limitations and addressing several other challenges.

II. Theoretical and Methodological Aspects

Clayey oil and gas reservoirs are complex natural systems composed of rock-forming and accessory minerals, organic matter (OM), and pore fluids. The reservoir potential and other properties of these rocks are shaped by geochemical interactions among their constituent components during lithogenesis. The extent of this interaction is determined by the textural characteristics of the rocks [1].

It is important to emphasize that the pore space of rocks is an integral element of their texture and evolves in tandem with changes in textural features. These features dictate the spatial arrangement and orientation of the rock components, thereby influencing reservoir properties.

The textural characteristics of rocks are closely linked to their material composition. The foundation of rock textures—and consequently, the pore system of clayey reservoirs—is established during sedimentogenesis and remains largely preserved through diagenesis and catagenesis.

Determination of clay content

In the study of petroleum source shales, the ability of gamma methods (GM) to assess the type of clay minerals and the overall clay content is of particular interest. In some cases, clay content is understood as granulometric clay content (pelitic fraction), independent of mineral composition, since this characteristic is crucial for evaluating the filtration properties of rocks. In other cases, structural clay content is considered, referring to the proportion of clay minerals containing chemically bound water, which influences the readings of acoustic logging (AL), neutron logging (NL), and pulsed gamma-gamma logging (PGGL).

It is well known [7] that the presence of clay minerals in sedimentary rocks, particularly those with high dispersion and bound water content, significantly affects many physical properties of rocks. As a result, the quantitative assessment of the degree of clay enrichment in sedimentary formations has become highly relevant, as this parameter is widely used in petroleum geology and geophysics.

Interest in evaluating clay content based on gamma spectrometry data remains strong. The analysis of radioactive element distribution across granulometric fractions has shown that thorium and potassium are predominantly associated with the pelitic and fine silt fractions, while uranium is mainly concentrated in the fine silt fraction with grain sizes of 0.01–0.05 mm. The variability of the mineral composition of clay cement across different stratigraphic sections and petroleum-bearing regions necessitates the search for relationships of the form $\mathbf{REE = F(K_{clay})}$ for specific stratigraphic intervals.

The content of accessory minerals in the heavy mineral fraction of reservoir rocks generally does not exceed 2%. The behavior of potassium is complex and can vary depending on the abundance of rock fragments, micas, feldspars, the ratio of potassium to sodium feldspar varieties, the degree of their transformation, as well as the composition and quantity of clay minerals present.

Determination of Porosity

It is known that the basis for determining the porosity of terrigenous rocks using neutron logging methods is the dependence of the porosity coefficient (K_p) on the hydrogen index ($\omega_\sum$), the tightness of which is regulated by variations in the values of the hydrogen content of the solid phase.

As an example, in the figure 1 shows a comparison of the equivalent moisture content and porosity of the formation rocks of the horizon VI of the PS.

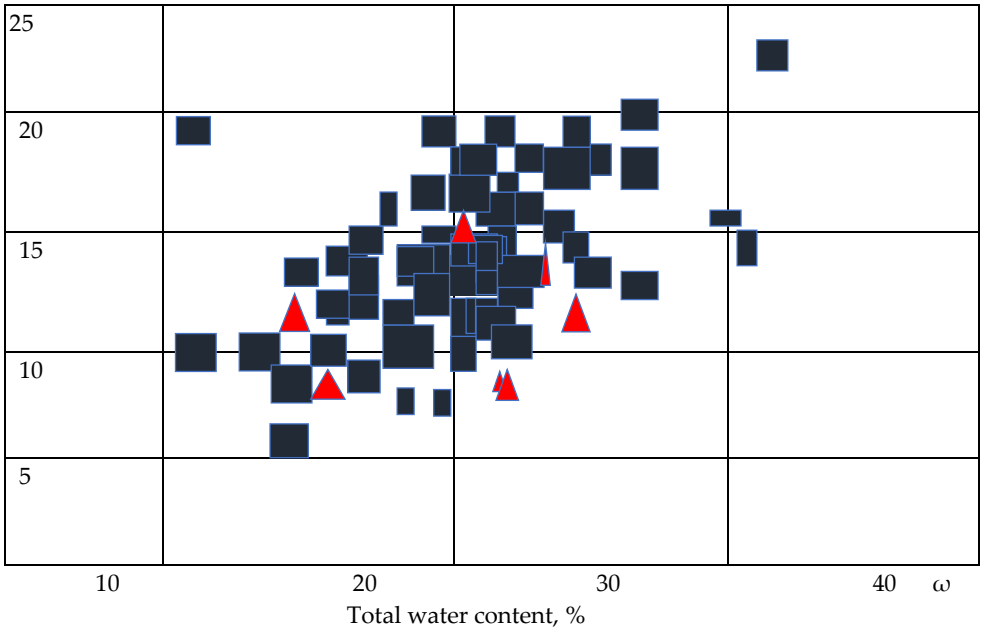


Fig. 1: *Comparison of the total hydrogen content and the porosity coefficient of the rocks of the VI horizon of the Garabaghli field*

The Garabaghli structure that oil-gas field confined is located 16 km south of the city of Shirvan, on the left bank of the Kura River, between the Kurovdag and Babazanan anticlines. The field area consists of a plain located 15-23 m below sea level (Fig.2).

The shale content methods, so the method of spontaneous potential (SP) and natural radioactivity (GL) can help take into account the effect of solid phase hydrogen on the neutron gamma logging (NGL) readings. Of the two possible options listed, the gamma method is more universal due to its independence from many geological and technological factors - mineralization and chemical composition (mineralization and chemical composition of formation water and drilling mud, type of solution, cementing, pyritization, etc.) [7, 10].

When studying clayey terrigenous reservoirs, simply increasing the sensitivity of neutron logging to changes in hydrogen content is insufficient. It is also necessary to determine the clay content, as the total hydrogen content of a clayey reservoir ($\boldsymbol{\omega_{\sum}}$), measured using neutron logging, consists of both the open porosity ($\mathbf{K_p}$) and the crystallization water of the clay material ($\boldsymbol{\omega_c^{cr}}$), expressed as:

$$\boldsymbol{\omega_{\sum}=K_{p+}\omega_c^{cr}}.$$

In formations where the radioactivity of the rock framework (i_{fw}) and the clay material (i_c) remains relatively constant, clay content—and consequently, the amount of crystallization water—can be determined from gamma logging (GL). However, in cases where the radioactivity of the clay material and the rock framework are comparable (i_c exceeding i_{fw} by no more than 3–4 times), the clay content estimated from GL is significantly influenced by the type of clay material and the reservoir structure.

To account for the effect of different clay types on gamma and neutron logging responses, it is useful to distinguish between dispersed clay content (C_{cc}) or clay cement and laminated or interspersed clay content (C_{cl}).

- Dispersed clay primarily replaces the nearly non-radioactive fluid in the pore space.

- Laminated and interspersed clay replaces the non-clay rock, whose radioactivity may be substantial [2,4,5].

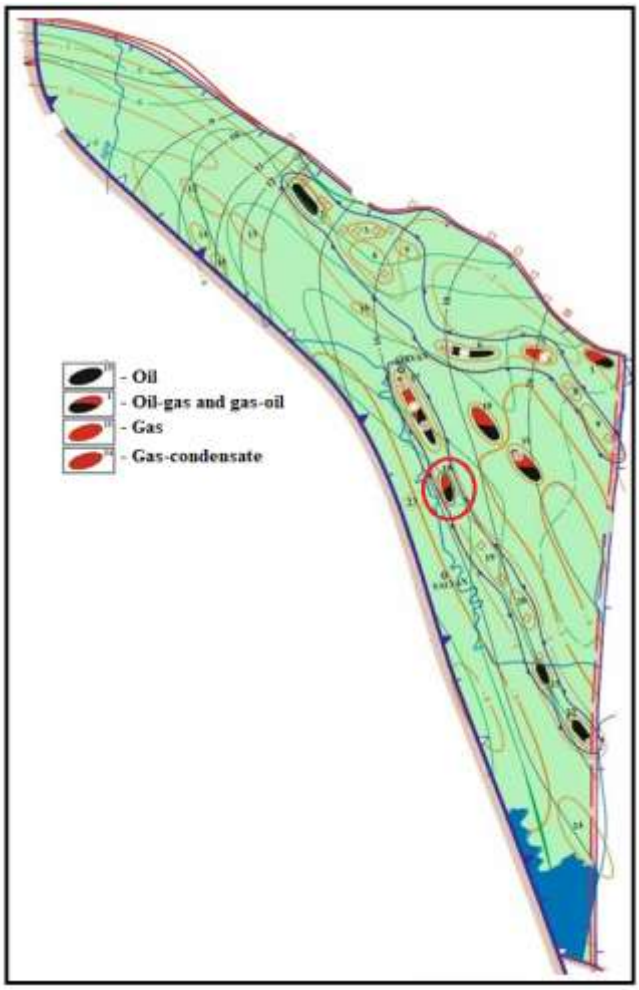


Fig. 2: *Location map of the Garabaghli structure*

In the latter case, the formation's radioactivity changes with increasing clay content by the difference in radioactivity between the clay and the non-clay rock.

Effect of clay type on hydrogen content

The variation in hydrogen content in a clayey formation also strongly depends on the type of clay material.

- Dispersed clay replaces water or oil with clay material, whose hydrogen content is at least twice as low as that of formation water or oil.

- Laminated or interspersed clay replaces rock, whose hydrogen content is typically close to or lower than that of the clay material.

Porosity Estimation in Clayey Reservoirs

Within a single hydrocarbon accumulation, the framework porosity of sand-clay reservoirs often varies within narrow limits and, within an acceptable margin of error, can be assumed to be constant. In this case, it is possible to determine the components of the clay material according to clay type (C_{cc} and C_{cl}) and, using the known framework porosity, calculate the open porosity of the reservoir using the equation:

$$K_p = [K_{pfw} - C_{cc}(1-K_{pc})]\,(1-C_{cl}) + C_{cl}K_{pc},$$

where K_{pc} represents the porosity of the clay material.

III. Results and Discussion

Let's consider the petrophysical basis for using a complex methods of neutron logging and natural gamma field to determine the porosity and shale content of oil and gas saturated reservoirs.

The method of combining neutron and gamma logging is widely used in the combined interpretation of well logging data in productive formations of the Garabaghli field.

The above combination of methods is due to the dependence of the hydrogen content of the solid phase of rocks, on the one hand, and their natural gamma activity, on the other, on the content of shale material.

The object of this study is the Productive series (PS) of the Garabaghli structure, which represents the primary oil and gas-saturated interval within the geological section. This formation has been intersected by deep exploration and production wells drilled across various parts of the area (Fig.3). The maximum thickness of the PS, recorded in a well located on the southwestern limb of the fold, reaches 2,063 meters. The fold axis exhibits a weakly expressed S-shaped structure, trending from northeast to southwest, which shifts to a southeastern, then meridional, and further to a north-southwestern direction near the southeastern plunge.

The geological structure of the Garabaghli oil field includes Productive series deposits, as well as Aghjagil and Absheron stage formations, which are overlain by Gadim Khazar and modern deposits.

Productive series is the main oil- and gas-bearing horizon of the field section. It has been intersected by the deepest exploration and production wells located in various parts of the area. The upper 1000 m of thickness, corresponding to the first five PS horizons, are the most fully covered.

The maximum PS thickness encountered in a well on the southwestern limb of the structure is 2063 m. The drilled part of the section is characterized by alternating sand and clay layers. The base of the PS, opened in wells located in the uplifted part of the northeastern limb, corresponds to the XV horizon, beneath which Paleogene deposits composed of clays were encountered at a depth of 4250 m.

Horizon I, consists of alternating sand and clay layers. In most wells at the crest of the structure, a 20–25 m thick sand bed saturated with oil is distinguished, characterized by an electrical resistivity of 3–10 Ohm.

According to the geological interpretations Horizon I is completely eroded at the crest and in a significant part of both limbs. In this horizon, on the southwestern limb of the structure, transgressive deposits of the Aghjagil stage are present. The total thickness of Horizon I according to the composite section is 137 m.

Horizon II, compared to Horizon I, is more clay rich. At its top, there is a 20-meter thick sand bed characterized by an electrical resistivity of 4–7 Ohm. Below, a 30–40 m thick clay layer is distinguished, under which alternating sand-clay deposits with a thickness of about 100 m occur. This horizon is also eroded at the crest and in the uplifted parts of both flanks of the structure. The total thickness of the horizon according to the composite section is 107 m.

Horizon III is mainly encountered in wells on the southwestern limb and the southern pericline of the structure. The section begins with a sand bed characterized by an electrical resistivity of 3–7 Ohm. Further down the section, the number of clays interbeds gradually increases. This horizon is also eroded over a significant area, resulting in the transgressive deposition of Aghjagil deposits in its place within the near-crest zone, or their complete absence. The total thickness of Horizon III, according to the composite section, is 136 m.

Horizon IV consists of alternating sands, aleurites, and clays. Its upper part is sandier than its lower part. At the base of the horizon, a 20–25 m thick clay bed is present. The sand beds are characterized by an electrical resistivity of 4–7 Ohm. This horizon is also significantly eroded, leading to the transgressive deposition of Aghjagil deposits in the near-crest zone. The total thickness of Horizon IV, according to the composite section, is 152 m.

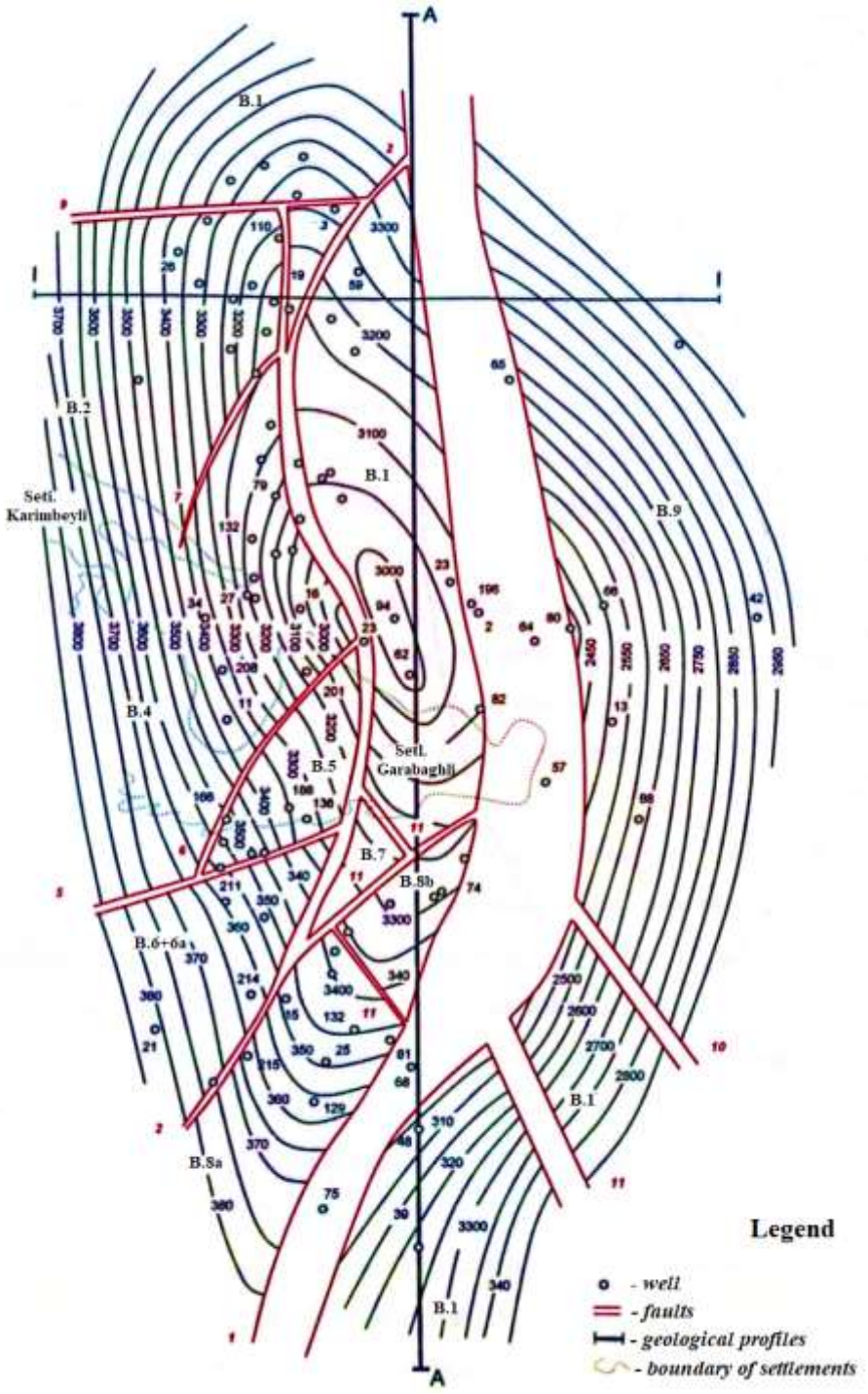


Fig.3: *Structural map of Garabaghli oil field based on the top of Horizon VI*

Horizon V is sandier than Horizon IV. At the top, it contains a 30–35 m thick sandy-clay bed. The middle part consists of alternating thin layers of sand and clay. The lower and middle sections are more clayey than the upper section. At the base, a 10–15 m thick clay layer is present, which is well-traced across the area. The sand layers are characterized by an electrical resistivity of 3–8 Ohm. Compared to the other (upper) horizons, this horizon is eroded over a small area, mainly within the crest of the structure. The total thickness of Horizon V, according to the composite section, is 206 m.

Horizon VI is sandier than Horizon V. The section begins with a 45–50 m thick sand bed, characterized by an electrical resistivity of 7–10 Ohm. In the middle part of the section, a 30–35 m

thick sand bed is separated from the overlying sandy layer by a 40 m thick clay interbed. The section terminates with a clay bed. The total thickness of Horizon VI, according to the composite section, is 206 m.

Horizon VII consists of alternating sand and individual clay layers, characterized by an electrical resistivity of 3–6 Ohm. The total thickness of the horizon, according to the composite section, is 126 m.

Horizons VIII–XI are represented by alternating sand and clay interbeds. The total thickness of individual horizons varies between 90–194 m.

Horizon XII begins with highly clayey formations. The middle part consists of a conglomeratic bed with a thickness of 80 m, while the lower part is composed of high clay layers. The total thickness of the horizon, according to the composite section, is 225 m.

Horizon XIII begins with a sand-clay bed with a thickness of approximately 90 m. The sand layers are characterized by an electrical resistivity of 4–6 Ohm, while the lower part of the section is represented by clays. The total thickness of the horizon, according to the composite section, is 220 m.

Horizon XIV consists mainly of clay layers. Near the top, individual thin sand layers are encountered. The total thickness of the horizon, according to the composite section, is 190 m.

Horizon XV begins with a conglomeratic bed with a thickness of 40 m, characterized by an electrical resistivity of up to 30 Ohm. The lower part of the section is composed of clays. The total thickness of the horizon, according to the composite section, is 185 m.

Oil and gas accumulations across all productive horizons of the PS are predominantly concentrated in the southwestern limb of the fold, with partial saturation in the southeastern pericline. The highest hydrocarbon saturation is observed in the southeastern section of this limb (Fig.4).

The stratigraphic sequence of the studied interval is characterized by alternating sandy and clayey layers of varying thickness. The lower portion is composed predominantly of clay content. Within the reservoir, clay material is distributed as isolated aggregates of clay particles, interspersed with subcapillaries. The presence of chemically bound water and radioactive elements in clay minerals significantly influences radiometric logging measurements. Specifically:

- The presence of chemically bound water leads to a discrepancy between neutron logging porosity (NL) and total porosity.

- An increase in clay content within the rock correlates with a systematic increase in its radioactivity.

As clay content increases, the effective porosity, permeability, and reservoir capacity of the rock decrease correspondingly.

Thus, the clay content of the formation is one of the key factors determining whether a rock can function as a commercial reservoir. However, the clay fraction also significantly affects the physical properties of the rock and the petrophysical relationships that form the basis for geophysical logging (GL) interpretation. This necessitates the widespread application of well-logging methods for determining the clay parameters of productive reservoirs, using correlation relationships between the responses of various geophysical techniques and clay content parameters.

Reservoirs differ from host rocks in terms of permeability, porosity, and clay content, which serve as the basis for their identification using geophysical methods.

As mentioned earlier, the effectiveness of Neutron Gamma Logging (NGL) is influenced by various geological and technological factors, with a small number of key factors having the most significant impact on the measurement results. These factors can be quantified and assessed. To address the task at hand, methods for determining the porosity of reservoirs using NGL data have been developed.

The essence of these methods lies in determining a more accurate value for the relative intensity of the layers by sequentially considering these factors. Among the geological factors, clay content (C_{cl}) was considered, as it governs the volume and structure of the pore space [6].

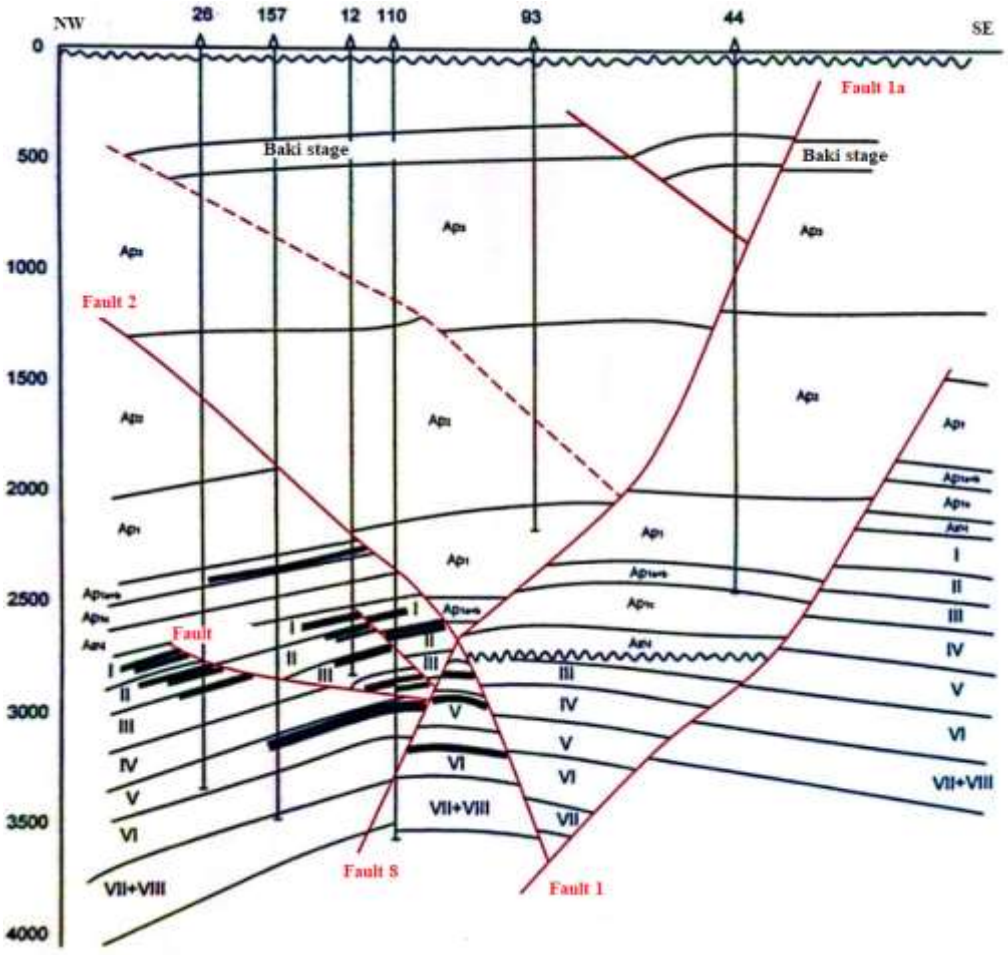


Fig.4: *Latitudinal geological profile by the line I-I*

Table 1: *Results of Porosity Calculations (K_p) Using NGL, LL, and Core Data (Garabaghli structure)*

Interval, m	H, m	GL C_{cl}, %	K_p, %			K_{sat}, %	Lithology
			NGL	EL	core		
2598-2604	6	19	19.6	16.8	17	0.39	Sandstone
2606-2613	7	18	18.3	17.0	18.1	0.36	Sandstone
2623-2628	5	22	17.1	13.9	14.9	0.5	Sandstone
2632-2636	4	23	18	15.9	17.7	0.54	Sandstone
2636-2641	5	23	20.8	22.8	21.3	0.42	Sandstone
2681-2688	7	24	22.7	24.8	21.8	0.30	Sandstone
2743-2748	5	22	21.5	19.9	21.1	0.34	Sandstone
2750-2756	3	26	22.1	24.8	20.7	0.25	Sandstone
2785-2796	11	25	22.9	23.8	21.2	0.22	Sandstone
2842-2847	5	29	18	14	17.1	0.30	Sandstone
2849-2855	6	25	19.6	17	18.2	0.23	Sandstone
2857-2864	7	31	17.4	16.1	18	0.36	Clayey sandstone
2867-2889	22	29	18,2	14.6	16.9	0.30	Sandstone
2922-2929	7	30	20.4	19.6	18.7	0.22	Sandstone
2931-2938	7	33	19.2	22.0	17.9	0.25	Sandstone
2940-2947	7	26	19.5	16.9	18.1	0.25	Clayey sandstone
2970–2976	6	30	19.2	21.7	20.2	0.22	Sandstone

Clay content (C_{cl}) was calculated separately using Gamma Logging (GL) diagrams (see table 1). The methodology involved two reference layers. The formal and physical similarity of the equations for the average relative intensity of NGL and Lateral Logging (LL) facilitates the correlation of data from these two methods.

The reference layers were used, which is one of the most widely used universal methods. The porosity evaluation was performed using linear interpolation based on the known K_p values of two layers (a dense and a highly porous one) of the same age, which eliminated the distorting effects of various wellbore and geological factors that are typically difficult to account for by other methods.

The calculated porosity coefficients, using the refined corrections, were compared with the data from LL (Lateral Logging) and core analysis.

As seen from the table, the K_p values determined using NGL (Neutron Gamma Logging) show good agreement with the core data and LL results, confirming the validity of the proposed approaches.

Conclusions

As a result of the work conducted, the following conclusions were established:

- Clay content is a fundamental characteristic parameter for determining the main petrophysical properties of reservoir formations. The relationship between the clay content coefficients determined from the core and those calculated from the gamma-ray data is strong, with an approximation reliability coefficient (R^2) of 0.87.
- Moderate clay content in the reservoir does not have a significant impact on the K_p value.
- Various ways to introduce corrections in NGL and Gamma-Ray Logging results were explored, and a corresponding algorithm was substantiated and implemented.
- The employed methodologies allow for confident and reliable determination of the porosity and clay content of reservoirs with a high degree of accuracy.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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VULNERABILITY ASSESSMENT FOR SUSTAINABLE DEVELOPMENT OF RURAL MOUNTAIN COMMUNITIES IN ZEMO RACHA, GEORGIA

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Abstract

Zemo Racha, a mountainous region in the historical and geographical heart of Georgia, is experiencing a severe demographic crisis caused by long-term declines in birth rates and widespread emigration. Between 1989 and 2024, the population of Oni Municipality fell by 58.7%. The situation is particularly severe in rural areas, where the average population age is 53.7 years. In 20 of the municipality's 64 villages, more than half of the population is aged 65 or over. Due to its proximity to the Russian border, Zemo Racha is strategically important for Georgia's security. Despite its natural potential for economic growth, including energy resources, biological resources and recreational opportunities, unfavourable geographical factors and shortages of relevant personnel hinder significant investment, especially in the tourism sector. The Georgian government's 2015 law, 'On the Socio-Economic and Cultural Development of High-Mountain Regions', has played a partial role in reducing out-migration. Despite these efforts, depopulation continues due to negative population movement indicators. This research project aims to investigate the opinions of the local population on the effectiveness of measures taken to combat depopulation, and to explore any spatial differences in these perspectives. Field surveys and interviews were conducted among local communities, a method that is less commonly used in geography. The study employed geographical selection of target zones to identify differences in population opinion within the research area. The study area was divided into clearly defined, relatively homogeneous geographical zones. This article presents an analysis of the survey results and examines the zonal characteristics of population viewpoints. This work was supported by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG) under grant number FR-23-13630 for the project titled "The Depopulation of Rural Settlements in Racha (the Northern Province of Georgia): Spatio-temporal Changes and Modern Problems".

Keywords: vulnerability assessment, mountain rural settlements, Zemo Racha, depopulation, local's opinion

I. Introduction

Racha is one of the fastest depopulating province of Georgia. It is located between the Greater Caucasus Range and its branches, therefore it is geographically remote from the country's central economic zone – Intermountain Plane.

The upper part of this region Zemo Racha is distinguished by particularly difficult conditions. A large part of the territory is mountainous and high-mountainous (1,000–4,000 meters above sea level). The amount of land suitable for cultivation is limited, and its fertility is relatively low. Mineral resources in the region are diverse, but reserves are limited, which makes extraction economically unprofitable. Unemployment is high, and incomes are low. The region is experiencing a long-term population decline.

In 2015, the Parliament of Georgia adopted the Law On the Development of Mountainous Regions, which provides certain material and social benefits for the local population. By the tenth year of the law's implementation, statistical data indicated a slowdown in the outmigration of the population from Zemo Racha. In any case, the population decrease is now caused not by emigration but by negative natural growth rates.

Despite some social progress, , the problem of retaining young people and attracting them back is far from being resolved due to limited economic opportunities. Apparently, overcoming the problem requires the planning and implementation of a special program to stimulate economic activity.

As global practice shows the effectiveness of state programs supporting high mountainous regions is strong when the study of problems, the planning, and implementation of activities are based on knowledge of regional and local specificities and on consideration of the interests of local communities. This approach inherently requires the active participation of local populations throughout all stages of the program, particularly in its initial phases. The main goal of the research conducted by the group of authors of this article was to study and spatially structure the specific features of Zemo Racha—its nature, demography, economy, and the interests of the local population and to represent them within a spatial framework.

To achieve this research goal (specifically, to study demographic problems, assess the effectiveness of the state program, and share the perspectives of the local population regarding the challenges), surveys of local residents were conducted in 23 out of 64 villages of the Oni Municipality in Zemo Racha. The survey covered all five geographical zones of the study area:

1.The settlement zone of the upper Rioni River Gorge;

2.The central zone along the Rioni River;

3. The settlement zone on the right slope of the Rioni Gorge;

4. The settlement zone on the left slope of the Rioni Gorge;

5. The high-mountainous zone of the Racha Range. A zonal analysis was conducted on the survey findings.

II. Demographic Background of the Study

In Zemo Racha (within the current boundaries of Oni Municipality), population decline began as early as the 19th century [8] and continued throughout the 20th century. As a result of well-known events in Georgia during the 1990s, the population of the municipality decreased drastically—by 25% (see Fig.1). The causes of this development were negative trends in natural population movement and large-scale emigration. This trend continued in the following years, and as a result of the emerging situation, Racha came to be classified among the "demographically dying" provinces [11].

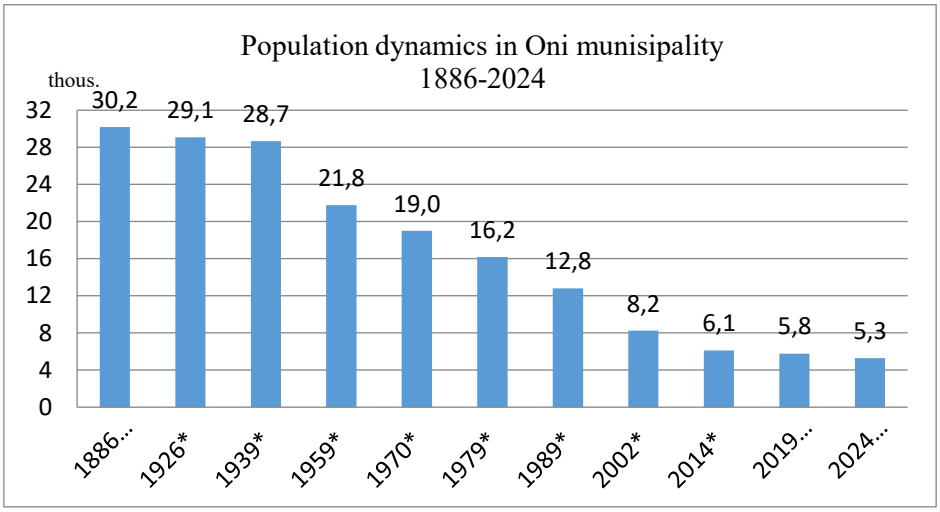


Figure 1: *Population Changes in the Zemo Racha*[1] *Source: * Census Data. National Statistics Office of Georgia. ** Current Registration Data. National Statistics Office of Georgia. *** Svod statisticheskikh dannykh o naselenii Zakavkazskogo kraia, izvlechennykh iz posemeinykh spiskov 1886 goda. Tiflis, 1893. P. 125 (in Russian).*[2]

According to the available data, birth rates in Oni Municipality have been falling steadily over time (see Table 1).

Table 1: *Natural Population Change in Zemo Racha*

Years	Crude birth rate (per 1000)	Crude death rate (per 1000)	Natural change (per 1000)
1950	22.0	10.0	12.0
1957	18.0	9.0	9.0
1970	16.8	12.5	4.3
1980	14.7	14.9	-0.2
1985	14.3	17.1	-2.8
1990	14.4	18.6	-4.2
1995	9.2	17.8	-8.6
2000	7.7	23.7	-16
2005	8.7	23.8	-15.1
2010	10.7	26	-15.3
2015	9.3	25.4	-16.1
2020	8.7	31.3	-22.6
2023	8.4	23.6	-15.2

Source: National Statistics Office of Georgia. ** Jaoshvili V. Proceedings of the Institute of Geography, 1961, p. 84; Lolashvili M. Problems of Demography and Sociology, Vol. 1. Lolashvili M. Demographic situation in Raha-Lechkhumi // Problems of demography and sociology. Collection of works. Vol. 1. Tbilisi, 2001. P. 202 (in Georgian).*

[1] *Zemo Racha (Oni Zone) did not constitute a separate administrative unit within the territorial-administrative division of the Russian Empire— Oni District encompassed the whole of Racha. In 1926, the Oni District was established, approximately within its current boundaries. Since 2005, the term "district" (raioni) has been replaced by municipality.*
[2] *** *Summary of Statistical Data on the Population of the Transcaucasian Region Extracted from the 1886 Household Lists. Tiflis, 1893, p. 125. (in russian)*

Recent data indicate that the crude birth rate in Oni Municipality has reached critically low level. In 2023, it stood at 8.4‰, which was 1.3 times lower than the national average. This figure was 1.8 times below the replacement level (15‰) required for simple population reproduction. The crude death rate was notably high. In the year under review, it stood at 23.6‰, which was two or more times higher than the level recorded in Georgia. The critical situation in the field of mortality is mainly explained by the high level of demographic aging of the population. The negative trends in both birth and death rates have directly affected natural population growth, which has been negative since the 1980s (see Table 1).

Between the 1989 and 2014 censuses, the rural population in all elevation zones of Oni Municipality declined significantly (Fig.2).

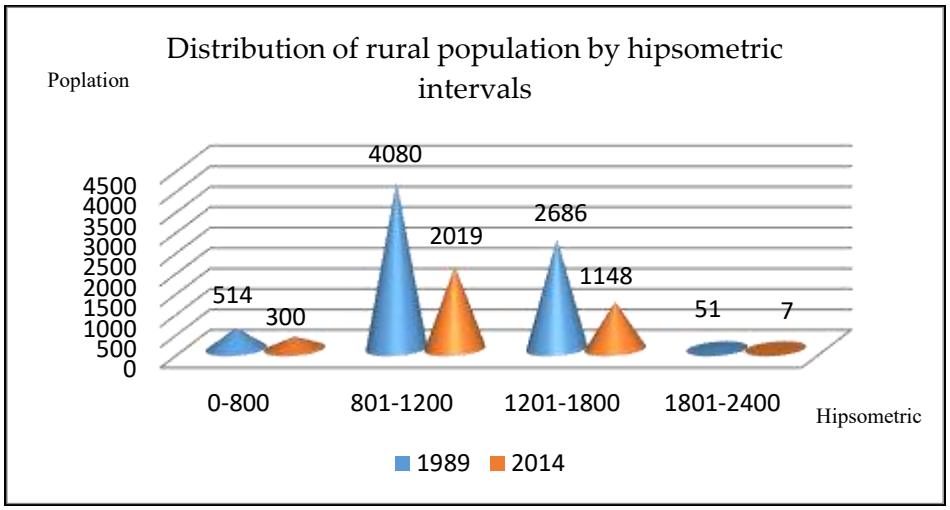


Figure 2: *Distribution of the Population of Oni's Villages by Hypsometric Levels; Source: National Statistics Office of Georgia.*

According to the 2014 census data, there are no longer any medium-sized villages—defined as those with populations between 201 and 500 inhabitants—within the boundaries of Oni Municipality. Four villages were recorded as uninhabited, while the number of very small villages—defined as those with 1 to 50 inhabitants—rose to 40, representing an increase of 17 compared to 1989 (Table 2).

Table 2: *Classification of Rural Settlements by Population Size*

	Grouping of rural settlements by population number					
	0	1-50	51-100	101-200	201-500	501-1000
1989	1	23	22	8	8	2
2014	4	40	12	4	4	0

According to our analysis, in 20 of the 64 villages within Oni Municipality, individuals aged 65 and older constitute more than half of the population. Based on the 2014 census data, the average age across the municipality was 49.5 years—44.0 years in the town of Oni and 53.7 years in rural settlements. Compared to 1989 figures, these averages reflect increases of 6.4, 8.4, and 5.1 years, respectively.

The primary driver of village depopulation in Zemo Racha is prolonged emigration. Unfortunately, since the 1990s, the National Statistics Office of Georgia (GeoStat) has not published internal migration data at the municipal level, limiting detailed analysis of migration patterns within the region. Our indirectly calculated migration balance shows that emigration was

particularly high during the period from 1994 to 2000. In that timeframe alone, the population decreased by 5,600 solely due to migration. From 2001 to 2013, the migration balance remained consistently negative.

Since the 2014 population census, a certain stabilization has been observed in migration processes. This was partly influenced by the enactment of the Law On the Development of Mountainous Regions". All settlements in Oni Municipality have been granted the status of a mountainous settlement, which provides residents with certain social benefits.[3]

Despite certain positive signs, most notably the slowdown of emigration, the depopulation process has not yet been halted due to persistently low birth rates.

III. General Regional Factors of Depopulation in Zemo Racha

The analysis of the demographic situation revealed that the continuous decline of Zemo Racha's population was primarily caused by a prolonged trend of labor emigration among local residents. The main factor behind this was the urbanization process that developed in the country, which became evident in Georgia starting from the 1870s—following reforms implemented in the Russian Empire—and has continued at varying rates up to the present day.

Among the factors hindering population retention in the study area, the following are notable:

- The region's peripheral location. It is situated at the northern edge of the country, surrounded by the high ridges of the Caucasus mountain system, and is somewhat isolated from both the country's internal and external economic centers.

- The harsh natural conditions of Zemo Racha. Winters are heavy with snowfall, and periodic destructive natural disasters (earthquakes, floods, landslides, mudslides) cause significant damage, while the environmental safety system does not function effectively. A tragic example of the impact of natural hazards is the Shovi resort disaster. In August 2023, a tragedy occurred at the Shovi resort, where a landslide resulted in the loss of more than 30 lives and rendered the area unsuitable for future recreational and tourism activities. This event caused a significant decrease in the number of tourists visiting Racha. Despite this setback, research indicates that local residents remain optimistic about the municipality's tourism development. This optimism is reflected in the opening of numerous new guesthouses [3].

- Natural resources are scarce—the economic reserves of minerals (barite, chalcedony, and others) are largely depleted; favorable flat surfaces for cultivation are limited due to fragmented terrain; the soil is not particularly fertile; pastures are mostly privatized (no longer considered public property); during heavy snowfall winters, villages scattered across mountain valleys and ravines are practically isolated.

- After the collapse of the planned "national economy," the new market economy functions only sporadically, mainly in the form of small and medium-sized businesses. These include the collection of conifer cones, the establishment in recent years of Georgian-Swiss livestock farms and pork production facilities in several villages—specifically in Sori, Ghari, Shkmeri, and Glola. The renovation of former resorts, such as Shovi and Utsera, faces significant challenges.

- The stabilization of the birth rate is hindered by the low number of women of reproductive age. The economy faces an acute shortage of young, energetic, educated, competent, and creative labor force, as well as a lack of service technologies and professional experience. In addition, there is a significant deficit of both public and private investment.

However, Zemo Racha also possesses economic resources that can support development, among which the following are noteworthy:

Significant tourism and recreational potential: appealing and healthy (healing) nature: high mountains, glaciers, mountainous rivers, temperate broadleaf, as well as coniferous forests, mineral

[3] The law has been in effect since January 1, 2016.

waters with therapeutic effect, fresh air, favourable climate, proper steepness of mountain slopes for winter tourism, yet underexplored karst massifs on the Racha Range with diverse features (caves, ice caves, subterranean rivers, vaucluses, travertines). The hospitable local population, cultural traditions, seasonal crowdedness in summer periods, which is mainly due to the previously migrated population.[3]

Zemo Racha has significant hydro power resources to support the local economy; however, due to vulnerable local ecosystems, their utilisation should be moderate, primarily focused on constructing small and medium hydro power plants, based on efficient ecological assessment.

On a national level, several social programmes have been elaborated.[4] Among these, the Law of Georgia "On Development of High Mountainous Regions" is the most prominent and has had a certain positive social impact; However, there is no visible economic impact, without which this province cannot attract young people and investors. As a consequence, there is a need for a targeted state strategy to support entrepreneurial development, including various types of tourism, such as leisure tourism, wellness tourism, rural, agri, and adventure tourism, as well as agricultural activities (animal husbandry, viticulture, and winemaking).

These are the general regional-level factors of the critical depopulation in Zemo Racha.

IV. The Results of the Survey

To determine how the current socio-economic conditions and their regulatory state policy and mechanisms are reflected in the population's status, migratory attitudes, and how state support programs correlate with the interests of the population, a field study was conducted in August of 2024 to survey the opinion of the population of Zemo Racha. The villages of this province that are prone to depopulation were selected as the main geographical study area. The population of the only city (Oni) in the province also took part in the survey. The representatives of the local administration, the local youth, and local actors engaged in tourism-related services were surveyed separately.

In addition to the survey, the in-depth interviews and Key Informant Interviews (KII) were also conducted.

In total, 23 out of total 64 villages in Oni Municipality were selected for the survey, covering five distinct geographical zones in Zemo Racha, in particular: 1. The settlements of the upper Rioni river gorge; 2. The settlements in the central zone along the Rioni River; 3. The settlements on the right slope of the Rioni Gorge; 4. The settlements on the left slope of the Rioni Gorge; 5. High-mountainous settlements of the Racha Range.

In total, 82 rural residents were surveyed, including permanent (67.1%) and seasonal (32.9%) dwellers, the latter meaning the temporary stayers in Racha during the summer period. The temporary stayers were primarily people who had previously migrated from Racha. The target villages were selected in such a manner as to ensure equal representation from all five geographic zones.

The respondents are relatively sparsely distributed. Most respondents were surveyed in the village of Ghebi (10 respondents) – the largest among the Upper Rioni gorge settlements. Nine respondents were surveyed in the village of Shkmeri, while one respondent per village was surveyed in the villages of Zemo Gona, Kharistvali, Mravaldzali and Khideshlebi. Due to outmigration, these villages experience the most significant population decline.

Women (51.2%) outnumber men (48.8%) among the surveyed respondents, which is somewhat similar to the gender distribution in the total population.

[4] *In particular: The Law of Georgia "On Development of High Mountainous Regions", "The 2023-2026 Oni Municipality Priority Document", "The 2024-2028 Oni Municipality Local Development Strategy", The survey of the needs, challenges, interest and resources of the youth".*

The age distribution of the surveyed rural dwellers is as follows: 30- to 45-year-olds represent 24.4% of the respondents, 46- to 65-year-olds – 45.1%, while adults aged 65 and over – 30.5%.

The majority (48.8%) of the surveyed respondents have a higher education degree, which is quite a substantial share. However, this is primarily driven by the seasonal residents. Among the other respondents, 19.5% had technical/vocational education, 24.4% had secondary education, 2.4% had incomplete higher education, 1.2% had incomplete secondary education, and 3.7% had basic education.

The agriculture sector (horticulture and animal husbandry) was the primary source of income for 47% of the surveyed respondents, followed by 17.6% of the respondents reporting work in the public sector, 13.7% - education, and 7.8% - tourism. For one respondent, an additional source of income was a small private enterprise in operation, while for another respondent, the author's honorarium.

The majority of respondents (52.6%) derive their additional income from the state pension, followed by supplementary state support, as per the law "On Development of High Mountainous Regions" – 35.1%, and tourism and hospitality industry – 12.3%.

It is worth noting that the majority of respondents (43.4%) fell into the highest income category on our scale, i.e., over 1000 GEL per month (equivalent to approximately 370 USD), while only 5.3% fell into the low-income category that is less than 300 GEL per month (approximately 110 USD). Considering that the social security and pension combined amount to approximately 400-500 GEL[5], we can assume that this category includes the unemployed or those without other basic income. It is worth noting that, based on the Geostat data, in total, 1769 households are registered for state-provided social security, while 903 households receive financial payments in Zemo Racha (Oni Municipality) (Geostat, 2024).

Concerning the respondents' positions on population decline in Zemo Racha and the experiences of their families in this process, the analysis has revealed that:

- Among all surveyed households, 117 household members have left their permanent place of residence, including 12 household members who have migrated internationally. Among the main countries of destination were Germany, France, Italy, Greece and Russia. The other migrated family members have settled in different regions of Georgia. In 22 cases, the migrated household members live in the same dwelling, while in the other 9 cases, they live separately.
- The vast majority of the surveyed (89.7%) do not have a desire to move to another Georgian region or abroad. Among those considering leaving their permanent places of residence, 8.8% of all surveyed would have moved to Georgia's capital, Tbilisi, and 4.4% would have chosen to live abroad.
- The main motivation for family members to leave Zemo Racha was "work search" according to more than half of the surveyed (52.1%), another 18.9% mentioned "improving living conditions", 17.9% mentioned educational reasons, 7.1% - treatment/medical care, 4.3% - family reunification and 1.7% - other reasons.
- It is also interesting to consider the respondents' views on the reasons for high migration from Racha in general. The majority of respondents identify the acute lack of employment opportunities as the main cause of population outflow (91.5%), followed by unfavorable natural conditions and limited resources (such as harsh winters, fragmented terrain, low soil fertility, etc.) – 72.0%, lack of healthcare and educational resources – 65.8%, the remoteness (isolation) of Zemo Racha from the country's main economic, cultural, and educational centers – 35.4%, and the poor condition of the internal road network – 30.5%. Seeking employment remains the primary motive for outmigration from Zemo Racha, which is understandable considering the dramatic economic decline over the past three decades.

[5] *The state pension in the high mountainous Oni Municipality is 400 GEL for the pensioners under 70 years of age and 540 GEL for people aged 70 and over.*

- A total of 98.8% of respondents believe that their material conditions need improvement. Nearly half of them (48.8%) assess their income as "unsatisfactory," while 42.7% consider it "satisfactory." Only 7.3% are satisfied with their income: 1.2% rate it as "very good," and 6.1% as "good."

Respondents' attitudes toward the state's social and economic programs are mixed. Most respondents view positively the support provided to villages in mountainous regions through the benefits granted under the "Mountain Law" (such as pension supplements, salary increases for teachers and medical personnel, etc.). However, 41.5% consider this support insufficient. According to them, greater assistance is needed from state institutions.

A large portion of respondents sees a major flaw in social programs: they believe that social assistance "kills the incentive to work," "destroys agriculture," and "makes peasants and farmers lazy," since cultivating arable land, pastures, and hayfields is associated with many challenges and high costs. As a result, agricultural lands are no longer used and have become overgrown. This attitude was also revealed during in-depth interviews.

Spatial Differences

The criterion for distinguishing the geographical zones of rural settlement in Zemo Racha is the general accessibility to income-generating resources. This includes factors such as: availability of natural resources and environmental conditions; economic-geographical location; conditions for private business development; presence of industrial companies and farms offering employment opportunities; proximity to public-sector organizations for employment; and availability of alternative income sources. The zoning in this study was done based on the geographical distribution of these factors.

Moreover, since complete data on the mentioned economic factors (statistics, registries, reports, etc.) are not always available, the study did not prioritize individual factors but rather selected characteristic combinations of them.

The Settlement Zone of the Upper Rioni River Gorge

This zone comprises the upper part of the Rioni River gorge, stretching in a northwest-southeast direction, and includes the villages situated on the southern slope of the main Caucasus watershed ridge: Ghebi, Chiora, Gona, Glola, and Shovi. These are the surveyed villages. The area is located at elevations ranging from 1250 to 1700 meters above sea level. This zone is relatively distant from the province's economic and administrative centers, Oni and Ambrolauri.

The population is traditionally engaged in peasant, subsistence, mostly natural (non-commercial) agriculture, with a focus on dairy and meat livestock farming, mixed crop and vegetable farming (corn and beans), and tourism (the resort of Shovi and the villages of Glola and Ghebi). The most profitable activity is considered to be the collection of conifer cones. In this zone, a small hydropower plant — "Chiorahesi" with a capacity of 15.85 MW — operates on the river Chveshura, though it does not serve as a significant source of employment.

Among the surveyed villages, the largest is Ghebi (296 residents)[6], followed by Glola (279), Patara Ghebi (128), and Chiora (116). The village of Gona is practically empty - 1 family (in 2025), it is a small resort with a seasonal population, which, as a result of the natural disaster of 2023, is currently not functioning.

The Central Zone Along the Rioni River

The central settlement zone extends along the Rioni River and the adjacent main road, located on the river's first and second terraces. The elevation ranges between 900 and 1100 meters above sea

[6] *The population size is based on the 2014 census. The results of the 2024 census are not yet available.*

level. The main activity here is traditional (peasant, mainly subsistence) agriculture — livestock farming, corn and bean cultivation, and to a lesser extent, fruit and viticulture. There is relatively high potential for therapeutic and wellness tourism, especially the resort of Utsera, its surroundings, and the slopes of Mount Shoda (with potential of winter tourism).

Due to their proximity to the municipal administrative center, the city of Oni, residents of villages in this zone have the opportunity to work in urban sectors — in trade, construction, and public sector organizations (administration, education, healthcare, etc.).

There are plans to build a large hydropower cascade on the Rioni River in this zone, with a total capacity of 206.1 MW. However, this project is disconnected from the local economy and will not serve as a significant source of employment.

The surveyed villages in this zone were: Utsera (260 residents), Zudali (32), Ghari (349), and Kvemo Bari (50 residents).

The Settlement Zone on the Right Slope of the Rioni Gorge

This third zone includes settlements located on the right slope of the narrow Rioni River gorge (Shoda Ridge), mainly in the gorge of the Sakaura River. Elevation ranges from 1100 to 1450 meters above sea level. The terrain is highly dissected with minimal flat areas. The slopes are predominantly southeast-facing.

The area is rich in natural resources, including forests, mineral waters, hydro-energy, and tourism-recreational potential. Residents' economic activity is limited to agriculture: livestock farming (mainly cattle) and crop production — corn and beans.

In this zone, a small hydroelectric power station— "Sakaurahesi" with a capacity of 4.75 MW — is in operation. The survey in this zone covered the villages of Sakao (77 residents), Khideshlebi (29), and Mazhieti (24).

The Settlement Zone on the Left Slope of the Rioni Gorge

This zone includes villages located on the left slopes of the Rioni River. Unlike the right slope, the terrain here offers relatively better conditions for agricultural production, which is why the number of rural inhabitants is higher. The elevation ranges from 950 to 1200 meters above sea level. Natural resources include forests and water. Residents' economic activity is limited to agriculture: livestock farming (mainly cattle), crop cultivation (corn and beans), and to some extent, viticulture and fruit growing. The survey in this zone included the villages of: Bokva, Zemo Bari, Kvashkheti, Gunda, Kvedi, Kvedrula, and Pipileti.

The High-Mountainous Zone of the Racha Range

This zone comprises rural settlements located on the high slopes and plateaus of the so-called "Maghran-Dvaleti Caucasus," Kedela Range (eastern part of Shoda-Kedela), and the Racha Ridge. The elevation ranges from 1200 to 1900 meters above sea level. In the past, the economy of this zone was primarily connected with the extraction and initial processing of mineral resources (barite in the village of Iri). Manganese deposits have been surveyed in the area surrounding Shkmeri.

A distinct advantage of this zone is Its better located transport links: a main road passes through here, connecting eastern Georgia to Zemo Racha via mountain passes. In the past, before the occupation of northern Shida Kartli by Russia, this road entered via the village of Iri. Currently, it enters through a newly built road passing via the village of Shkmeri.

Today, residents' economic activities are limited to dairy and meat livestock farming (mainly cattle), and partially to crop cultivation — corn, beans, and potatoes. The survey in this zone included the villages of: Mravaldzali (7 residents), Shkmeri (23), Iri (43), Tsedisi (53), and Kharistvali (14).

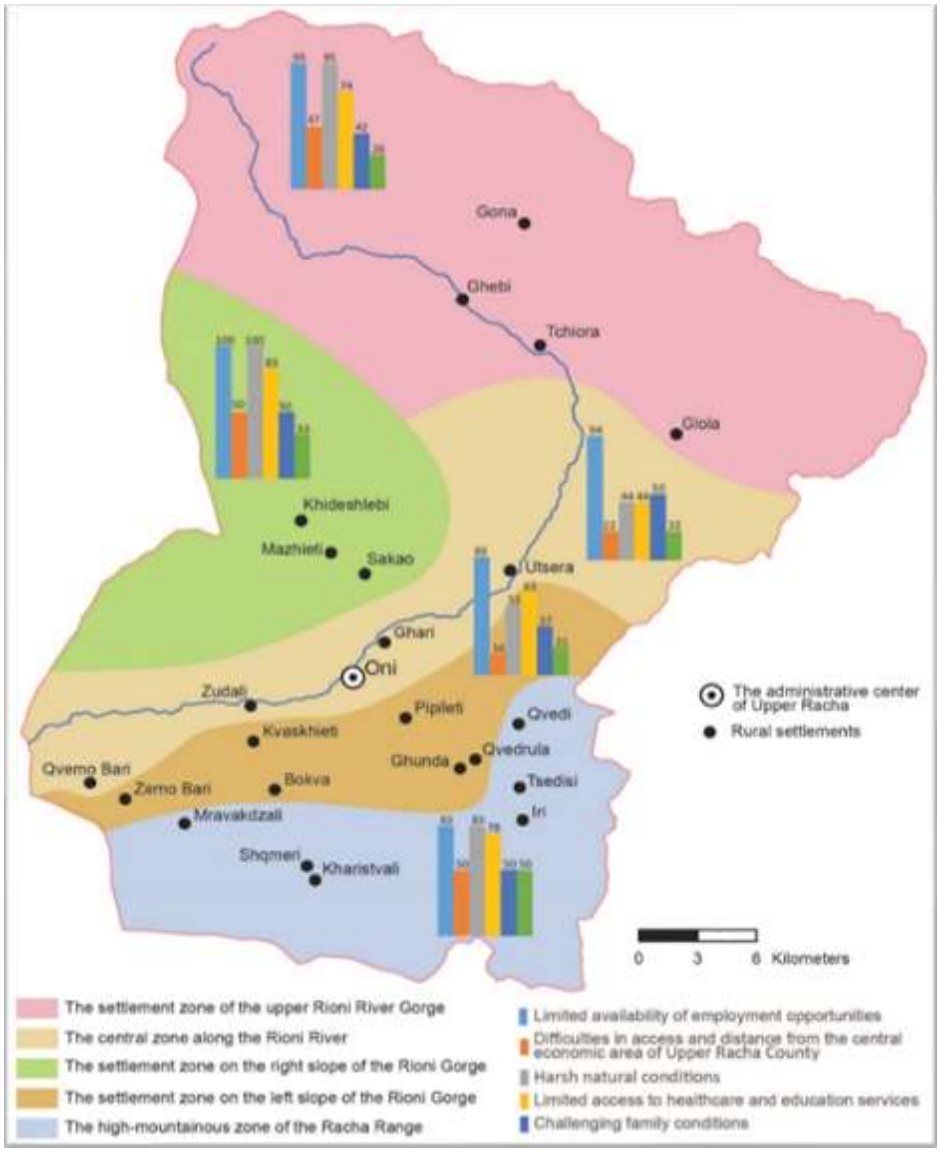


Figure 3: *Distribution of Rural Residents' Perspectives on Migration Causes by Geographical Zone*

In all respondent groups, the most significant reasons for migration were identified as "lack of employment opportunities" and "harsh natural conditions" (the latter being considered somewhat less significant by respondents from the second (central) and fourth (left slope) zones).

Unemployment is a critical issue, as only a small portion of the remaining population in Zemo Racha is employed. For example, according to the official statistics of Oni Municipality for 2023, only 828 individuals are employed in the business sector, which represents just 15.3% of the municipality's total population. The importance of employment has grown particularly since the 1990s, when the traditional rural economy based on agrarian household production collapsed, and opportunities for employment in agriculture (kolkhozes, sovkhozes) and state-owned mining enterprises disappeared.

As for the harsh natural conditions of Zemo Racha, they manifest in heavy snowfall during winter, a lack of flat land suitable for farming, and frequent, destructive natural disasters. This factor

is especially significant in Zone 1 – the upper, high-mountain section of the Rioni Gorge, Zone 3 – the right bank, which is relatively steep, and Zone 5 – the highland plateaus and basin settlements.

Geographic location (distance from Georgia's central regions) is a major factor for villages in Zones 1, 3, and 5, which are relatively remote from Zemo Racha's only main road.

Social factors (such as limited access to healthcare, education, and social services) are considered less significant in the central (second) zone. This is explained by the proximity of villages in this zone to Oni – the administrative center of Zemo Racha, where such services are concentrated.

V. Conclusion

Data from the period since 2014 shows that emigration has significantly decreased. Currently, population decline is occurring not due to outmigration of local residents, but rather due to a sharp drop in birth rates. This phenomenon can be explained by the specific effects of the "Mountain Law." In particular, the social benefits and professional bonuses defined by this law do not necessarily contribute to the overall retention of the local working-age population (migration tendencies still persist among them) or to attracting young people, but rather to the settlement of pensioners and people employed in public sector professions. This, in turn, alters the age structure of the region's population and contributes to demographic "aging".

The crisis in the villages of Zemo Racha over recent decades has been exacerbated by the decline of traditional peasant farming and the agro-industrial complex.

There may be prospects for the villages of Zemo Racha through the purposeful development of the region's recreational potential. Locals consider tourism to be the main pillar of the economy in the future. Despite the Shovi tragedy, the sector is gaining momentum, with accommodation and food facilities being constructed.

The survey revealed that the rural community cannot influence local government decisions. The community is politically, economically and socially inertial - it is guided by the old relationships, which is generally characteristic of post-Soviet societies. Families remaining in these villages tend to adapt to limited living conditions. At the same time, the research showed that the local community has developed its own views on the problems of Zemo Racha, which sometimes differ from official narratives, and its members are aware of their own interests.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ECOTOXICOLOGICAL CHARACTERISTICS OF SOME THERMAL WATERS OF THE GURIA REGION, SURROUNDING HABITATS AND POTENTIAL POLLUTION RISKS

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Abstract

This study aimed to conduct a comprehensive assessment of the ecotoxicological indicators of the thermal waters in the Khajalia and Dzimiti areas of the Guria region (Lanchkhuti and Ozurgeti), as well as the cenotic features of the surrounding landscapes. The organoleptic, physicochemical and bacteriological properties of the waters were evaluated in situ, and their ionic and elemental compositions were analysed in a laboratory setting. The results revealed that the pH of Dzimiti water is weakly alkaline, it is highly saline, and it has a mineral-thermal profile. In contrast, Khajalia water is non-mineral and exhibits an alkaline average response. High concentrations of NH_4^+ and NO_2^- ions in both waters indicate ecological vulnerability due to the absence of sanitary protection zones. Boron concentration above the permissible limit was detected in Dzimiti water, while methane dominated the accompanying gases (>50%). Bacteriological indicators suggest a potential risk of contamination. Meanwhile, coenotypes were identified and their species and structural features described. A map was created using GIS to illustrate the coenotic structure of the landscapes surrounding the thermal waters.

Keywords: thermal waters, cenotopic structure, field measurements, chemical and elemental composition, associated gases

I. Introduction

Thermal waters are an essential natural resource with energy, medicinal, and ecological importance. Studying their physicochemical and biological properties is important both scientifically and practically, since the use of thermal waters relates to health, tourism, energy security, and environmental concerns. Currently, special emphasis is placed on ecotoxicological studies, which aim to analyze the chemical, microbiological, and ecological parameters of thermal waters to assess their sustainable use and environmental impact. Over 700 thermal water deposits for balneological and industrial use have been identified in Georgia; however, only a few of them have been thoroughly studied and practically utilized. Experts report that over 250 natural and artificially drilled springs are known today, with water temperatures ranging from 30°C to 109°C, and the total debit is approximately 160,000 m³ per day and night. Most are located in western Georgia [4,5]. The country's thermal waters stand out for their diversity: they include both low- and high-mineralized types, each suited to different needs. In Georgia, thermal waters are viewed as an inexpensive and nearly limitless energy source. Most of them are characterized by medicinal properties, high temperature, relatively low mineralization, and high content of chemical

elements. From a commercial and ecological perspective, thermal waters are regarded as one of the most accessible, environmentally safe, and stable energy resources, which plays an essential role in the fight against climate change [2,3,6].

The Guria region covers the southern peripheral part of the Kolkheti Plain and the northwestern branches of the Meskheti Range. Its area is 2,042 km², constituting 2.9% of the country's territory. Administratively, the region includes the municipalities of Ozurgeti, Lanchkhuti, and Chokhatauri. Guria is abundant in surface water resources, featuring many small lakes and about 25 medium to small mountain rivers. Forest ecosystems cover 48% of the territory. The climate is subtropical and is characterized by altitudinal zonation [10].

Guria is rich in mineral and thermal waters, known for their healthful properties, although many are currently neglected and need infrastructure improvements and cleaning. The full potential of these waters remains untapped for drinking, medicinal, and industrial uses. Along the banks of the Supsa River, in lowland and hilly areas, as well as in forest groves, there are several springs containing hydrogen sulfide suitable for both bathing and drinking [1].

The actuality of the work lies in the fact that the Guria region has substantial thermal water resources, most of which are minimally or not at all utilized. A significant problem is that a comprehensive study of the ecotoxicological indicators of groundwater has not been carried out in the region, considering their ecological assessment and pollution risks. This is a necessary prerequisite for evaluating the potential of water resources and ensuring their rational and effective use.

Based on this, the study aimed to perform a comprehensive ecotoxicological assessment of certain thermal waters in the Guria region, evaluate their potential, and identify promising directions for their usage. Two locations were chosen as research targets: Khajalia thermal water in Lanchkhuti municipality and Dzimiti thermal water in Ozurgeti municipality, along with the cenotic structure of their surrounding landscapes. There has been no comprehensive assessment of ecotoxicological indicators for these waters so far, which highlights the significance and accuracy of the presented study.

II. Research materials and methodology

The prerequisite for conducting the research was processing literary sources and searching for scarce theoretical materials on geothermal waters. During the information review, it was found that a comprehensive study of the organoleptic, physicochemical, and microbiological indicators, elemental composition, assessment of the sanitary-microbiological state at the current stage, determination of the content of associated gases in the waters, evaluation of the water use prospects, and consideration of pollution risks have not been performed on the Khajalia and Dzimiti study waters.

To conduct a comprehensive study, field scientific expeditions were planned in the Lanchkhuti and Ozurgeti municipalities of the Guria region. These included a reconnaissance study of the surrounding areas to gather background information on vegetation [23,25]. Field measurements were taken on the Khajalia and Dzimi thermal waters, and samples were collected for further analysis [8]. Additionally, the organoleptic characteristics of the waters were also evaluated [17], along with the measurement of several parameters: temperature, air pressure, pH, electrical conductivity, and salinity [7].

The main analyses were performed at the laboratories of Analytical Chemistry and Plasma Atomic Emission Spectrometry at Batumi Shota Rustaveli State University. Methods widely accepted in hydrochemical practice were used for analysis: active acidity (pH) was measured with a portable device - Cloud Prime Portable pH Test Meter with 0.01 precision - pH-009(I)A [16]; mercurimetric and acidimetric methods were used for the determination of chloride and hydrocarbonate ions [18, 19]. The calcium and magnesium content, along with the total water

hardness in samples, was measured using the complexometric method [12]. The concentration of fluorides and hydrogen sulfide, as well as biogenic (diluting) compounds (NH4+, NO3-, NO2-, PO43-, SO42- ions), were determined using photometric methods on an ultraviolet spectrometer [13, 20, 11]; the concentration of macro- and microelements was measured by plasma atomic emission spectrometry ICPE-9820 [24].

Sanitary and bacteriological analysis of water measured the number of saprophytic microorganisms and lactose-positive Escherichia coli bacteria using the titration method [21]. The hydrocarbon content in thermal waters was determined using gas chromatography; the analysis was performed on a Thermo Focus GC gas chromatograph (with an aluminum ionization detector, Column DH-100, 0.25mm, 0.25μm, 0.5 μm). The stationary phase was methylsiloxane, and the chromatography was conducted in pressure mode at 345 kPa. The mobile phase was helium, and the injector temperature was 250°C [9]. Determination of gases accompanying water was carried out in field conditions using a Portable 6-in-1 Gas Detector [14]. Temperature, electrical conductivity, and salinity were measured in the field with a HI 98194 pH/EC/DO Multiparameter device [22]. Mapping of locations was performed using geographic information systems (GIS**)** [15].

III. Results and Discussion

Structural Features of Cenotypes of Landscapes Surrounding the Study Sites. The aim of the study conducted in the Ozurgeti and Chokhatauri Municipalities of the Guria Region is to assess the ecological conditions of the landscapes surrounding the study sites, including the analysis of structural features of vegetation, cenotypes, anthropogenic impacts, and conservation needs.

The landscapes around the thermal springs of Khajalia village (Lanchkhuti Municipality) are dominated by human agricultural activities, including farming plots, vegetable gardens, and small settlements. These activities influence the structure of the vegetation layer, grass coverage, and soil stability (Fig. 1).

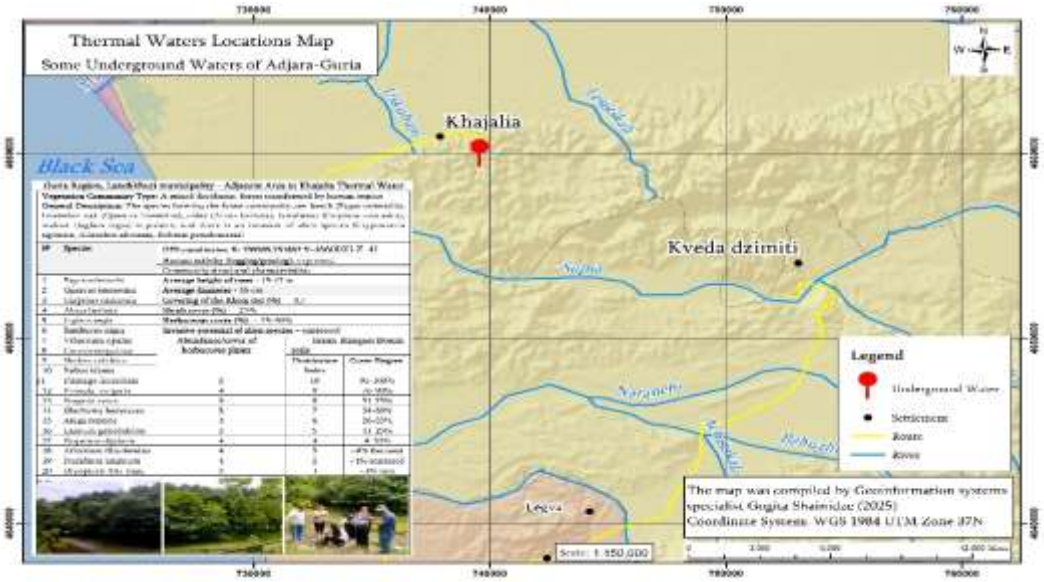


Figure 1: *Guria, Lanchkhuti Municipality, area near Khajalia thermal water.*

Local biodiversity is maintained, although there is a decrease in native species due to the impact of invasive plants and human activities. Presented cenotype: Mixed polydominant forest transformed by human impact - represents a plant community dominated by several tree species (Fagus orientalis, Quercus imeretina, Carpinus caucasica, Alnus barbata, Juglans regia), shrub

species (Sambucus nigra, Viburnum opulus, Cornus sanguinea, Hedera colchica, Rubus idaeus), and herbaceous species (Plantago major, Primula magaseifolia, Paspalum digitaria, Athyrium filix-femina, Pteridium tauricum). Despite minor cutting and grazing, the structure of the cenotype is somewhat modified, especially regarding the tiers and sections of the herbaceous layer.

Secondary meadow communities around the Dzimiti thermal water in Ozurgeti municipality have developed due to intensive human activity (such as farming, grazing, and road development. They represent a modified natural grasslands). The meadow ecosystems are primarily made up of Cultural-agrarian and synanthropic vegetation (including Lolium perenne, Festuca pratensis, Dactylis glomerata, Trifolium repens, and Medicago sativa). The community (phytocoenosis) includes native species with moderate coverage (Plantago lanceolata, Achillea millefolium, Taraxacum officinale). The herbaceous cover ranges from 60% to 80%. The dominant species are Lolium perenne, Trifolium repens, and Dactylis glomerata. No layer differentiation is observed. Intense invasive pressure is observed, with Solidago canadensis and Ambrosia artemisiifolia actively spreading, occupying vacant niches, and reducing the distribution of native species (Table 2).



Figure 2: *Guria region, Ozurgeti municipality, area surrounding Dzimiti thermal water.*

Ecological-conservation features are manifested in: high anthropogenic transformation (roads, agrocenoses, grazing); spread of invasive species (remains one of the main threats); tendency to reduce biodiversity (degradation of local vegetation cover). The tendency to reduce biodiversity is manifested in the degradation of local vegetation cover.

Field measurements. As a result of field measurements at the study locations, it was found that the waters of Khajalia and Dzimi are transparent, colorless, and have a distinct hydrogen sulfide odor. The water in Dzimiti is highly brackish, and gas bubbles are actively observed on the water surface at both locations (Table 1).

Table 1: *Organoleptic features of Guria thermal waters*

Indicator	Location	Characteristic
Colour	Khajalia	Colorless liquid
	Dzimiti	Colorless liquid
Smell	Khajalia	Specific, pungent odor characteristic of isooctane, faint odor characteristic of hydrogen sulfide
	Dzimiti	Weakly pronounced odor characteristic of

		hydrogen sulfide
Taste	Khajalia	Weakly pronounced taste characteristic of hydrogen sulfide
	Dzimiti	Strong salty taste
Appearance	Khajalia	Gas bubbles are actively observed on the surface.
	Dzimiti	Gas bubbles are actively observed on the surface.
Transparency	Khajalia	Transparency
	Dzimiti	Transparency

The water at Dzimiti is warm (26.40°C), while at Khajalia it is cool (17.0°C). Khajalia's thermal water is moderately alkaline (pH 8.5), whereas Dzimiti's is weakly alkaline (pH 7.92). Based on electrical conductivity, Dzimiti's salinity is high, measuring 1290 mg/l (Table 2).

Table 2: *Assessment of physicochemical characteristics of Guria thermal waters in field conditions*

Location	**Physical and chemical parameters**				
	Temperature, °C	**Air pressure, mbar**	**pH**	**Electrical conductivity µS/Sm**	**Salinity, mg/L**
Khajalia	17.0 (cool)	1021.5	8.5 Medium alkali	715	356
Dzimiti	26.40 (warm)	1019	7.92 Weak alkali	25910	12990

The gases accompanying thermal waters are mainly methane, with a concentration exceeding 50% (by volume) at both locations. The CO2 content ranges from 136% to 143%, and the waters do not contain CO. The oxygen concentration in the gases accompanying Khajalia water is 1.78 times higher, and the hydrogen concentration is 2.5 times higher compared to similar measurements in Dzimiti water. A specific component in both waters is hydrogen sulfide, but this parameter is much higher in the gases accompanying Dzimiti water compared to Khajalia water.

Table 3: *Gas concentrations in Guria thermal waters under field conditions*

Location	**Concentration of gases accompanying water, mg/l**					
	O_2 Vol %	**CO_2 mg/L**	**CH_4 Vol %**	**H_2 mg/L**	**CO mg/L**	**H_2S mg/L**
Khajalia	3.20	143	>50	7.0	–	0.3
Dzimiti	1.8	136	>50	2.8	–	3.1

Ionic, multielemental, and bacteriological analysis of waters. Dzimiti thermal water is very hard (49.0 mEq/L), with a high concentration of Ca^{2+} (1080 mg/L) and HCO_3^- ions (445.3 mg/L). Khajalia water is not hard (see Table 4). The Cl^- ion concentration in Dzimiti water is 2.18 times higher, making it significantly more saline than Khajalia water. Notably, the concentration of NH4+ and NO2- ions in the waters at both locations exceeds the maximum permissible concentration, which indicates the lack of sanitary protection zones around the thermal waters, making them vulnerable to the risk of pollution and its high degree. These risks are even more serious when we consider that nitrite ions are both intermediate products of conversion to nitrates (due to their oxidation) and have the ability to be transformed in the human body into nitro compounds, most of which have carcinogenic, mutagenic, and teratogenic effects. PO43- and F- ions were also detected in the waters, although their content did not exceed the Maximum permissible concentration (MPC). A specific component of the thermal water at both locations is hydrogen sulfide. The thermal water at Dzimiti is likely to have a chloride-calcium-sodium ionic composition, while the water at Khajalia is chloride-sodium. The thermal water at Khajalia is not

mineral, whereas the thermal water at Dzimiti is mineral thermal (temperature: 26.40°C, mineralization: 1557.9 mg/l).

The multielement analysis of the waters showed the following order of macroelement concentrations: at the Dzimi location - Na>Ca>K>Mg>P; at the Khajalia location - Na>Ca>P>K>Mg (Table 6). The waters studied do not belong to the iron and silicon types because they have low contents of these elements.

Among microelements, the boron content in Dzimiti water is significantly higher than the maximum permissible concentration (>6.25 mg/l, LDQ - 0.5 mg/l) (Table 7). No heavy metals—Cd, Pb, V, Be, Ti, Sb, Hg—and microelements—Cu, Co, Cr, Mo, Ni, Zn, Se—were detected in the water. The content and concentrations of Mn, Li, Ba, and As do not exceed the MPC (Table 8).

Table 5: *Ionic Composition of Guria's Thermal Waters*

Parameter, dimension	Location		Norm
	Khajalia	Dzimiti	
HCO_3^-, mg/L	61.0	445.3	**400**
Hardness, mg/eq/l	0.25	49.0	**7-10**
Ca^{2+}, mg/L	2.82	1080.0	**140**
Mg^{2+}, mg/L	0.9	69.0	**85**
Cl^-, mg/L	4420.0	9615.0	**250**
NaCl, mg/L	7293.0	15864.8	
NH_4^+, mg/L	2.22	6.0	**2.0**
NO_2^-, mg/L	1.29	0.68	**0.2**
PO_4^{3-}, mg/L	2.78	0.038	**3.5**
F^-, mg/L	0.269	0.49	**0.7**
SO_4^{2-}, mg/L	–	–	**250**
H_2S, mg/L	2.9	23.1	**0.03**
Dry residue, mg/l (mineralization)	291.14	1557.9	**1000**

Table 6: *Macroelements, mg/l*

Location	K	Ca	Mg	Na	P
Dzimiti	274	1080.0	69.0	2790	0.062
Khajalia	0.952	2.82	0.9	234	1.743
Maximum permissible concentration (mpc)	**20.0**	**140**	**85**	**200**	**3.5**

Table 7: *Microelements, mg/l*

Location	Fe	Si	B	Al	Mn
Dzimiti	0.0114	4.23	6.25 H	0.0009	0.001
Khajalia	0.0205	4.94	0.23	0.0042	0.0015
Maximum permissible concentration (mpc)	***0.3***	***10***	***0.5***	***0.5***	***0.05-0.1***

Table 8: *Ultramicroelements, mg/l*

Location	As	Li	Ba
Dzimiti	–	0.0145	0.0036
Khajalia	0.0392	0.0228	0.0018
MPC	***0.05***	***<0.03***	***0.1***

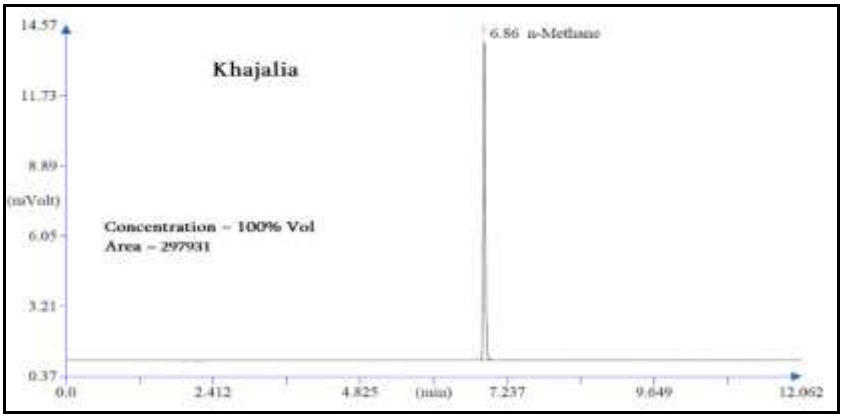
By determining the concentration of fecal contamination in the studied waters, it was found that the total number of saprophytic microorganisms in Khajalia water was 70/1 ml, and in Dzimiti water, it was 50/1 ml (Table 9). The total number of Escherichia coli bacteria in Khajalia water was 140/1 ml, and in Dzimiti water it was 75/1 ml.

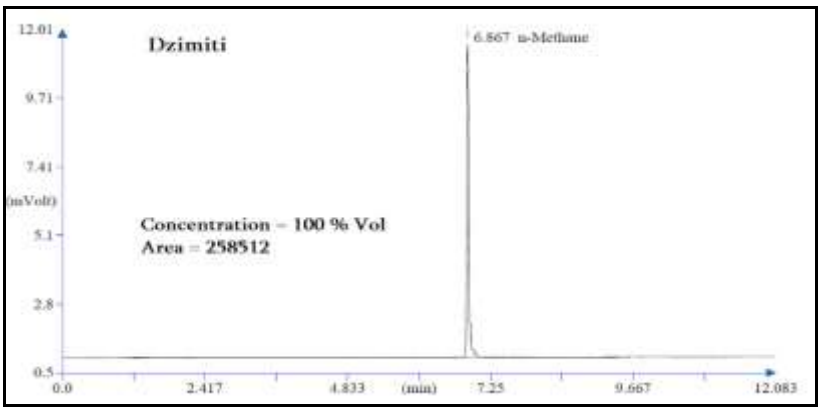
Although the indicators at the mentioned locations were within the standard (<300/1l), this circumstance once again indicates the possibility of an increase in the risk of bacteriological contamination of thermal waters if the boundaries of sanitary protection zones adjacent to the waters are not established, which would make it possible to protect them from the polluting influence of anthropogenic factors outside the boundaries.

Hydrocarbon composition of the gases accompanying the Guria thermal waters. In the gases surrounding the water samples taken at both locations, 100% of the hydrocarbon content was recorded as methane. However, comparing the peak areas, it can be seen that the methane concentration in the gases accompanying the Khajalia water is higher (297931 mVolt*min), which is due to the lower amount of other gases in it compared to the Dzimiti water.

Table 9: *Sanitary-bacteriological indicators of Guria thermal waters*

Parameter, dimension	Location		Norm
	Khajalia	Dzimiti	
Total number of saprophytic microorganisms, units/1ml	70	50	No more than 100/1mL
The number of bacteria of the lactose-positive coli group (Coli index), units / 1l	140	75	No **more** than 300/1L





IV. Conclusion

- The thermal waters of Khajalia and Dzimiti have significant potential; their quality indicators are mainly positive and contribute to both medicinal and energy use.
- Infrastructural and technological limitations hinder the efficient use of the resource, while the idle flow of water causes thermal and ecological pollution of the surrounding area.
- A high risk of anthropogenic impact characterizes thermal waters due to the lack of sanitary protection zones and headwater facilities.
- Using thermal energy as a renewable and environmentally friendly resource is vital for strengthening Georgia's energy security and represents an important direction of sustainable development.

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE ROLE OF HUMAN CAPITAL IN THE CONCEPT OF SUSTAINABLE DEVELOPMENT OF REGIONAL ECONOMIC SYSTEMS

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Abstract

This article is devoted to studying the essence and significance of human capital, and identifying its role in the concept of sustainable development. The chosen topic of research is undoubtedly very relevant, even on a global scale, in the context of economic development and digitalization. After all, sustainable development is responsible for a range of actions aimed at satisfying basic human needs while preserving environmental resources. In other words, sustainable development requires an approach to the environment that does not harm future generations' ability to meet their needs. The article also reveals the three main components responsible for sustainable development: ecological balance, economic growth, and social responsibility. Human capital is undoubtedly a vital component of sustainable development and a valuable resource for any state, as it is responsible for economic growth and development. Therefore, the task of any country is to focus on human capital and its constant development and improvement. This is because each of us realizes that the well-being of any state depends directly on human capital.

Keywords: metamodernism, economic behavior, infrastructure organizations, business strategies, uncertainty, organizational transformation

I. Introduction

In the conditions of modern developing economic relations, a very important place is given to the phenomenon of our research – human capital.

The rapid development of human capital covers the period from the second half of the 19th century to the present day.

Undoubtedly, the research topic we have chosen is very relevant at any stage of society and humanity development.

After all, it is human capital that acts as a kind of incentive to ensure the competitive

advantages of a particular country or individual enterprise.

Today, almost every developed and developing country sets the goal of human capital prosperity as the fundamental strategy for the development of its state.

It is no coincidence that today's labor market pays great attention to the development of personnel, improving their qualifications, as a driving force for ensuring the profitability and sustainability of the enterprise.

But, despite this, in the modern world there are a number of problems that are accompanied by a discrepancy between educational programs and business development processes.

In this regard, we often face situations where entrepreneurship complains about the level of training of graduates, but at the same time, business does not take any serious steps to interact and support educational institutions.

It should be noted that, in general, large corporations have their own corporate universities and professional training centers, which are aimed at developing and strengthening the knowledge of human capital.

This is undoubtedly a very expensive, but effective way to develop a business.

Thus, we can note the fact that the modern development of an innovative economy using new techniques and technologies with maximum preservation of the environment is focused on the implementation and achievement of the sustainable development concept.

What is this concept of sustainable development? What principles is it based on? We will try to answer these and other questions in the course of revealing the essence of our research topic.

So, sustainable development means development that is aimed at meeting the needs of the present moment, provided that these actions will not in any way harm future generations in meeting their needs.

In this concept, the fundamental goal is the sustainable development of all components of both the social and economic structure of society, in particular human resources.

In addition, we'd like to note the historical fact that it was in 1992 in Rio de Janeiro at the UN World Conference that the 27 basic principles for ensuring sustainable development of society were adopted.

The primary principle was to care for people, ensuring and respecting their rights to a healthy and prosperous life in harmony with the environment.

II. Methods

The main aim of our research is to study the essence and significance of human capital in the concept of sustainable development of mankind.

The object of this scientific article is human capital.

The subject of the research is the identification of the main factors responsible for sustainable development.

In the course of writing this scientific work, we relied on the research of both domestic and foreign economists, as well as on textbooks, teaching aids, periodical articles and Internet resources.

III. Results

Certainly, the concept of sustainable development would not have gained such momentum and widespread distribution if there were not the necessary prerequisites, both in the economic and social environment.

The main premise was the great changes that have taken place since the second half of the 20th century.

While previously only a small proportion of European and North American countries were among the main participants in economic growth, now the situation is different, and almost the entire world is participating in this process in accordance with the uniform principles of the global economy.

Earlier in the 50s and 60s, many developing countries focused on achieving economic efficiency.

At that time, the opinion prevailed that only by achieving economic efficiency could development and prosperity be achieved and the problem of social inequality could be eliminated as much as possible both among individual countries and at the global level.

But with that, it was often noted that in many developed countries there was a small efficiency in the economic sphere in matters of organizing the competent distribution of costs for natural resources.

It was the 70s that served as a push in developing countries among the poor strata of the population in matters of creating preconditions for income redistribution.

Slowly people began to understand and realize that the only solution to correct the current situation was to take certain actions on a large scale and at the global level.

Now the development has moved to a new level, responsible for stable growth with an emphasis on social goals.

First of all, much attention was paid to the poor strata of the population with the aim of reducing them. That is, the social sphere began to hold an important place along with economic efficiency.

The next key step was to focus on environmental protection.

This was due to the fact that since the 80s, a huge amount of information had been collected regarding environmental conditions, where it was clearly stated that economic development is out of the question without protecting the natural environment.

At the same time, this issue was clearly emphasized that no other problem in any way relieves us from the need to solve environmental problems. And any neglect of nature is simply unacceptable.

Thus, based on the above, we have concluded that the concept of sustainable development originates from the unification of the three components discussed above, i.e., economic, social and ecological environment.

In this regard, one can often see the formation of three main goals of sustainable development: ensuring ecological integrity, efficiency and environmental justice.

Thus, let us combine all the above information using the classification of three main factors of sustainable development:

- The ecological factor responsible for the boundaries of the development of civilization;
- Economic factor in the context of transformations of the market environment;
- Social factor, covering human rights and duties, demographic situation, etc.

At the same time, it is very important to understand that for the effective operation of the factors considered, it is necessary to put principles and ideas for preserving the environment into people's minds.

IV. Discussions

In addition, we would like to consider the essence of an important component of economic development – the Human Capital Index, which acts as an integral indicator of the volume of human capital that a child born today can accumulate by the age of 18.

In this case, all risks that may be associated with the poor level of education and health care in the country in which he lives are considered.

Moreover, an important element is that this index measures the contribution of education and health systems to the labor productivity of individuals through deep macroeconomic calculations.

Typically, the Human Capital Index ranges from 0 to 1.

In this case, the index can have a value of 1 only if a child born today can have a good health, expressed in not retardation of growth and reaching at least 60 years of age, as well as in the situation of receiving a formal education.

So, in other words, a country's score shows the level of its distance from the optimal indicator of complete education and good health.

In a situation where this index reaches a value of 0.70, we can conclude that the level of future income that a newborn child can expect will be 70% of the level that could be achieved with a complete education and good health.

In addition, it is important to note that the considered index of human capital may well be linked to future scenarios of income development, both for individual states and for people.

In the situation of compiling this index to a level of 0.50, it can be concluded that in the future the amount of GDP per worker could be about twice as large if this country achieved the target indicator of complete education and good health.

Unfortunately, to this day, the problem of sustainable development of human capital remains very relevant, especially in developing countries.

In particular, according to the data provided for 2020, more than a fifth of young children faced the problem of having low growth compared to their age. These values could also increase due to the pandemic.

Another important problem is the lack of proper education, which, of course, has a negative impact on the economic development of a particular country.

According to our research, we found that there are a number of countries in which, compared to other countries, children of the same age significantly lag behind one another in the level of knowledge they have acquired.

A similar situation is observed with regard to medical services. In particular, it is mainly the poor strata of the population that suffer.

In addition, one of the great problems of the modern world is the lack of clean drinking water in certain regions, which causes mortality among the child population.

It should also be noted that according to the Human Development Index, updated in 2020, the productivity of almost 65% of children born would, under the most favorable conditions, be half of what could be achieved if they had good health and could receive a complete education.

In our opinion, the current situation serves as clear evidence of a crisis in the development of human capital.

This, in turn, will have a negative impact on economic growth and may increase the poverty threshold up to and including 2030.

It is very important to understand that the lack of human capital is a serious and dangerous trend even today, especially in the context of globalization, the development of new technologies, and the current demographic, social and climatic situation throughout the world.

Human capital is also very vulnerable to the impact of various conflicts and pandemics, as they negatively affect the phenomenon of our study by increasing mortality, reducing sources of income, causing problems in the educational and health environment.

All this, of course, reduces people's productivity.

Despite this, many countries underestimate the importance of investing in human capital.

But it is important to understand that, in spite of the difficulties, there are also a number of countries that, through various transformations, were able to influence the development of human capital, in particular, Singapore, the Republic of Korea, Ireland, etc.

V. Conclusions

Thus, we have revealed the topic of our scientific research by identifying the essence and significance of human capital in the concept of sustainable development. Undoubtedly, the phenomenon of our study occupies a key place in the activities of any state, ensuring the growth and development of both individual entities and the country as a whole. In this regard, we recommend that each country pay maximum attention to the processes of reproduction and assessment of human capital. After all, without observing this principle, the long-term and prospective existence of a unified state is out of the question.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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SOME RESULTS OF THE STUDY OF THE NUMBER OF DAYS WITH FOG PER YEAR IN GEORGIA IN 1993-2022

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Abstract

Fog poses a serious threat to many sectors of the economy, particularly aviation and other types of transport. In this context, many countries around the world are giving great importance to fog research, especially in light of climate change. In Georgia, such research has also been a priority for many decades. This paper presents the results of a statistical analysis of data on the number of foggy days per year at 40 meteorological stations in Georgia (18 and 22 stations in eastern and western Georgia, respectively) between 1993 and 2022. The altitude range of the Eastern Georgian stations is from 362 to 1,744 metres above sea level (m a.s.l.), and the range for the Western Georgian stations is from 2 to 2,025 m a.s.l. In particular, it was found that the average number of days with fog per year at one meteorological station in Eastern Georgia is 22 (with a range of 0 to 111 across individual years), and 48 in Western Georgia (with a range of 0 to 325). There is a linear connection between the maximum and minimum number of days with fog and the average number of days with fog. In both eastern and western Georgia, an increasing linear trend in the average and maximum number of foggy days with altitude is observed. The variability of the number of foggy days at twelve stations with continuous thirty-year time series was studied. It was found that, compared to 1993-2007, a significant increase in the number of foggy days was observed at four stations between 2008 and 2022, while a decrease was observed at only one station. Trends in the number of foggy days per year for some stations were studied for the period 1993–2022. Thus, the trends for Akhalkalaki and Khashuri are linear, while the trend for Mta-Sabueti is a second-degree polynomial.

Keywords: fog, number of days with fog per year, climate change, statistical analysis, trend

I. Introduction

Fog has a significant impact on the environment, global and regional climate, heat and radiation balance of the atmosphere, air quality, water, flora and fauna, air-surface interaction, etc. [1-5]. Fog poses a serious threat to many sectors of the economy, including all types of transport, especially aviation [6-8]. Therefore, fog research is given great importance in many countries of the world, especially given climate change. In Georgia, such research is also considered a priority and has been carried out for many decades [1, 2, 5-7, 9-14].

For example, a detailed analysis of the variability of the number of fog days per year and some reasons of these variations in different locations of Georgia is given in [9-12]. In [13] the detailed statistical analysis of number of days with the fog, duration of fogs, number of days with the haze and duration of haze in Dusheti (Georgia) in 1941-1990 are present. As a whole in these years there was a tendency of the decrease of the number of days with the fogs and duration of fogs, and increase in the number of days with the haze and the duration of haze. In [6,7] the results of the study of fog characteristics at the Tbilisi airport are presented.

Obtaining new information allows for regular updates of the climatology and variability of the number of foggy days per year in different regions of Georgia, taking into account local conditions and climate change. The results of these studies based on observations at 40 stations from 1993 to 2022 are presented below.

II. Study area, material and methods

Study area – Georgia, 40 meteorological stations (Table 1); 18 and 22 stations locations in Eastern and Western Georgia, respectively. The altitude range of meteorological stations in Eastern Georgia is from 362 to 1744 m a.s.l., and in Western Georgia - from 2 to 2025 m a.s.l.

Table 1: *Coordinates and altitudes above sea level of weather stations.*

Location	Lat, °N	Lon, °E	Height a.s.l., m	Location	Lat, °N	Lon, °E	Height a.s.l., m
Eastern Georgia				Akhalkalaki	41.42	43.48	1716
Akhalgori	42.12	44.48	760	Akhaltsikhe	41.63	43	982
Bolnisi	41.45	44.55	534	Bakhmaro	41.85	42.32	1926
Dedoplistskaro	41.47	46.08	800	Bakuriani	41.73	43.52	1665
Dusheti	42.30	44.87	920	Batumi	41.65	41.63	2
Gori	41.98	44.12	588	Chakvi	41.73	41.73	30
Gurjaani	41.75	45.8	410	Chokhatauri	42.02	42.26	150
Khashuri	42	43.57	709	Goderdzi	41.63	42.52	2025
Kojori	41.67	44.70	1381	Khulo1	41.65	42.32	914
Kvareli	41.97	45.83	449	Khulo2	41.65	42.30	1338
Lagodekhi	41.82	46.3	362	Kobuleti	41.76	41.78	7
Sagarejo	41.73	45.33	802	Kutaisi	42.27	42.6	114
Shovi	42.7	43.68	1507	Lanchkhuti	42.10	42.03	10
Stepantsminda	42.67	44.65	1744	Mta-Sabueti	42.03	43.48	1242
Tbilisi	41.72	44.8	403	Poti	42.13	41.7	4
Tbilisi,Airport	41.68	44.95	462	Sachkhere	42.35	43.42	415
Tbilisi,Varketili	41.75	44.77	432	Sairme	41.9	42.75	910
Telavi	41.93	45.48	568	Senaki	42.20	41.95	6
Tsalka	41.6	44.08	1457	Torsa	42.39	41.79	14
Western Georgia				Tseva	42.08	43.13	508
Abastumani	41.75	42.83	1265	Zugdidi	42.52	41.88	117

Data of the Georgian National Environment Agency about number of days with fog per year in the period from 1993 to 2022 are used. The analysis of data is carried out with the use of the standard statistical analysis methods of random events and methods of mathematical statistics for the non-accidental time series of observations [15, 16]. The following designations will be used below: Mean – average values; Min – minimal values; Max - maximal values; St Dev - standard deviation; σ_m – standard error; R^2 - coefficient of determination; R – coefficient of linear correlation; C_v – coefficient of variation, %; K_{DW} – Durbin-Watson statistic; α - level of significance; 95%(+/-) and 99%(+/-) - confidence intervals of average value; N- number of days with fog per year; H - elevation of terrain, meter a.s.l. Comparison of mean values of N in two 15 - year periods of time

(1993-2007 and 2008-2022) was produced with the use of Student's criterion with the level of significance α not worse than 0.25. The degree of correlation was determined in accordance with [16]: very high correlation ($0.9 \le R \le 1.0$); high correlation ($0.7 \le R < 0.9$); moderate correlation ($0.5 \le R < 0.7$); low correlation ($0.3 \le R < 0.5$); negligible correlation ($0 \le R < 0.3$). The curve of trend is equation of the regression of the connection of the investigated parameter with the time at the significant value of the determination coefficient and such values of K_{DW}, where the residual values are accidental.

III. Results

Results in Table 2-4 and Fig. 1-9 are presented.

In Tables 2 and 3 statistical characteristics of the number of days with fog per year in Eastern and Western Georgia in 1993-2022 are presented. In Fig. 1 and 2 for clarity maps of distribution of the average and maximum number of days with fog per year on the territory of Georgia in 1993-2022 are presented.

As follows from Table 2, in Eastern Georgia the range of changes in the average values of N for each station is: 3 (Akhalgori) – 73 (Kojori), minimal: 0 (Akhalgori; Kojori; Tbilisi, Varketili) – 22 (Sagarejo), maximum: 11 (Akhalgori) – 111 (Kojori). The averaged at one meteorological station number of days with fog per year is 22. The range of changes values of C_v is: 31.2 % (Dedoplistskaro) – 164.4 % (Tbilisi).

Table 2: *Statistical characteristics of the number of days with fog per year in Eastern Georgia in 1993-2022.*

Location	Mean	Min	Max	St Dev	σ_m	C_v ,%	Count	95%(+/-)	99%(+/-)
Akhalgori	3	0	11	3.3	1.0	103.6	13	1.9	2.5
Bolnisi	25	11	39	8.0	1.5	31.8	30	2.9	3.8
Dedoplistskaro	53	12	85	16.7	4.6	31.2	14	9.1	11.9
Dusheti	29	3	68	17.8	5.1	60.6	13	10.1	13.2
Gori	11	4	29	5.3	1.0	49.9	30	1.9	2.5
Gurjaani	7	1	20	4.7	1.3	64.7	14	2.6	3.4
Khashuri	10	1	25	5.8	1.1	57.6	30	2.1	2.8
Kojori	73	0	111	30.5	8.5	41.8	14	16.6	21.8
Kvareli	6	1	12	3.0	0.9	48.7	13	1.7	2.3
Lagodekhi	10	2	33	7.9	2.2	76.0	14	4.3	5.6
Sagarejo	45	22	78	16.7	4.6	37.3	14	9.1	12.0
Shovi	32	2	66	18.4	3.8	58.4	24	7.5	9.9
Stepantsminda	31	3	67	19.9	5.5	63.8	14	10.8	14.2
Tbilisi	13	1	71	20.6	4.0	164.4	27	7.9	10.4
Tbilisi,Airport	19	3	31	8.8	2.1	46.0	18	4.2	5.5
Tbilisi,Varketili	9	0	36	11.0	3.0	121.2	14	6.0	7.9
Telavi	10	1	24	6.1	1.1	61.3	30	2.2	2.9
Tsalka	13	2	30	7.1	1.3	53.4	30	2.6	3.4

In Western Georgia (Table 3) the range of changes in the average values of N for each station is: 3 (Akhalkalaki) – 282 (Mta-Sabueti), minimal: 0 (Abastumani, Akhalkalaki, Bakuriani, Batumi, Chokhatauri, Kobuleti, Senaki, Zugdidi) – 248 (Mta-Sabueti), maximum: 11 (Zugdidi) – 325 (Mta-Sabueti). The averaged at one meteorological station number of days with fog per year is 48. The range of changes values of C_v is: 6.9 % (Mta-Sabueti) – 171.8 % (Kutaisi).

Table 3: *Statistical characteristics of the number of days with fog per year in Western Georgia in 1993-2022.*

Location	Mean	Min	Max	St Dev	σ_m	C_v ,%	Count	95%(+/-)	99%(+/-)
Abastumani	5	0	20	6.1	1.8	112.5	13	3.5	4.6
Akhalkalaki	3	0	12	3.1	0.6	88.9	30	1.1	1.5
Akhaltsikhe	9	2	22	4.4	0.8	52.3	30	1.6	2.1
Bakhmaro	69	42	106	18.9	5.7	27.4	12	11.1	14.6
Bakuriani	36	0	99	28.0	6.6	78.7	19	12.9	17.0
Batumi	5	0	21	5.1	1.3	109.5	16	2.6	3.4
Chakvi	6	1	17	4.5	1.3	82.0	13	2.6	3.4
Chokhatauri	8	0	69	13.8	2.6	163.6	30	5.0	6.6
Goderdzi	197	154	219	17.6	4.9	8.9	14	9.5	12.5
Khulo1	27	2	66	14.4	3.7	53.5	16	7.3	9.6
Khulo2	130	68	181	29.8	8.3	23.0	14	16.2	21.3
Kobuleti	12	0	34	7.6	1.4	61.3	30	2.8	3.7
Kutaisi	7	1	72	12.5	2.3	171.8	30	4.5	6.0
Lanchkhuti	16	5	35	10.4	3.0	65.5	13	5.9	7.8
Mta-Sabueti	282	248	325	19.4	3.6	6.9	30	7.1	9.3
Poti	23	13	49	8.8	2.0	38.3	20	3.9	5.2
Sachkhere	14	2	24	7.0	2.1	49.0	12	4.1	5.4
Sairme	133	14	261	70.9	18.3	53.3	16	35.9	47.2
Senaki	7	0	18	5.6	1.6	85.8	13	3.2	4.2
Torsa	14	1	56	15.5	4.5	114.6	13	8.8	11.5
Tseva	46	21	68	14.3	4.1	30.8	13	8.1	10.6
Zugdidi	4	0	11	2.7	0.6	72.8	22	1.1	1.5



Figure 1: *Distribution of the average number of days with fog per year on the territory of Georgia in 1993-2022.*



Figure 2: *Distribution of the maximum number of days with fog per year on the territory of Georgia in 1993-2022.*

Fig. 3 shows the graphs of the correlations between the maximum and minimum number of foggy days per year with their average values.

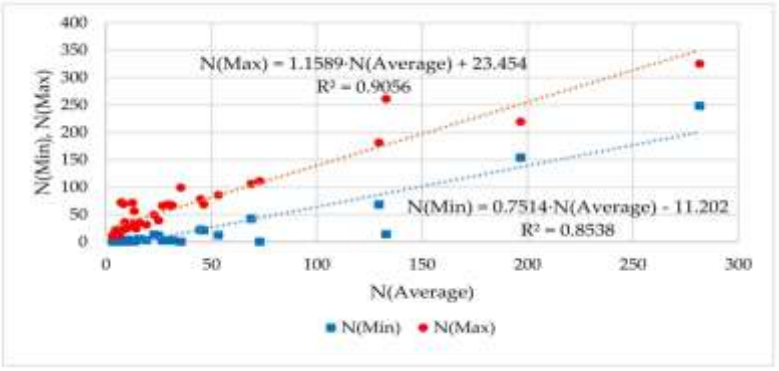


Figure 3: *Linear correlation and regression the maximum and minimum number of days with fog per year with average number of days with fog per year in Georgia in 1993-2022.*

As follows from Fig. 3 degree of these correlations were very high: for pair N(Min) – N(Average) value of R is 0.92 and for pair N(Max) – N(Average) value of R is 0.95.

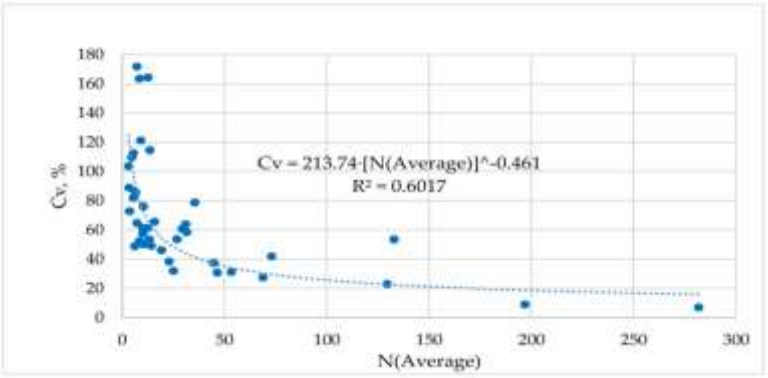


Figure 4: *Connection of coefficient of variation with the average number of days with fog per year in Georgia in 1993-2022.*

Connection of coefficient of variation with the average number of days with fog per year has a power form (Fig. 4). With the increase in the values of N(Average), a significant decrease in the values of C_v is observed.

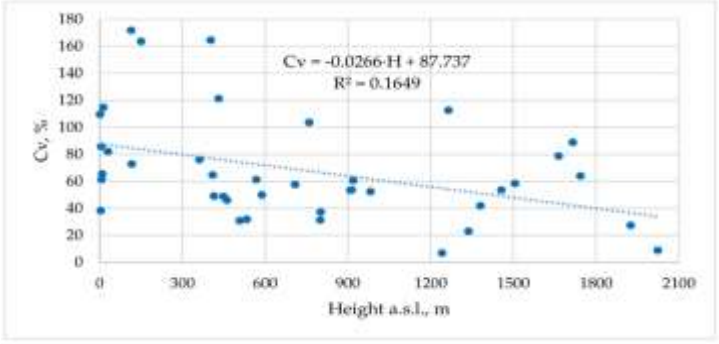


Figure 5: *Connection of coefficient of variation of the number of days with fog per year with the height on the territory of Georgia in 1993-2022.*

The relationship between the coefficient of variation of the number of days with fog per year and the altitude of the terrain in Georgia has the form of an inverse linear relationship (Fig. 5). For pair C_v – H value of R is 0.41 (low correlation).

In Fig. 6 and 7 vertical distributions of the maximum and average number of days with fog per year on the territory of Eastern and Western Georgia are presented. For all cases, there are tendencies towards increasing values N(Average) and N(Max) with the altitude of the place. For Eastern Georgia (Fig. 5) for pair N(Average) – H value of R is 0.52 (moderate correlation) and for pair N(Max) – H value of R is 0.50 (moderate correlation).

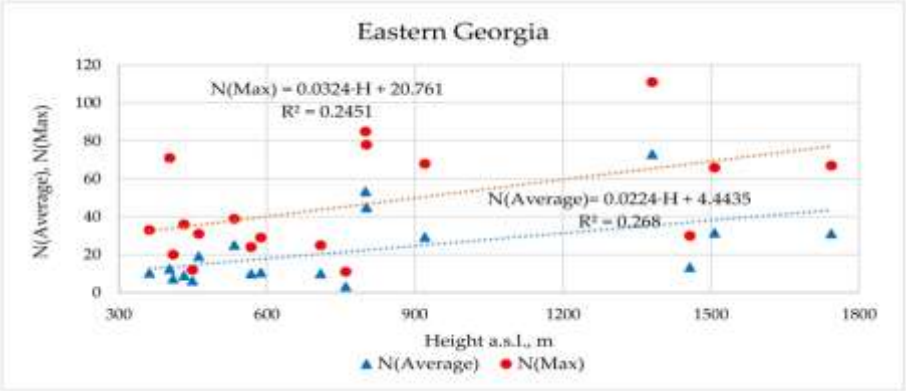


Figure 6: *Vertical distribution of the maximum and average number of days with fog per year on the territory of Eastern Georgia in 1993-2022.*

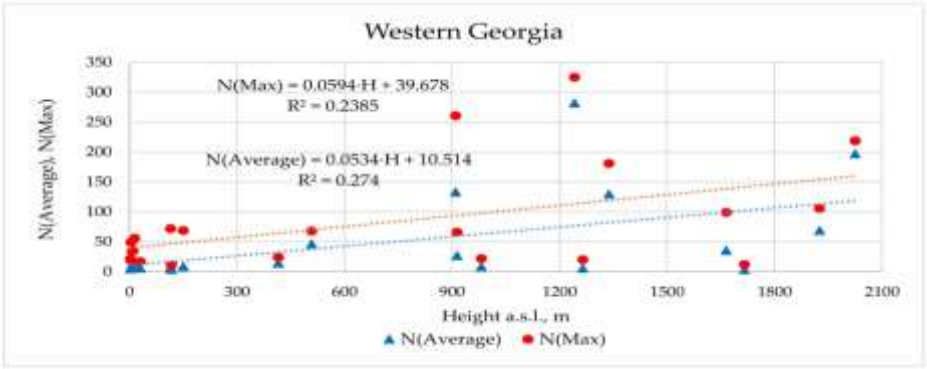


Figure 7: *Vertical distribution of the maximum and average number of days with fog per year on the territory of Western Georgia in 1993-2022.*

For Western Georgia (Fig. 7) for pair N(Average) – H value of R is 0.52 (moderate correlation) and for pair N(Max) – H value of R is 0.49 (low correlation).

In Table 4 data on difference between of the average number of days with fog per year in 2008-2022 and 1993-2007 for 12 locations with a continuous thirty-year time-series of observations are presented. As follows from Table 4 in 2008-2022, compared to 1993-2007, a significant increase in the number of days with fog was observed at four stations (Chokhatauri, Khashuri, Mta-Sabueti, Tbilisi), and a decrease at only one (Akhalkalaki).

Finally, in Fig. 8 and 9 examples of trends of the number of fog days per year for Akhalkalaki, Khashuri and Mta-Sabueti in 1993-2022 are given.

Table 4: *Difference between of the average number of days with fog per year in 2008-2022 and 1993-2007 for 12 locations of Georgia.*

Location	1per.(1993-2007)	2 per.(2008-2022)	2 per.-1 per.	α
Akhalkalaki	4.4	2.5	-1.9	≤0.25
Akhaltsikhe	9.2	7.8	-1.4	>0.25
Bolnisi	26.0	24.1	-1.9	>0.25
Chokhatauri	2.8	14.1	11.3	≤0.25
Gori	10.4	10.7	0.3	>0.25
Khashuri	7.3	13.0	5.7	≤0.25
Kobuleti	11.0	13.9	2.9	>0.25
Kutaisi	10.3	4.3	-6.0	>0.25
Mta-Sabueti	276.9	286.7	9.8	≤0.25
Tbilisi	6.2	17.7	11.5	≤0.25
Telavi	9.5	10.5	1.1	>0.25
Tsalka	14.8	11.9	-2.9	>0.25

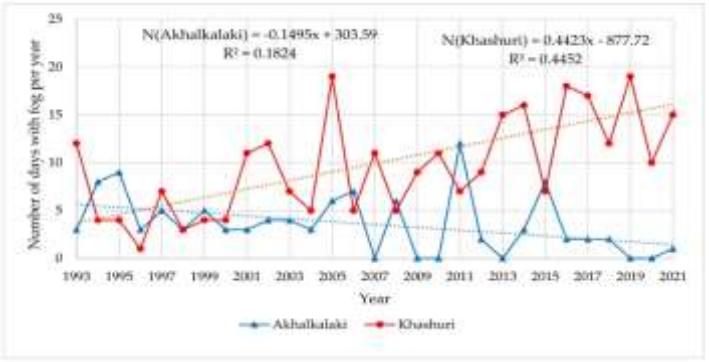


Figure 8: *Trend of the number of days with fog per year in Akhalkalaki and Khashuri in 1993-2022.*

Trends of the number of days with fog per year in Akhalkalaki and Khashuri have a linear form (Fig. 8). Akhalkalaki (K_{DW} = 2.37, α = 0.05); Khashuri (K_{DW} = 2.23, α = 0.05).

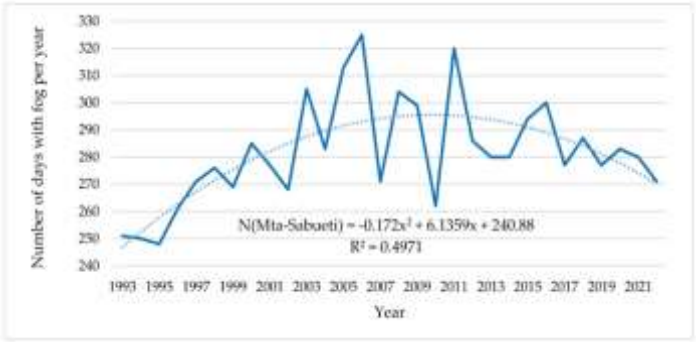


Figure 9: *Trend of the number of days with fog per year in Mta-Sabueti in 1993-2022.*

Trend of the number of days with fog per year in Mta-Sabueti (Fig. 9) have form of a second-degree polynomial (K_{DW} = 2.64, α = 0.01).

IV. Conclusion

In Eastern Georgia the range of changes in the average values of number of days with fog per year (N) for each station is: 3 (Akhalgori) – 73 (Kojori), minimal: 0 (Akhalgori; Kojori; Tbilisi, Varketili) – 22 (Sagarejo), maximum: 11 (Akhalgori) – 111 (Kojori). The averaged at one meteorological station number of days with fog per year is 22. In Western Georgia the range of changes in the average values of N for each station is: 3 (Akhalkalaki) – 282 (Mta-Sabueti), minimal: 0 (Abastumani, Akhalkalaki, Bakuriani, Batumi, Chokhatauri, Kobuleti, Senaki, Zugdidi) – 248 (Mta-Sabueti), maximum: 11 (Zugdidi) – 325 (Mta-Sabueti). The averaged at one meteorological station number of days with fog per year is 48.

Vertical distributions of the maximum and average number of days with fog per year on the territory of Eastern and Western Georgia tends to increase with increasing altitude.

A difference between of the average number of days with fog per year in 2008-2022 and 1993-2007 for 12 locations with a continuous thirty-year time-series of observations are studied. In 2008-2022, compared to 1993-2007, a significant increase in the number of days with fog was observed at four stations (Chokhatauri, Khashuri, Mta-Sabueti, Tbilisi), and a decrease at only one (Akhalkalaki). Trends of the N in Akhalkalaki and Khashuri have a linear form, and in Mta-Sabueti - form of a second-degree polynomial

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ENVIRONMENTAL RISKS AND RECYCLING OF POLYMER WASTE FOR WATER PURIFICATION FROM OIL CONTAMINATION

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Abstract

The increased production of polymer-based materials has made polymer waste management more challenging. Plastic bottles, medical tubing, bags and polymer foams are all persistent environmental pollutants. The recycling of these materials often requires high energy consumption and is commonly accompanied by the emission of toxic compounds and gases, posing significant environmental risks. This study investigated waste materials from the furniture manufacturing and packaging industries, which are primarily made of porous polymers. FTIR spectroscopy was employed to analyze their polymer composition. The results indicate that the dominant polymer constituents in municipal waste are polyethylene, polypropylene, polystyrene, and polyurethane. The potential use of waste porous polymeric materials for purifying water contaminated with oil and petroleum products (PPs) was also examined. Porous polymers were used as sorbents in the water treatment process. Their sorption capacity (g/g) and the factors affecting sorption efficiency — including pH, temperature and loading density — were analyzed systematically. Research indicates that polyurethane demonstrates the highest sorption efficiency. Under dynamic conditions in sorption columns, polyurethane effectively reduces the concentration of oil contaminants in water to levels permissible under wastewater discharge regulations.

Keywords: waste polymers, sorption, waste water purification, diesel removal

I. Introduction

With the increasing production of polymer-based products, the issue of polymer waste disposal, such as used bottles, medical tubing, plastic bags, and polymeric sponges, has become a significant challenge [1]. Polymeric waste poses a growing environmental threat [2,3,15].

Since 1950, approximately 8.3 billion metric tons of plastic have been produced, with only 9% being recycled into secondary raw materials and 12% incinerated [4]. In many cases, recycling is not a feasible option due to its high energy requirements and the emission of toxic compounds and gases into the environment during the process [5,15].

In addition to recycling, the development of technologies for the secondary utilization of polymer waste is crucial. Using waste polymeric materials for the treatment of petroleum-contaminated water simultaneously addresses two environmental challenges: plastic waste management and oil pollution remediation [6,7,8,15].

The study by Aboul-Gheit et al. [9] demonstrated through laboratory experiments that certain plastic waste materials, including polyethylene (PE) and polypropylene (PP) waste powders and sheets, as well as polyurethane (PU) foam, possess a high oil sorption capacity. These materials have the potential to be effectively utilized for oil spill remediation in marine environments.

The studies by Nguyen et al. [10] and Haridharan et al. [11] emphasize the potential of innovative polymeric sorbents in mitigating ocean pollution. These sorbents demonstrate enhanced porosity and improved biodegradability.

The highly porous structure of sorbents can be achieved through various techniques. One modification approach involves the fabrication of polymeric sorbents with a three-dimensional structured framework [12, 15].

Shredded hydrophobized polyurethane, treated with silanes, is widely used for oil spill remediation. After collecting, approximately 80% of the absorbed oil can be recovered through mechanical squeezing, enabling the material to be reused [13, 15].

Various types of porous materials, both natural and synthetic, are utilized as sorbents [14-18]. From an economic and efficiency perspective, sorption using synthetic sorbents is particularly advantageous. In this approach, the sorbent matrix consists of waste (secondary) polymeric materials, which themselves contribute to environmental pollution.

This study aims to develop a cost-effective approach for treating water contaminated with oil and petroleum products by utilizing locally sourced polymer waste materials as sorbents.

To optimize purification conditions, the study investigates the impact of key factors on treatment efficiency, including sorbent loading density, pH and temperature effects on the sorption process.

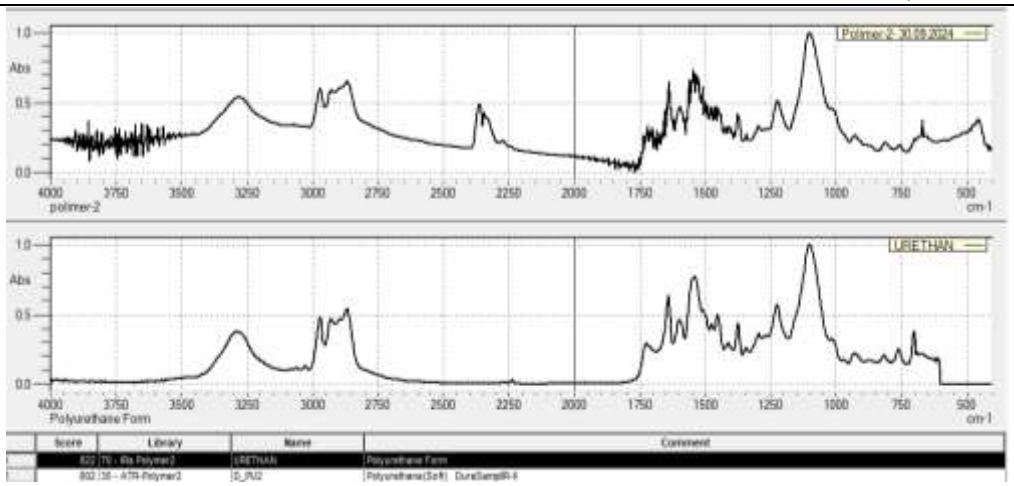
II. Experimental part

Materials. The objective of the research was to assess the feasibility of employing synthetic polymers for the treatment of water contaminated by petroleum products. To this end, samples of diverse polymeric materials were obtained (see **Images:** Samples of diverse polymeric materials), predominantly consisting of locally sourced waste porous polymers from furniture manufacturing, packaging materials, and other sources.

The analysis was performed using an FTIR IRSpirit spectrophotometer (Shimadzu) to identify the polymers studied. Spectral scans were conducted on the FTIR spectrophotometer, and the Shimadzu database was utilized for spectral comparison. Based on the obtained spectra (see Curve 1: Identification of the Unknown Polymer), the polymers were identified as polyurethane (PU), polystyrene (PS) (in four different modifications), low-density polyethylene (PE), starch-based foam, and polyester



Images: Samples of diverse polymeric materials

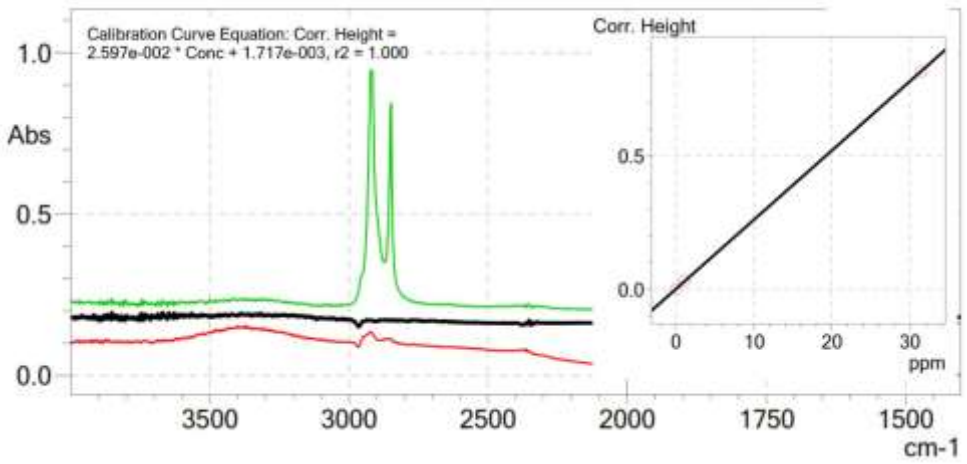


Curve 1: *Identification of the Unknown Polymer*

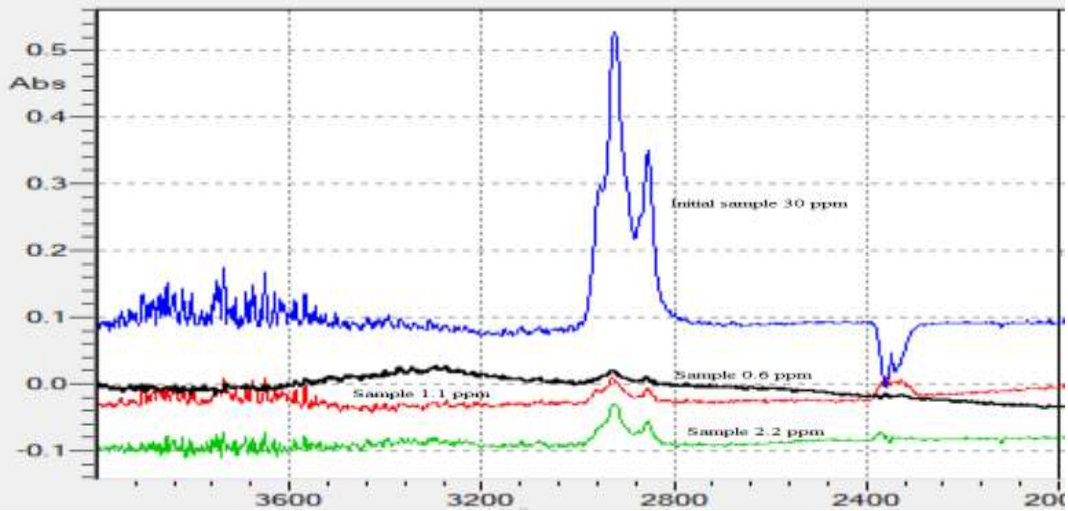
The first curve represents the polymer under investigation, while the second curve corresponds to polyurethane. The spectra were obtained using an FTIR IRSpirit spectrophotometer.

These polymers are derived from industrial waste and secondary raw materials. For example, expanded polystyrene (EPS) foam is widely used for thermal insulation, packaging, and construction. Polystyrene materials are commonly utilized in the form of rigid sheets or small granules (packing peanuts), which serve as protective cushioning during transportation. Starch-based foam, a biodegradable packaging material, is typically manufactured from plant-derived starch. Polyurethane is employed for packaging fragile items due to its high shock-absorbing properties. Expanded polyethylene (EPE) foam is extensively used for packaging, insulation, and cushioning. Polyurethane is also widely applied in the production of upholstered furniture, making furniture manufacturers its primary source.

Methods. To determine the concentration of petroleum products in water, the Standard Test Method for Solvent-Free Membrane Recoverable Oil and Grease by Infrared Determination (D7575 – 11) [19] was applied. In this method, the test solution was filtered through an OSS Clear Shot membrane filter (cartridge), and the concentration of sorbed oil and petroleum products was subsequently determined using Fourier-transform infrared (FTIR) spectroscopy. The application of this standard eliminated the need for solvent-based extraction.



Curve 2: *The FTIR of the background was obtained using an FTIR IRSpirit spectrophotometer.*



Curve 3: *Petroleum Product Concentration in the Initial Sample and Various Filtrate Samples*.

To determine the concentration of petroleum products in an unknown sample, 10 mL of the analytical solution was passed through a membrane filter (OSS part: 1013 SPE) using a syringe. The filter cartridge was then dried for 10–15 minutes under a dry air stream. Subsequently, the concentration of petroleum products was measured using an IRSpirit spectrophotometer. The obtained infrared spectra were analyzed by measuring the peak heights from the baseline at 2920 cm^{-1}.

Processing. To assess the sorption properties of porous polymers, an aqueous solution artificially contaminated with petroleum products was prepared. For the preparation of a solution with a known concentration, 500 mg of diesel (gas oil) was dissolved in 1 L of water. To ensure homogenization, the resulting emulsion was subjected to ultrasonication for 30 minutes at 40°C.

Construction of Adsorption Curves. To evaluate the sorption properties of the studied polymers, eight different sorbents were introduced into glass sorption columns. The amount of petroleum products adsorbed onto the polymeric sorbents under dynamic conditions was assessed using an initial aqueous solution. After each 100 mL addition of the initial solution, the concentration of petroleum products remaining in the filtrate was measured according to the D7575 – 11 standards.

During the experiment, the adsorption capacity (q_a, mg/g) was calculated to evaluate the adsorption process. The following equation was used:

$$q = \frac{(C0 - C\ ) \times V}{m}$$

where: C_0 – Initial oil concentration; C – Oil concentration in the filtrate (ppm); V – Volume of the filtrate (mL); m – Mass of the sorbent (g).

III. Results and Discussion

To investigate the sorptive properties of the studied polymers, sorbents were introduced into glass sorption columns. Diesel sorption from the initial aqueous solution by various polymeric sorbents was analyzed under dynamic conditions. After each addition of 100 mL of the initial solution, the concentration of residual petroleum hydrocarbons in the filtrate (ppm) was measured.

Based on the experimental results polyurethane was identified as the sorbent with the most favorable sorption properties. The sorption process was analyzed under varying pH conditions and different temperatures of the test solution.

The collected data were utilized to generate curves (see curves below) depicting the concentration of residual petroleum hydrocarbons (ppm) in the filtrate following the passage of the solution through the sorbent.

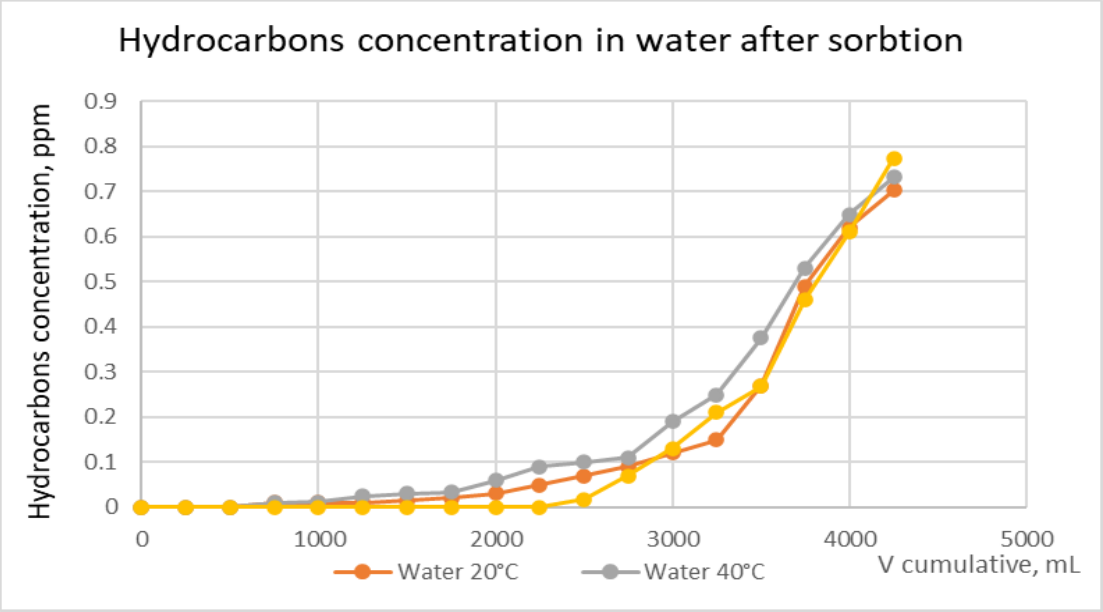


Figure 1: *Hydrocarbons concentration in water after sorbtion*

Based on the data, it can be concluded that neither an increase in temperature nor acidification of the solution significantly affects the sorption process.

The sorption capacity of polyurethane was assessed by measuring the mass of petroleum hydrocarbons retained on the sorbent (see Fig.2).

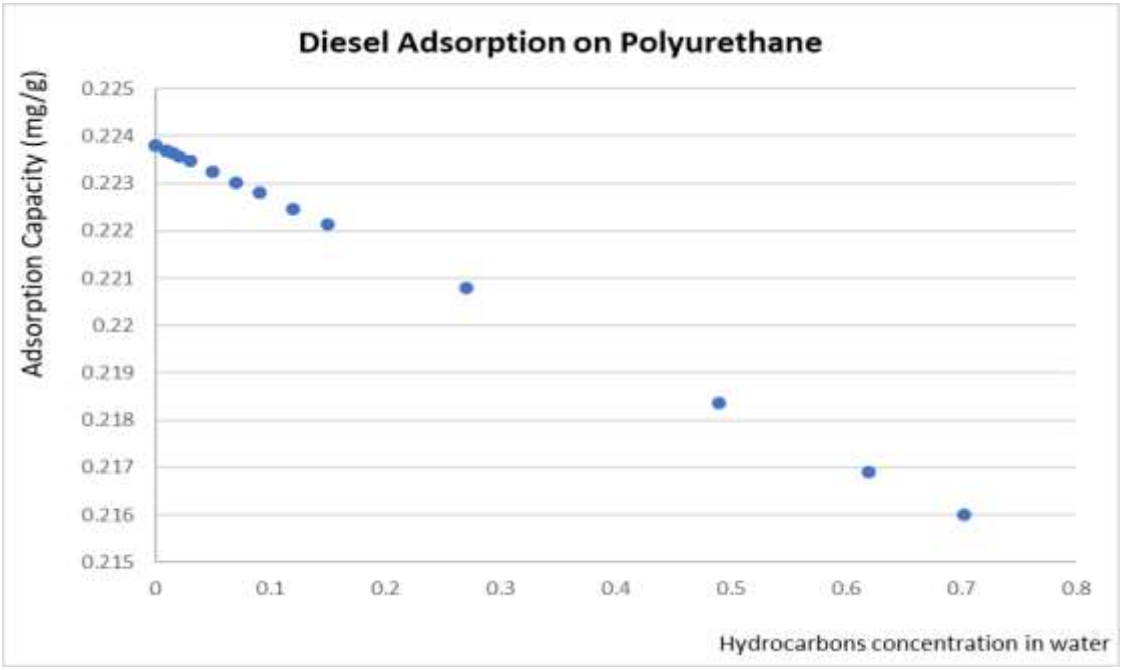


Figure 2: *Isotherm Curve for Diesel Adsorption on Polyurethane (T=20 ^{0}C)*

The relationship between sorbent loading density and sorption capacity was examined. As illustrated in Fig. 3, sorption capacity increases as the loading density of the sorbent increases.

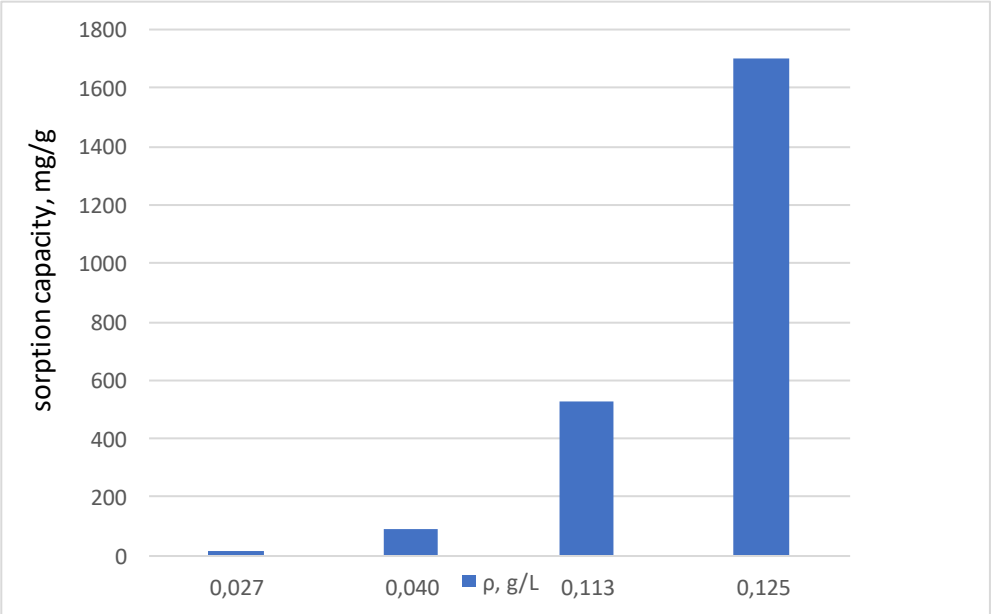


Figure 3: *The Impact of Sorbent Loading Density on Sorption Capacity*

IV. Conclusion

Locally produced waste-derived porous polymeric materials were examined, with polyurethane (PU), polystyrene (PS), low-density polyethylene (PE), starch-based foam, and polyester identified as primary components. Among these materials, polyurethane was selected as the most effective sorbent due to its superior sorption properties. The diesel sorption process on polyurethane was studied under dynamic conditions, considering different sorbent loading densities, pH levels, and test solution temperatures. It was found that variations in temperature and pH have no significant impact on the sorption capacity of polyurethane. The low cost of polyurethane (as it is derived from waste), along with its high sorption capacity and stability during regeneration, suggests that polyurethane is a promising material for the treatment of water contaminated with petroleum products, particularly at low concentrations.

Acknowledgement

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CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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ASSESSING CARBON STORAGE AND GREENHOUSE GAS RISK REDUCTION IN MIXED BROADLEAF-CONIFER AND PURE PINE FORESTS NEAR AKHALTSIKHE, GEORGIA (2019-2025)

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Abstract

This study evaluates the accumulation of aboveground carbon from 2019 to 2025 in two forest types near Akhaltsikhe in Georgia (at an altitude of approximately 1,500 meters): an uneven-aged mixed broadleaf-conifer forest and a pure Pinus sylvestris stand. The analysis focused on four native species — Carpinus orientalis, Quercus petraea subsp. iberica, Quercus macranthera and Pinus sylvestris — to evaluate their responses to stand composition and their respective contributions to carbon storage in relation to mitigating the risk of greenhouse gases. In the mixed stand, C. orientalis exhibited the highest carbon gain (59.2%), followed by Q. macranthera (34.2%) and Q. petraea subsp. iberica (6.3%). Pinus sylvestris showed limited carbon accumulation in the mixed forest, but performed better in monoculture with an average height of 18.8 meters and a 19.6% increase in carbon. These variations highlight species competition and their differing capacities to sequester carbon, which is critical for understanding forest ecosystem functions in carbon cycling. Conducted in Georgia's mountainous region, the study quantifies the amount of harmful greenhouse gas CO_2 absorbed and stored by native forest ecosystems, thereby mitigating the risks posed by rising atmospheric carbon concentrations and global climate change. The study emphasizes the crucial role that forest structure and species diversity play in enhancing the potential for carbon sequestration and mitigating greenhouse gas risks.

Keywords: carbon sequestration, above ground biomass, species composition, mixed vs. pure stands, temperate forest ecosystems

I. Introduction

Forest ecosystems are key regulators of the terrestrial carbon cycle, sequestering atmospheric CO_2 in aboveground and belowground biomass and thereby functioning as important long-term carbon sinks [1]. However, the efficiency of carbon storage depends significantly on forest structure, species composition, and management practices [2].

In boreal and temperate regions, Pinus sylvestris often forms monospecific stands characterized by fast growth and high biomass density [3]. The regional variant Pinus sylvestris var. caucasica, native to the Caucasus Mountains, is adapted to nutrient-poor, rocky soils and can reach heights of 25–35 meters with a lifespan extending over several centuries [4, 5].

Yet, mixed-species forests, especially those involving conifer, broadleaf combinations, have shown enhanced carbon storage capacity compared to monocultures due to complementary resource use and structural diversity [6, 7]. In Georgian mountain forests, broadleaf species such as Carpinus orientalis, a small understory tree reaching 6–8 meters in height and adapted to dry,

shallow soils [8], and oaks like Quercus macranthera and Quercus petraea subsp. iberica, which grows up to 25–30 meters in height and thrives in humid and dry montane conditions, respectively, contribute to vertical forest stratification and increased carbon accumulation [9, 10].

Regional studies within Georgia are limited but highlight the importance of land-use change on carbon budgets [11]. While prior work has explored national-scale carbon dynamics, long-term, plot-based investigations of native mixed and pine forests in the Georgian mountain zone remain scarce. By remeasuring permanent sample plots in mixed and pine-dominated stands between 2019 and 2025, our study will allow for a longitudinal assessment of species-level carbon dynamics.

Through this approach, we aim to:

1. Quantify aboveground carbon accumulation across two forest types,
2. Understand interspecific competition and structural development,
3. Provide data applicable to greenhouse gas risk assessment in Georgia's mountain ecosystems.

This research not only extends existing regional knowledge but also contributes to broader climate-relevant policy and sustainable forest management strategies.

II. Methods

Study areas are located near Akhaltsikhe. Figure 1 shows the study areas on the map, while Table 1 summarizes the geographical data for study plots. Akhaltsikhe is situated in the Samtskhe–Javakheti region of southern Georgia, serving as the administrative center of Samtskhe–Javakheti and Akhaltsikhe Municipality. The town lies within a mountain depression known as the Akhaltsikhe Hollow, typically at elevations ranging from 900 to 1,500 m above sea level [12].

Topographically, Akhaltsikhe occupies a mid-elevation zone within a broader mountainous landscape: the Trialeti and Meskheti Ranges to the north, and the Javakheti Plateau to the south and east. The terrain supports a transition between the valley flood-plain (of the Kura/Mtkvari River) and the surrounding uplands, with local elevation between approximately 950 m and 1,575 m.

Climatically, the region has a continental mountain climate, with mean annual temperatures near 9.5 °C, average January temperatures around -1.4 °C, and July averages near 19.5 °C [12]. Precipitation ranges from 400 mm to 1,400 mm annually, with lower values in the Akhaltsikhe basin and higher rainfall on elevated slopes; transitional zones receive roughly 508–654 mm/year, peaking in May–June and lowest in December–January [13]. The pure pine plot observed no significant structural changes compared to earlier measurements. The only differences were the death of one tree and a slight loss of height in several others, caused by snow damage. In the mixed-species plot, changes were more notable: five trees were cut during management activities, four died naturally, and seven new trees were added to the dataset after reaching the minimum measurement size.

Table 1: *The summarized geographical data for study plots*

Plot Type	Longitude (°, ', '')	Latitude (°, ', '')	Exposition	Inclination (°)	Altitude (m)
Mixed Forest	41.6077	42.9771	E	7	1559
Pure pine Forest	41.6078	42.9769	E	6	1499



Figure 1: *Location of the study plot south of Akhaltsikhe, Georgia. The image shows the forest area used for research, situated near the town in the Samtskhe–Javakheti region.*

Field Measurements and Data Processing.

In 2025, a remeasurement was carried out in the same pure Pinus sylvestris and mixed stands previously surveyed in 2019 within the Akhaltsikhe municipality. During this fieldwork, updated values for diameter at breast height (DBH) and total tree height were recorded for all trees with a DBH of 7 cm and higher, as the usual DBH caliper was used for tree Diameter at breast height measurement, and the vertex clinometer was used for tree height measurement. These two parameters were sufficient to reassess stand structure, estimate growth over time, and update aboveground carbon estimates.

No new wood samples were collected in the current phase. Instead, previously obtained data, such as wood density and carbon content percentage, were used. Pure pine stands showed 51% while mixed stands showed 53%, from 2019 measurements through oven-dried mass and laboratory combustion methods. This approach provided consistency and allowed for a reliable comparison of changes over a five-year interval [14].

The basal area (BA) of each tree was calculated using the standard formula (1) [15, 16]:

$$G = \frac{\pi \times (DBH/2)^2}{10000} \quad (1)$$

To estimate stem volume, a taper-based volume equation was used, adapted from Bettinger:

$$V = F \times H \times G \quad (2)$$

where H is tree height and F is a form factor (species-specific), derived from local growth conditions.

Stem biomass was estimated as:

$$\text{Biomass} = V \times P \quad (3)$$

where P is the wood density (kg/m³), obtained from the 2019 sampling.

To estimate stem carbon content, the following equation was applied:

$$\text{Carbon} = \text{Biomass} \times C\ \% \quad (4)$$

where C% is the carbon concentration in oven-dried biomass, previously measured for this stand.

After this, the averaged data was multiplied by 3,65 to find the exact number of carbon sequestration. All data were scaled to a per-hectare basis using the plot area and expansion factor. A slope correction was applied to adjust for terrain inclination. The resulting metrics included tree density, total stem volume, biomass, and carbon stock per hectare [17, 18].

III. Results and Discussion

Morphometric and Carbon Changes in Mixed and Pure Pine Plots

This section presents the changes in tree morphometric characteristics and carbon-related variables between 2019 (or 2020 for pure pine) and 2025. The mixed-species and pure pine plots exhibited positive growth trends in DBH, height, volume, biomass, and carbon sequestration. The mixed forest plot includes broadleaf (Carpinus orientalis, Quercus petraea iberica, Quercus macranthera) and conifer (Pinus sylvestris) species, while the pure plot consists mainly of Pinus sylvestris.

General Growth Trends are given in Tables 2, 3, and 4.

Table 2: *Average Tree Morphometric and Carbon Data per Species*

Tree No.	Species	Year	DBH, cm	H, m	Volume 2019, m³	Biomass 2019, kg	Dry Bio 2019, kg	Carbon 2019, kg	Carbon Seq. 2019, kg
Mixed forest plot									
7	Carpinus orientalis	2019	20.46	15.3	0.4134	211.29	163.52	76.85	280.51
		2025	21.58	15.42	0.4866	248.74	192.46	90.46	330.16
44	Quercus petraea ssp. iberica	2019	18.31	14.35	0.2935	152.25	116.52	54.77	199.9
		2025	19.58	14.73	0.3389	176.01	134.51	63.22	230.74
15	Quercus macranthera	2019	22.2	16.58	0.4762	243.57	188.18	88.45	322.82
		2025	24.61	17.69	0.5873	300.07	231.87	108.98	397.77
98	Pinus sylvestris	2019	19.81	14.69	0.3309	172.02	131.43	61.77	225.47
		2025	21.27	15.16	0.3908	203.17	155.24	72.96	266.31
Pure pine forest plot									
1	Prunus avium	2019	7	5.9	0.0132	7.13	5.56	2.95	10.75
		2025	8.5	6.2	0.0157	8.45	6.59	3.49	12.76
4	Picea orientalis	2019	9.5	7.33	0.0272	28.41	22.16	6.08	22.18
		2025	12.7	9.2	0.0526	42.87	33.98	11.74	42.87
59	Pinus sylvestris	2019	24.63	20.45	0.4998	269.89	210.52	111.57	407.24
		2025	25.88	21.73	0.5577	301.15	234.89	124.49	454.4

Table 3: *Percentage Change in Parameters from 2019/2020 to 2025*

Tree No.	Species	DBH % ↑	H % ↑	BA % ↑	Volume % ↑	Biomass % ↑	Dry Bio % ↑	Carbon % ↑	Carbon Seq. % ↑
Mixed forest plot									
7	Carpinus orientalis	5.48%	0.78%	12.89%	17.69%	17.71%	17.71%	17.71%	17.71%
44	Quercus petraea ssp. iberica	6.90%	2.64%	12.80%	15.49%	15.60%	15.43%	15.44%	15.44%
15	Quercus macranthera	10.83%	6.70%	18.11%	23.37%	23.16%	23.25%	23.23%	23.23%
98	Pinus sylvestris	7.36%	3.43%	13.33%	18.09%	18.10%	18.13%	18.13%	18.13%
Pure pine forest plot									
1	Prunus avium	21.43%	5.08%	12.90%	18.94%	18.54%	18.53%	18.53%	18.53%
4	Picea orientalis	33.68%	25.59%	53.57%	93.75%	50.89%	53.39%	93.75%	93.31%
59	Pinus sylvestris	5.07%	6.25%	5.26%	11.60%	11.59%	11.58%	11.58%	11.58%

The updated data clearly demonstrate a consistent increase in tree growth and carbon storage across all species over the six-year period. Among the broadleaf species, Quercus macranthera exhibited the highest relative growth, with increases exceeding 10% in DBH, 6.7% in height, and over 23% in volume, biomass, and carbon-related metrics. These findings underscore its strong adaptive growth potential in mixed-species stands. In the mixed forest plot, Pinus sylvestris showed stronger growth performance (18.09% volume increase) compared to the same species in the pure pine plot, which only achieved an 11.60% increase.

This supports the idea that mixed-species stands can enhance individual tree growth and ecosystem productivity. Such patterns align with global research indicating that species richness enhances forest productivity and carbon sequestration potential [19].

Interestingly, trees in the pure pine plot, particularly Picea orientalis, showed extreme growth rates—with a 33.68% increase in DBH and a 93.75% increase in volume and carbon sequestration. While this may reflect species-specific growth dynamics or microsite advantages, it also suggests that particular species can thrive in monocultures under favorable conditions. Pinus sylvestris in the pure stand had a greater height increase (6.25%) than in the mixed stand (3.43%), likely due to intense vertical competition common in even-aged monocultures. This behavior is well-documented in silvicultural studies, where trees grow taller and thinner in dense stands to access light [20]. Overall, the findings highlight the ecological and climate benefits of species-diverse forests, showing that mixed-species plots not only support greater biomass accumulation but also enhance carbon sequestration. These results prove that biodiversity promotes resource-use efficiency, ecosystem resilience, and long-term forest sustainability [21, 22].

Table 4: *Tree number, volume, biomass, carbon content, and carbon sequestration for mixed forest and pure pine stands in 2019 and 2025*

Forest type	Year	Tree number (trees/ha)	Volume (m^3/ha)	Biomass (kg/ha)	Carbon content (kg/ha)	Carbon sequestration (kg CO_2-eq/ha)
Mixed forest	2019	720	234.90	121,682.53	43,799.61	159,868.59
	2025	807	298.67	154,880.69	55,698.66	203,300.12
Pure pine forest	2019	787	364.11	196,621.54	81,283.35	296,684.21
	2025	787	406.88	219716.91	90830.97	331533.05

Between 2019 and 2025, mixed forests increased by 12.1% in tree density, 27.1% in volume, 27.3% in biomass, 27.2% in carbon content, and 27.2% in carbon sequestration.

Between 2019 and 2025, the mixed broadleaf–conifer forest demonstrated stronger relative growth than the pure even-aged pine stand. The mixed stand's tree density increased by approximately 12%, while volume, biomass, carbon content, and CO_2-equivalent sequestration all rose by about 27%. In contrast, the pure pine stand maintained constant tree density but still achieved around 11–12% gains in volume, biomass, carbon, and sequestration. This contrast reflects the structural differences between the stands. The mixed forest is uneven-aged, composed of both mature trees and younger recruits that emerged during the six-year period, enabling vigorous growth. Meanwhile, the pure pine stand is even-aged, limiting recruitment and therefore displaying slower relative growth, though its biomass and carbon stocks remain high.

Such patterns align with global experiment findings that mixed-species and uneven-aged stands often outperform monocultures in productivity and carbon sequestration, mainly due to complementary resource use and structural diversity. mixed-species forests were about 15% more productive than average monocultures, particularly in climates with adequate rainfall [23]. From a carbon-risk perspective, both stand perform essential but different roles. The mixed forest acts as a "growth engine," sequestering carbon rapidly through active recruitment and fast-growing young trees. The pine stand functions more like a "carbon reservoir," storing large amounts of carbon in mature biomass. This dual role—rapid uptake and long-term storage—enhances the forest landscape's resilience to climate-related disturbances.

Forest age dynamics are crucial to understanding carbon fluxes. Younger and mid-aged stands sequester carbon more rapidly per hectare, whereas aging forests contribute more to carbon storage than removal rates. Regrowing forests currently contribute more to global carbon uptake than old-growth systems, though the latter remain vital as stable carbon stores [24]. Simulations in New Brunswick showed that older hardwood-dominated forests continued accumulating carbon over time, underlining the value of mature stands [25]. Moreover, old forests—though slower in growth—possess substantial carbon reserves and provide ecosystem stability.

Mature and old-growth stands act as long-standing carbon pools, reinforcing the importance of preserving such structures [26, 27, 28, 29].

Risk mitigation is another benefit of mixed and uneven-aged stands. Structural and species diversity tends to buffer forests against disturbances such as pests, fires, and droughts, reducing the likelihood of abrupt carbon release. For example, mixed-species forests in Europe have been shown to sustain less storm damage than monocultures. These insights suggest that this regional forest system performs both roles essential to climate mitigation: the mixed stand accelerates carbon uptake, while the pine stand secures long-term carbon. The combination enhances ecosystem resilience and mitigates greenhouse gas risk effectively.

V. Conclusion

With the growing risks from greenhouse gas emissions and climate change, healthy forests are more essential than ever. They are natural carbon sinks, helping to remove CO_2 from the atmosphere and store it for long periods. Understanding exactly how much carbon different forests can store and how these changes over time is key to protecting and managing them effectively. Even small-scale studies can provide valuable insights. Though limited to only two study plots, the data collected here adds another piece to the puzzle. Comparing measurements from different years shows how carbon sequestration potential changes as trees age. Such information can help predict biomass and carbon trends in forests with similar species composition and climatic conditions.

While this study covers a small area and cannot represent all forest types in the region, it is an informative starting point. Our next research stage will expand to more plots, species, and repeated measurements over time. This will strengthen the accuracy of the data and allow for more meaningful comparisons. Forests are our allies in slowing climate change, but only if we understand and protect them. Even small, focused research projects like this contribute to that knowledge, helping to build the larger picture, one study at a time.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INTEGRATION OF SUSTAINABLE DEVELOPMENT PRACTICES INTO BUSINESS MODELS OF ECONOMIC SYSTEMS: PRINCIPLES OF THE GREEN ECONOMY

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Abstract

This article discusses the fundamental principles, directions and priorities for incorporating the green economy ideology and sustainable development practices into the operational processes of major Russian corporations. This study is relevant because it is necessary to introduce sustainable business practices into modern economic models of Industry 5.0. The methodology combines theoretical and empirical methods, including an analytical review of literature on the research topic, statistical and comparative analysis, and elements of SWOT analysis. The study aims to provide empirical evidence of the growth of corporate responsibility in terms of the adoption of green economy ideology and management practices within large companies. To achieve this goal, the activities of Russian companies such as Sber, Yandex, Lukoil, Rostec, Norilsk Nickel, Mail.Ru Group (VK), Beluga Group and X5 Group were reviewed. The main practices of Russian companies in terms of digitalization, sustainability, brand development and innovation were summarized. Conclusions were drawn about the growth of corporate responsibility in terms of achieving sustainable development goals. The prospects for the further integration of green economy models into modern business ecosystems were identified.

Keywords: sustainable development, green economy, green investments, innovation, digitalization, ecosystem, business model

I. Introduction

In the context of evolving geopolitical conditions and "some imbalance in global economic dynamics, reflected in a steady decline in economic growth" [1], Russian companies are increasingly required to implement innovative strategies to maintain competitiveness and foster long-term economic growth. Economic development under these new conditions is a creative process that "integrates all economic sectors to develop innovative products and services" [2]

Flexibility in responding to market shifts, combined with a focus on digitalization, innovation, and sustainable development, is crucial. The development vector of many Russian

companies includes creating "ecosystems to foster community engagement and social ties" [3], integrating new technologies, "promoting sustainable human capital development" [4] and adopting "advanced corporate management and planning practices" [5]. These efforts enable companies not only to secure strong positions in the domestic market, but also compete globally. This underscores the relevance of this research, as well as the need and novelty of introducing sustainable business practices into modern Industry 5.0 economic models.

II. Literature Review

The implementation of Sustainable Development Goals in business has become a central topic in economic scientific discourse. Therefore, all literature can be categorized into several thematic blocks. The general issues of market transformation amid shifting economic paradigms are being explored by leading Russian and foreign scientists (I. Gladkov, S. Glazyev, S. Tronin, M. Epstein et al.). Digitalization of economic processes, markets, and businesses has drawn special attention of Russian scientists following the adoption of the Digital Economy of the Russian Federation program. Scholars from the Financial University under the Government of the Russian Federation and the Russian Academy of National Economy and Public Administration (O. Brizhak, M. Buyanova, A. Kalinina, I. Averina, E. Kochetkov, D. Vasiliev, A. Sapozhnikov, and others). Further research of A. Sysolyatin, I. Kushova, L. Rudenko highlights ecosystem development, energy-efficient solutions, branding, and the enhancement of intellectual capital.

Environmental and green finance topics – such as green technology funding and environmental project investments – are addressed by Siedschlag, I. Eyraud L., Clements B., Wane A., S. Kodaneva. The role of economic and socio-cultural institutions in the transition to a green economy is a key area of interdisciplinary focus confirming the timeliness and relevance of this study (L. Terzić, A. Strizhak, T. Butova, V. Reutov).

III. Methods

This research employs the combination of theoretical and empirical methods. The theoretical component includes and analytical literature review. Empirical methods involve statistical and comparative analysis, along with elements of SWOT analysis.

IV. Results

Russian companies actively adopt digital and sustainable practices to enhance competitiveness through increasing efficiency, minimizing costs and improving the quality of services provided. PJSC "Sber" exemplifies the successful shift from traditional banking to a multiservice digital ecosystem, including e-commerce, logistics, healthcare and education. Leveraging artificial intelligence and big data management, Sber offers personalized solutions, which expands its customer base, and improves operational efficiency. Such approach has allowed Sber PJSC to integrate into the daily lives of customers, thereby strengthening audience loyalty and conquering new market segments [6].

One more example of successful application of modern practices is Yandex. Initially a search engine, it has evolved into a large ecosystem and has become a leader in various sectors of the Russian market. The success of this company is due to a combination of several factors: innovative use of technology, deep data analysis and integration of services. Yandex.Go combines ride-hailing, carsharing and delivery services. The most important component of gaining success was the introduction of machine learning and artificial intelligence algorithms through which the company optimized logistics and enhanced user experience. In an increasingly competitive

environment, this allows Yandex to exceed consumer needs and provide tools that greatly simplify their daily lives. Tis complex of measures makes a significant difference to a company's competitive advantage.

An important aspect of the modern competitive strategy is the commitment to environmental responsibility. A great example is the activity of the oil and gas company PJSC Lukoil. In recent years, the company has been actively working to reduce the environmental impact of its operations by introducing energy-efficient technologies and optimizing production processes. Significant investments in renewable energy, including the construction of solar and wind power plants, allow the company to meet environmental standards and maintain a positive reputation as a responsible market player. Such a strategy contributes to the formation of a long-term competitive position against the increasing interest in environmentally friendly technologies in the international market [7].

Rostec, a high-tech conglomerate, produces innovative defense and civilian technologies. It successfully uses innovative technologies and scientific developments to achieve sustainable development. Rostec actively invests in research and development, drives unique high-tech solutions and materials. One of the examples is the production of innovative aviation technology, which is used in both civil and military spheres, enhancing Russia’s global competitiveness in high-tech sectors [8].

Important trends in achieving competitive advantage through the corporate social responsibility (CSR) mechanism are of particular significance. Companies that integrate sustainable development into their strategy not only strengthen their socio-economic development, but also create additional value for consumers and partners. Norilsk Nickel, the largest producer of platinum group metals, implements large-scale projects and CSR practices to reduce its carbon footprint and improve the environmental situation in the regions where it operates. The use of advanced waste treatment and recycling technologies allows the company not only to meet the requirements of international environmental standards, but also to maintain a positive reputation, which strengthens investor confidence and market position [9].

As for the technology sector, the company VK (formerly Mail.ru Group) highlights the importance of diversification and continuous innovation of digital products in strengthening a company's competitive position. In addition to social networks such as VKontakte and Odnoklassniki, its digital ecosystem also spans online education, cloud platforms, and solutions for businesses. These initiatives are aimed at creating a broad ecosystem that unites millions of users, companies and developers, forming a stable customer base and ensuring a high level of interaction between its participants [10,11, 23-25].

In addition, the export potential of Russian companies plays an important role in modern practices. Thus, the Beluga Group’s (a premium alcoholic beverages producer) commercial success is associated with the strong brand development, investments in marketing campaigns in international markets and maintaining high quality standards. Owing to its effective work with a foreign audience, the Beluga Group has achieved success in the markets of Europe, China, and North America, which indicates the effectiveness of the chosen strategy with the focus on the authenticity of the brand and compliance with international quality standards.

In modern Russia, the raising awareness of using data and analytics for making managerial decisions has also become an important source of competitive advantage. Companies such as X5 Group focus on large-scale retail digitalization projects, introducing AI-driven inventory and logistics systems to analyze customer needs and personalize offers in outlets. Platforms based on the principles of big data help companies adapt to local demand, reduce costs and retain customers through a point-to-point approach to their needs.

Table 1 summarizes the main practices across Russian companies, emphasizing digitalization, sustainability, brand development, and innovation. Amid the key methods are: the creation of ecosystems, the implementation of energy-efficient solutions, brand strengthening, the

development of intellectual capital and the digitalization of business processes [12, 26-27]. This allows Russian companies to adapt successfully to the changing conditions of the domestic and global markets.

Thus, many Russian companies demonstrate successful examples of implementing modern practices for achieving competitive advantage. These practices range from the introduction of digital technologies into operational processes to the contribution to the environmental responsibility and brand strengthening, which enables companies to compete both domestically and internationally. Obviously, the key factor in their success is not only the ability to adapt to changing market conditions, but also a strategic focus on long-term development, where innovation, knowledge and integration of latest management tools become the main source of sustainability. It is precisely such practices that allow Russian companies to gain a strong credible position in the context of high technology, environmental transformation and global competition.

Table 1: *Trends in the formation of conditions for the sustainable development of companies*

Company	The practice of moving towards sustainable development	Key achievements and effects
Sber	Digitalization of business and creation of an ecosystem of services; the transition from the traditional banking model to a multiservice platform, including e-commerce, logistics, educational and medical services; active use of big data technologies, artificial intelligence and personalization.	Increasing customer loyalty and significantly expanding the audience by integrating multiple services; speeding up operational processes, reducing costs; strengthening its position as a key player in the domestic market and expanding market segments.
Yandex	Innovative use of technologies; development of an ecosystem; integration of transport, logistics and digital tools; using machine learning and analytics algorithms to optimize services such as Yandex.Go.	Providing leadership in the segments of e-commerce, logistics and transport services; faster order processing, lower costs, and increased user loyalty; creating a high-tech platform that adapts to the needs of customers.
Lukoil	Focus on sustainable development and environmental responsibility; implementation of energy-efficient technologies; optimization of production processes; investments in renewable energy.	Reduction of the carbon footprint, compliance with international environmental standards; maintaining the company's positive reputation in foreign markets; attracting strategic investors and new partners focused on environmental principles.
Rostec	Investments in research and development, specialization in the creation of high-tech products; production of innovative solutions for the civil and defense sectors, including automation and new materials; development of institutions that ensure the inflow of investments.	Development of unique products with high added value, maintenance of global competitiveness in high-tech segments, development of institutions that ensure the conversion of savings into investments; access to international markets through innovative technologies.
Norilsk Nickel	Implementation of corporate social responsibility, focus on environmental projects; development of technologies for production purification, waste recycling and emission reduction.	Improving the environmental situation in the areas of presence; formation of a positive image in the international arena; compliance with the standards of the "green" economy provides access to new partners and markets focused on responsible production.
Mail.ru Group (VK)	Continuous product renewal and diversification: development of platform solutions, including online education, cloud technologies, social networks and business platforms.	Expanding the audience through comprehensive services, strengthening interaction between users and companies; formation of a large-scale ecosystem that makes the company's internal relations more stable in the face of market changes.
Beluga Group	Strengthening the brand and its promotion in the international arena; investments in marketing campaigns, maintaining global standards of quality and uniqueness of products.	The brand's popularity is growing in the European and Asian markets, and its export potential is strengthening; compliance with international quality standards, which attracts customers in the premium segment of alcoholic beverages.
X5 Group	Digitalization of management processes in retail trade; the introduction of automated inventory management systems, the use of artificial intelligence to personalize product ranges.	Increased the efficiency of logistics and inventory management; reduced costs by optimizing the supply chain; strengthened the customer base by precisely adapting the product range and service to the needs of local markets.

The transition to a sustainable economy requires substantial public and private investment in green technologies and social-environmental projects [13]. Green investments contribute to environmental protection, job creation and long-term economic resilience. The pace of green capital accumulation has accelerated in recent years, following the technological progress, economies of scale, strong political support, and favorable public opinion. Green investments have become a key driver of the energy industry growth [14,28]. At the micro level, green investments positively correlate with financial performance: an increase in green investments contributes to an improvement in the economic performance of enterprises [15].

In recent years, green investments in Russia have drawn increasing attention of researchers and practitioners, especially within the context of global climate change and gradual shift towards sustainable development. Key projects include investments in the following sectors:

Renewable energy –solar, wind, and hydro power;

Energy efficiency – infrastructure upgrades to reduce energy consumption;

Waste management –recycling and waste sorting systems;

Ecological transport – electric vehicles and cycling infrastructure;

Green bonds – instruments for financing green projects.

The Government is active in this area through various initiatives and programs aimed at supporting the green transition.

In 2023, global clean energy investments reached $1.9 trillion, which is 10% more than in 2022 and significantly exceeds the $1.1 trillion invested in fossil fuels. Between 2024 and 2030, projected annual growth is 10% for renewable (solar and wind) installations, 25% for energy storage, and 17% for electric vehicles (all this significantly exceeds the expected growth rates of the global economy and demand for fossil fuels during this period) (Green Investment Group's Progress Report 2024).

However, the Morgan Stanley Capital International World Index data shows that renewable energy investments yield more consistent returns than oil and gas post-2016. Investment multipliers for all withdrawn assets in renewable energy sources and oil and gas, which demonstrate the level of actual income received by investors from the withdrawn assets, are shown in Fig. 1. (MSCI Private Capital).

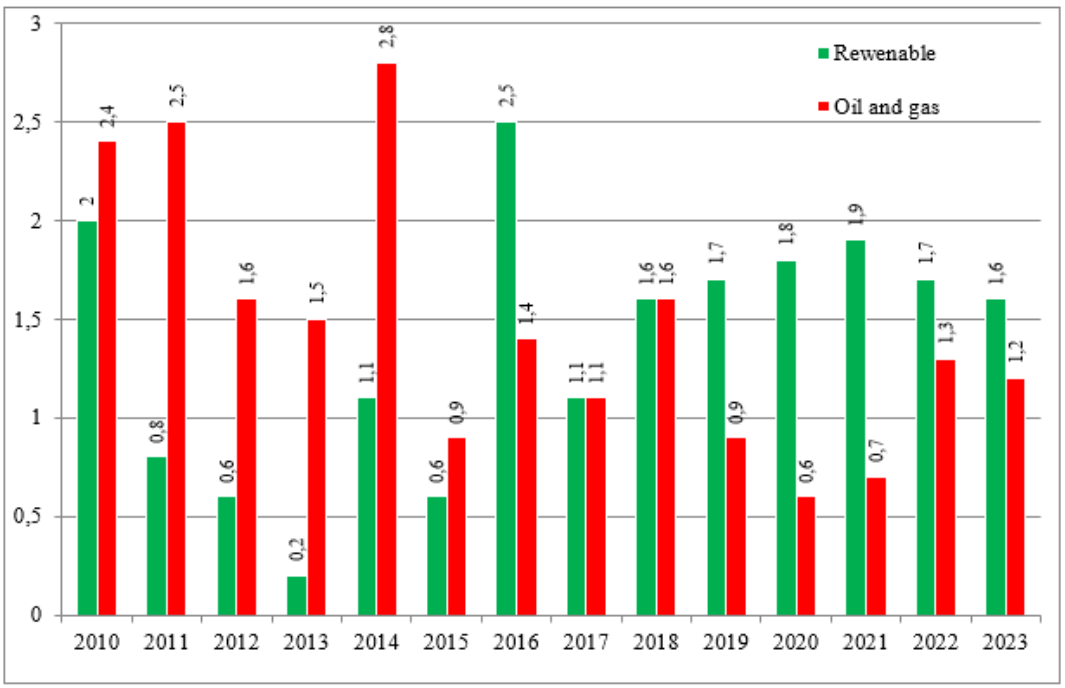


Figure 1: *Pooled investment multipliers for exited holdings*
Source: MSCI Private Capital; Green Investment Group's Progress Report 2024

Renewable energy outputs have shown positive returns (excluding fees) in all years since 2016, compared with only two years of positive returns between 2010 and 2015. Since 2016 (excluding 2018), the profitability of released assets in renewable energy sources has exceeded the profitability of oil and gas. This is in stark contrast to the period before 2016, when oil and gas outperformed renewable energy between 2010 and 2015. However, challenges remain, including the exit of private funds and short-term profitability concerns.

According to the Global Green Finance Index 12 (2023), ESG analytics, energy efficiency, and renewables are top areas of investor interest. The least attractive areas of green financing are: Climate Risk Stress Testing, Green Loans, Greentech Venture Capital (Fig. 2).

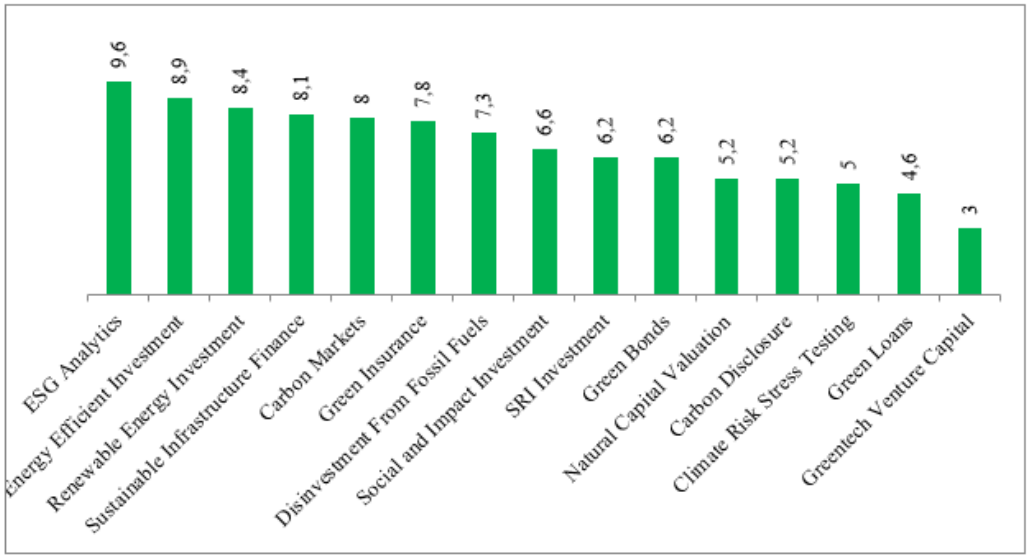


Figure 2: *Areas Of Green Finance Of Most Interest To Respondents, Percentage Of Total Mentions*
Source: Global Green Finance Index 12

The areas of green finance that, according to the results of this study, have the greatest impact on sustainable development are shown in Fig. 3.

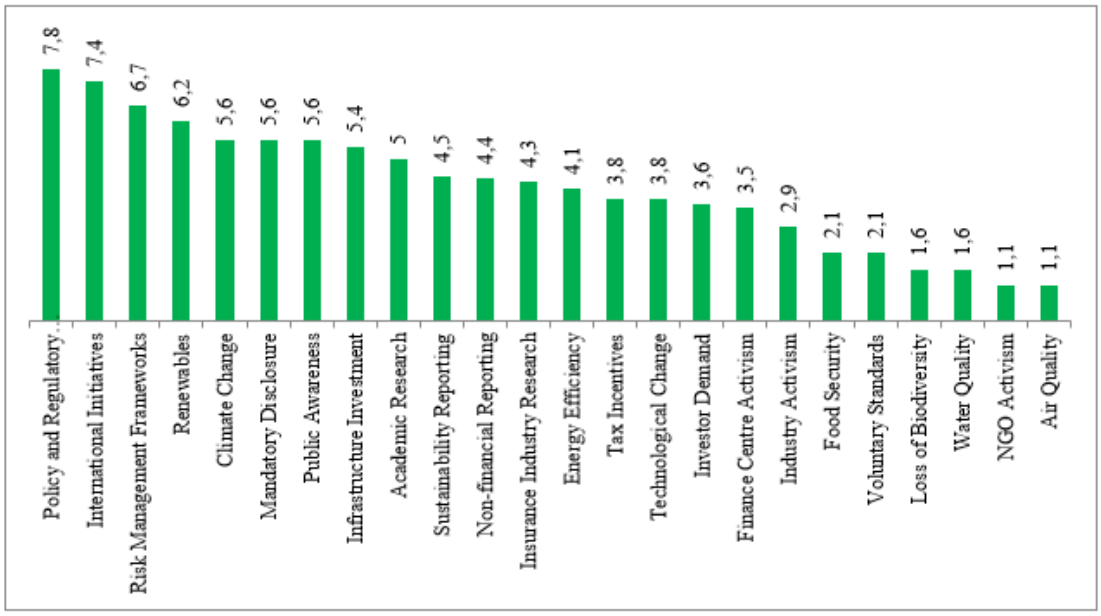


Figure 3: *Drivers Of Green Finance, Percentage Of Total Mentions*
Source: Global Green Finance Index 12

Key drivers that have the greatest impact on sustainable development are: Policy and Regulatory Frameworks, International Initiatives, and Risk Management Frameworks. Drivers as air quality, NGO activity, and loss of biodiversity are the least frequently mentioned by respondents. These results highlight the continuing importance of policy, regulation, and international cooperation in the development of green finance.

The leading centers of green financing are large cities: London, New York, Geneva, Zurich, Luxembourg, Stockholm, Washington, Los Angeles, Singapore, Copenhagen, Amsterdam, Montreal, San Francisco, Sydney, Chicago.

As for the Russian financial market, as of June 2025, the volume of sustainable bond debt reached 405 billion rubles, with green bonds accounting for 223 billion (Bank of Russia, Securities Statistics). As the analysis of debt securities issued on the domestic market sector shows (Fig. 4), a notable spike in occurred in 2022, amounting to 133660 million rubles (i.e. more than 10 times compared to 2020) and confirming increased interest in green finance [16-19].

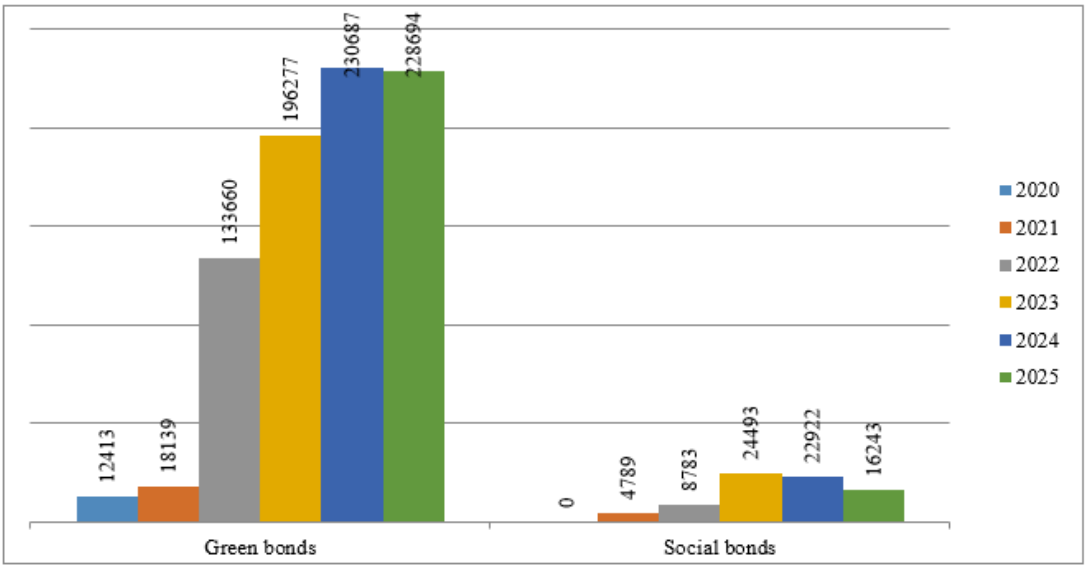


Figure 4: *Amount outstanding of debt securities issued in domestic market and included in sustainable development at nominal value (taking into account redemption), Millions of Rubles*
Source: Bank of Russia, Securities Statistics.

In 2024, the figure reached 230687 million rubles, having slightly decreased to 2286.94 million rubles in 2025. The peak growth in the issue of social bonds occurred in 2023, reaching 24493 million rubles. Since 2024, the social bonds issuance has decreased by 1571 million rubles, and in 2025 – by 8250 million rubles, compared to 2023, reaching 16243 million. The rapid growth in the issuance of green and social bonds indicates an increased investor interest in sustainable development, support of social projects and green initiatives. Investing in such projects contributes to the environmental responsibility, social justice, and creates incentives for sustainable economic growth.

V. Discussion

The study confirms that Russian public and private companies are actively adopting eco-friendly innovative business models and practices in order to achieve sustainable development goals.

However, our overview did not cover the existing barriers such as insufficient investment, weak infrastructure, and administrative hurdles that impede the full realization of "green

transformation" [20]. There is a significant need in specific institutions aimed at developing green investment in Russia. The transition of Russian society from a model of total consumerism to a model of responsible consumption plays the key role in the implementation of the concept of sustainable development [21-22,29].

Additionally, cultural and ethical attitudes toward sustainability remain inconsistent, affecting the pace of progress.

VI. Conclusion

Technological transformation and breakthroughs have created opportunities for deeper integration between nature and society. Yet, over the past decades, humanity has been facing the problem of climate change, continuous reliance on outdated practices in the energy sector, slowly raising responsibility for damage made to nature by economic activity, and continual exploitation of natural resources. Humanity must shift from extractive to regenerative economic behavior.

However, the potential to quickly reverse environmental degradation should not be overestimated. The balance of influence still favors those who continue ignoring the greenhouse effect, water scarcity, and waste issues. The longer it takes to ignore the inadequate attitude towards the environment, where we extract vital resources from, the more challenging it will be to solve the problems accumulated in it.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INFORMATION RISK MANAGEMENT BASED ON FUZZY COGNITIVE MODELING

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Abstract

The article examines information risk management using fuzzy cognitive modelling. Within the framework of the FCM methodology, a graph was constructed to identify the cause-and-effect relationships between the main concepts in the subject area that give rise to risk, in order to assess current risk levels. A method for determining an acceptable level of risk under subjective uncertainty, based on expert information, was developed. To determine the acceptable risk level for an organisation, the functional dependence of the probability of loss on its scale was established, and a graph of this dependence was created. To more fully reflect the decision-maker's opinion on the volume of acceptable risk, the concept of an acceptable risk curve was applied. This allows both numerical and verbal expert assessments to be taken into account, reducing the level of subjective uncertainty. An algorithm for constructing this curve was also developed.

Keywords: Fuzzy cognitive model, acceptable risk zone, information security, linguistic variable, polygon of possible risk values, tolerant risk zone

I. Introduction

Any activity, except for material and energy flows, necessarily contains an information component. At the same time, in ensuring the reliable functioning of information processing processes and achieving the required level of information security, the management of risks of violation of information properties (confidentiality, availability, integrity, etc.) in the process of its processing (information risk management) plays a special role. The problem of information risk management is a complex task that combines a number of different areas: the preparation of an agreed opinion on the acceptable level of risk; assessment of the current state of risks in the coordinate space "harm from threats - probability of realization of the danger"; finding acceptable measures for the decision-maker to reduce the risk level to target values; implementation of the solutions found. At the same time, most of the parameters used in the process of preparing management decisions do not have crisp (numerical) values, are formulated by experts in verbal form and are subjective. In addition, there is an ambiguity of the concept of "risk", as well as opportunities to eliminate various manifestations of risk and its negative consequences. Thus, the assessment and management of risks arising in the information processing process is a complex, poorly structured, and poorly formulated type of activity.

II. Problem solving methods

Risk management includes risk analysis (assessment), development and implementation of management decisions. Risk analysis involves identifying vulnerabilities and threats, assessing possible impact, which allows choosing adequate protective measures for those systems and processes in which they are needed. It helps the company rank the list of risks, determine and justify the reasonable cost of protective measures and make the security of the functioning of information systems cost-effective, relevant, timely and capable of responding to threats.

1. Algorithm for determining acceptable risk based on expert information

One of the basic, or "central" concepts of the risk management process is the concept of acceptable risk. Acceptable risk is understood as the risk that a decision-maker is willing to accept in a given situation [8].

In the mathematical formulation of the problem, the risk quantity is usually calculated using the following formula:

$$R = P \otimes U ,$$

so, here P is the probability of an unfavorable event occurring;
U is its consequences;
$\otimes$ – is a composition that is determined in a certain sense .

However, the prices obtained in this way are not sufficiently informative for the decision-maker and do not allow him to make informed choices in management decisions.

Therefore, another approach is needed to assess acceptable risk, which is based on the following assumption: the greater the potential harm, the lower the probability of its occurrence must be for the decision-maker to be willing to accept it. Thus, the essence of the concept of "acceptable risk" can be written as follows:

$$\forall U \exists ! P : P^*(U) = P \tag{1}$$

Based on this, it is generally proposed to consider the functional dependence of the probability of a certain loss occurring on its quantity, which is described by the acceptable risk curve:

$$P^* = P^*(U), \tag{2}$$

so that here $P^*(U)$ is a monotonically decreasing function reflecting the acceptable probability $U^{\min or}$ of the occurrence of damage ; $U^*: U^* \in [U^{min\,or}; U^{crtic}]$- is the damage that is insignificant for the decision maker, that is, the value below which damage is not taken into account; U^{critic} - critical, that is, is the maximum acceptable damage for the decision maker, since the probability of its occurrence should be minimal and ideally tends to zero.

P(U)* can be varied. For example, the probabilities of possible losses in accidents are often described by a Gaussian distribution [18; 118]. In some cases, $P^* = a/(1+\exp(b\cdot(U-U^{\min or}))$ it is appropriate to use a function that describes an S-shaped curve.

P^* The following function can be used as a quantity:

$$P^* = a \cdot \exp(b \cdot (U - U^{\min or})), \tag{3}$$

so that here: the constant a $U^{\min or}$ corresponds to the probability of minimal "insignificant" damage occurring; the constant b U^{critic} determines the rate of decrease in the acceptable probability of accepting damage as it approaches its value.

The choice of the exponential function for the approximation is due to its widespread use in describing experimental data in various fields. In particular, the exponential function provides a good approximation of the piecewise linear Farmer function, which is widely used in assessing the risks associated with man-made accidents and natural disasters [11;12].

Formation of an expert group

The following should be considered when establishing an expert group to determine the

acceptable risk quantity and selecting experts to be included in it:

- experts should be selected from among managers;
- experts should be selected from departments that ensure reliable operation of the information processing process;
- experts should be selected from departments dealing with the economic (financial) support of the organization's activities;
- certain external experts should be selected by agreement.

It is also necessary to include experts who are familiar with the organization's activities and have qualifications and experience in the field of information technology application and (or) information security, as well as in the field of economics and enterprise management.

The independence of the experts is one of the most important issues. There should be no factors (commercial and financial interests or other pressures) that could influence the decisions they make. Thus, the composition of the expert group should consist of at least four experts.

The Delphi method can be used to coordinate the opinions of experts [9; 10].

Algorithm for constructing an acceptable risk curve

classify the amount of potential damage to an organization's assets as a result of an adverse event ( ). While verbal forms are used to describe categories of damage, the Harrington scale is used to compare numerical values for different damage classes [96]: “Negative damage” - 0.1·U U_i^{critic}; "Slightly significant damage" - 0.29·U ^{critic}; "Moderate damage" - 0.51·U ^{critic}; "Significant damage" - 0.72·U ^{critic}; "Critical damage" - 1·U ^{critic}.

2) The decision maker U_i assesses the probabilities of occurrence $R^* = \{(U_i; P_i^*)\}_{i=\overline{1,N}}$ of various categories of harm : P_i^* in terms of their acceptability.

3) The values U_i indicated at the reference points P_i^* are approximated by the continuous function in expression (3) using the least squares method. As a result of the approximation, the values of the coefficients ***a*** and ***b*** are found.

A graphical representation of the acceptable risk function is depicted below (Fig. 1).

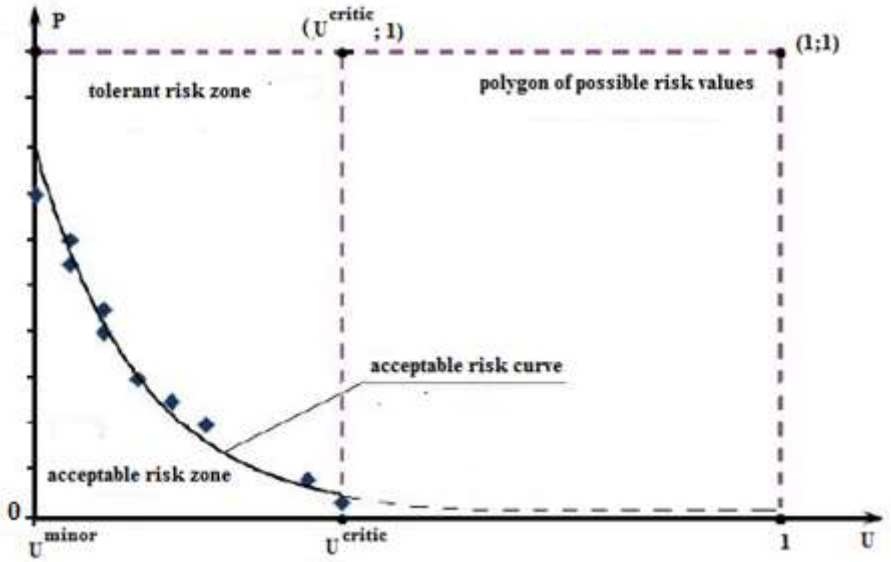


Figure 1: *Graph of the acceptable risk function*

Along with acceptable risk, the concept of tolerable risk is also used in risk management, that is, the maximum level of risk that an organization can tolerate without significant damage to its financial and competitive position [9;6]. Typically, the tolerable risk level is defined as a share of the company's authorized capital and is determined by the internal risk management policy. In Figure 1, this concept corresponds to the tolerable risk zone located on the border of the rectangle

with vertices (U ^{minor} ; 0), (0; 1), (U ^{critical} ; 1), (U ^{critical} ; 0). The rectangle with vertices (U ^{minor} ; 0), (0; 1), (1; 1), (1; 0) is called the polygon of possible risk values. The area bounded by the coordinate axes and the acceptable risk curve constitutes the acceptable risk zone.

In the case of a discontinuous P* function, the acceptable risk quantity is found using the following formula:

$$R^{accep} = \left\lfloor \int_{U^{\min or}}^{U^{critic}} P^*(U)dU \right\rfloor / \left(U^{critic} - U^{\min or}\right). \quad (4)$$

In formula (4), the denominator represents the area of the tolerant risk zone. Dividing the tolerant risk zones into areas allows us to normalize the risk level with respect to the critical value.

2. Building a fuzzy cognitive model for assessing current (relevant) risks of information processing

The fuzzy cognitive model (FCM) methodology involves constructing a fuzzy cognitive graph that reflects the relationship between the main factors of the subject area and their mutual influence; assessing the state of factors and the degree of their influence on other concepts in the hierarchy; and calculating the values of concepts above the hierarchy based on the known values of the factors affecting them. Let's consider each of these stages.

2.1. Construction of a fuzzy cognitive graph

A fuzzy cognitive model for assessing current and relevant risks of information processing can be described as an 8-level graph as follows (Fig. 2).

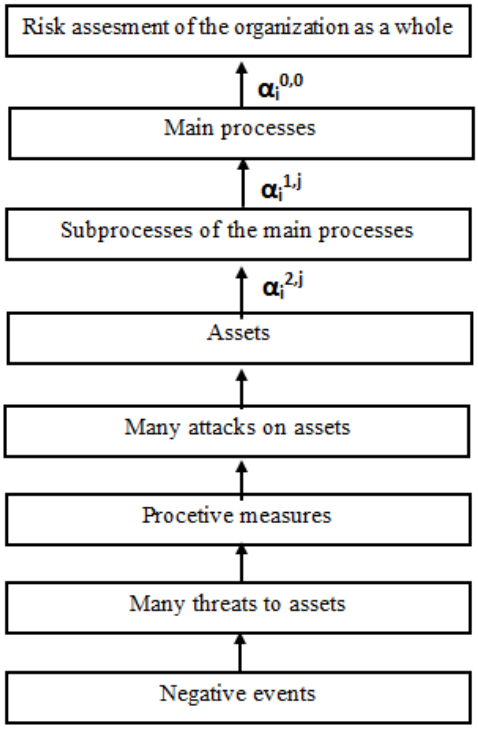


Figure 2: *Levels of the FCM graph for assessing current risks*

Let's denote the described graph by G and explain it level by level:

At the lower, 7th level, there are concepts that reflect the probability of a negative event that could pose a threat to the information assets involved in the organization's core business processes. In general, each negative event can pose many threats of varying intensities with varying probabilities, which in turn determines the level of possible damage to the organization's information assets.

Therefore, at level 6, I_i concepts are located that reflect the intensity and probability of occurrence of possible threats caused by negative events of level 7. In this case, intensity is understood as the potential harm that a threat can cause. P_{I_i}

At level 5 I_i, concepts $Z_{P_{I_i}}$ reflecting the effectiveness of the protection measures applied to reduce their quantity Z_{I_i} and quality P_{I_i} are located.

At level 4, there are concepts that correspond to the probability and degree of destructiveness (carried out despite the implementation of security measures and threats) of attacks on information assets supporting the organization's sub-processes.

At Level 3 risks to assets reflect the likely deterioration of the condition of the organization's information assets.

At Level 2 concepts reflect risks to sub-processes of the organization's core processes and describe the decomposition of level 1 concepts. The decomposition is carried out until it is possible to identify all significant information assets that may be subject to attacks.

At Level 1 includes concepts that reflect risks to the organization's core processes (i.e., the likely reduction in the quality of the execution of a key event).

At Level zero includes an assessment of the information processing risks of the organization as a whole and a corresponding overall (integrated) risk assessment.

The values of some concepts included in the graph hierarchy can be determined numerically. For example, after processing the collected statistical data, numerical data are obtained. However, in most cases, it is difficult to determine the values of factors numerically, and therefore it is necessary to resort to expert assessment methods. Expert assessments are usually verbal in nature. Therefore, to formalize the information received from the expert , it is necessary to include a linguistic variable L, *the values of which are a set of terms:*

QL = {Low (A); Below Average (OA); Average. (O); Above Average (OY); High (Y)}. (5)

To move on to quantitative description, it is appropriate to associate this term set with a five-level classifier, where the membership functions of fuzzy numbers describe a trapezoid given in the segment [0; 1]:

{ "A" (0; 0; 0.15; 0.25); "OA" (0.15; 0.25; 0.35; 0.45); "O" (0.35; 0.45; 0.55; 0.65);
"OY" (0.55; 0.65; 0.75; 0.85); "Y" (0.75; 0.85; 1; 1)}, (6)

Using a classifier allows you to move from a qualitative (verbal) description of a parameter to a quantitative description in the form of a corresponding membership function of fuzzy trapezoidal numbers.

If, in addition to qualitatively assessed factors (“fuzzy”), FCM contains concepts whose values are quantitatively determined crisp , then it is appropriate to use the proposed method for the joint use of quantitative and qualitative information [4]. Thus, the following formula is used to calculate the quantitatively measured F_i It involves calculating the normalized value according to the factor . $\overline{F_i}$

$$\overline{F_i} = (F_i - F_{\min})/(F_{\max} - F_{\min}), \quad (7)$$

where F_{max} and F_{min} are the maximum and minimum values of F_i, respectively .

is described by $(a_1 = a_2 = a_3 = a_4 = \overline{P_i})$ a fuzzy number X such that (a_1, a_2, a_3, a_4). If has $\overline{P_i}$ a quantity δ error, then $a_1 = a_2 - \delta; a_2 = a_3 = \overline{P_i}; a_4 = a_3 + \delta$. Thus, the normalized crisp value of the factor is described as a special case of a fuzzy in the interval [0;1].

To take into account the interaction of concepts in a cognitive graph, $\{\alpha_{ij}\}$ it is necessary to consider the set of weights of the edges of this graph.

2.2. Determination of the intensity of interaction of factors

$\{\alpha_{ij}\}$ The values of the weights from the set (usually, $\alpha_{ij} \in [-1;1]$) can be obtained by interviewing experts. For example, in the Situation and Compass systems, the expert compiles a set of linguistic assessments reflecting the strength of the influence. Then, each element of the set of assessments is depicted as equidistant points on the [–1; 1] partition [6].

The Canvas system uses indirect methods to determine the strength of the impact: the expert estimates the possible change in the impact factor values for a given change in the result factor value. According to the authors, this should help reduce the error in the expert assessment [6].

These approaches involve moving the maximum price from the lower to the upper level of the FCM, and this is based on the assumption of the independent influence of causes on the influencing factors.

If the value of the increase in the resulting factor is related to the combined effect of several factors, then the contribution of each causal factor must be determined differently. Such models were proposed by Roberts and later analyzed in the works [5;12].

At this point, "it should be noted that "soft" quality measurements such as comparison, class assignment, ordering are much more reliable than subjective probabilities, quantitative assessments of the importance of criteria, "weights" of utilities, etc." [2; 7]. In addition, in most cases, experts have difficulty in providing accurate numerical assessments. As a result, it is preferable to use ranking methods whose application requires only the ranking of factors.

In [4], a modification of the non-rigorous ranking method was proposed to assess the intensity of fuzzy relationships between factors. According to this, the expert numbers all the criteria in increasing order of importance. Sometimes, cases are also allowed when the expert cannot distinguish some criteria from each other. In this case, during the ranking, the expert puts them in the same position in an arbitrary order. Then the positions of the sorted list are numbered sequentially. The rank of the factor is determined by its number. If several factors that do not differ from each other are in the same position, then the number of its group in the ranking is taken as the rank of each of them. The values found by this method are a generalization of the concept of Fishburne weights to the situation where, in addition to preferences, there are also indifference relations.

When using this method, it is necessary to determine the dominance relations in the graph *G :*

$$E = \{GF_i(e)GF_j \mid e \in (>, \approx)\}, \quad (8)$$

here GF_i and GF_j Factors located at the same level of the hierarchy; $\approx$ *indifferent* attitude; $\succ$ It is a relationship of superiority.

allows us to determine normalized Fishburne weights (connection weights) for the arcs of the graph GD_{ij} *G* for the case of the joint influence of several causal factors on the effect factor.

When determining the "weights" of the main business processes, their contribution to the organization's activities (for example, the share of profit attributable to the main process) is taken into account. Thus, the "weights" of the main process and sub-processes are normalized by the number 1. In turn, the weight coefficients of information assets in the sub-process are defined as the sensitivity of the sub-process to the failure of this asset and can take values from 0 to 1.

2.3. Calculation and defuzzification of fuzzy values of fuzzy cognitive model concepts

In FCM , to calculate the values of concepts, it is necessary to linguistically estimate the values of the parameters of the lower levels of the hierarchy (using the values of the QL term-set) and determine the set of influence weights $\{\alpha_{ij}\}$. Then, the influences of the concepts located lower in the hierarchy are aggregated according to the rules $\boldsymbol{R}_i$, so in this case, additive, multiplicative, minimax, etc. curves of the vector criterion can be used. In this case, if it is possible to compensate for the values of some factors by others, an additive curve can be used. Unlike an additive curve, the value of a multiplicative curve decreases sharply with a decrease in the individual individual

scores. This allows us to take into account such options when making decisions, when each of the factors is significant and there is no mutual compensation between them. In especially critical cases, it is necessary to use extreme (minimum or maximum) values (the "weakest link" principle). In this case, it is appropriate to use the centroid method to compare trapezoidal fuzzy numbers, since the calculation of "average" values most fully reflects the characteristics of this type of fuzzy numbers [4].

When assessing the risks arising from the combined effects of a finite number of independent hazards, the following additive equation can be used:

$$F = \sum_i \alpha_i F_i , \tag{9}$$

where are the weights of the influence of α_i the quantity F_i factors on the F factor.

In this case $\alpha_i \in [0;1]$, when finding the svyortkas, the values of some concepts must first be inverted to take into account their negative effect. To find the inverse value (inversion) of the linguistically described factor *F*, the following formula can be used:

$$Inv(F) = (1 - \mu(F)), \tag{10}$$

Here $\mu(F)$ F is the membership function of the fuzzy number corresponding to the linguistic value of the factor.

When finding the svortkas, the product or sum of linguistic values is understood as the product or sum of the corresponding fuzzy numbers. It is also possible to use special software for calculations with fuzzy numbers .

The result of operations with fuzzy numbers is also a fuzzy number that must be defuzzified in order to make a judgment about the quantitative level of indicators. The "center of gravity" method can be used to defuzzify the calculated fuzzy value. When choosing trapezoidal fuzzy numbers of type (6) as a classifier, the defuzzification function (Def) of an arbitrary trapezoidal fuzzy number A will have the following form:

$$De(A) = (a_2 + a_3) / 2 . \tag{11}$$

For example, a verbal score of "above average" (OY) corresponds to a trapezoidal number (0.55; 0.65; 0.75; 0.85). Its fluency is (0.65+0.75)/2= 0.7.

The resulting defuzzified value is a metric characteristic that reflects the state of the concept in the FCM.

The following tuple can be used as a fuzzy cognitive graph to assess the current risks of information processing :

$$RSK =< G, QL, \{\alpha_{ij}\}, R, Def >, \tag{12}$$

where G is a fuzzy cognitive graph reflecting the relationship of the main concepts involved in risk assessment; QL is the term-set of linguistic evaluations of parameter values (2.5) with the corresponding fuzzy classifier (2.6); $\{\alpha_{ij}\}$ is the set of weights of the languages of the graph G to find which preference relations are determined on the graph, which in turn allows us to determine normalized Fishburne weights (relationship weights) for the arcs of the graph G using the non-strict ranking method; R is a set of rules that aggregate the influence of various lower-level concepts on the higher-level concept; Def is the fuzzy value defuzzification function obtained as a result of calculations using the fuzzy cognitive graph.

If it is necessary to include new knowledge obtained as a result of studying the processes affecting the risk level in a specific system in the proposed model, it is advisable to present this knowledge as a low-level fuzzy cognitive model built according to the scheme described above. This method of hierarchically constructing fuzzy models allows for the unification of the description of knowledge and contributes to its more efficient storage and processing.

In general, the values of fuzzy cognitive model concepts depend on time ***t*** . Thus, when assessing risks at t = 0, it is necessary to give the initial values of the factors. Then, to find the values of the concept *Kj* for discrete values of *t = 1, 2, 3, ...*, the following formula can be used:

$$K_j(t+1) = K(t) + H(\Delta K_i, RSK, t+1), \quad (13)$$

where ΔK_i - are the increments of the concepts K_j affecting K_i -; - is the generalized function of the impact $H(\Delta K_i, RSK, t+1)$ on the output price ΔK_i determined by the RSK tuple K_j.

Threats I_i intensity and their P_{I_i} The apparatus used to find values reflecting the probability of occurrence depends on the sources of occurrence of negative events at the initial moment in time.

When the threat to information assets is associated with objective processes of a technogenic or natural nature, probability theory and mathematical statistical methods can be used. As a result of their application, the threat P_{I_i} The probability of occurrence is determined and, after normalization, the intensity of each threat I_i is evaluated by the corresponding membership function in [0;1]. In this case, the number 1 corresponds to the intensity of the threat that leads to the complete destruction of the concept to which this threat is directed.

If the threat is associated with a subjective factor, then it is necessary to build a separate low-level FCM, that is, a "subject model". In this case, depending on the degree of loyalty of the subject, the goals he sets, etc., it is necessary to take into account the level of motivation for his actions, the level of his psychological and physical capabilities, his competence (level of knowledge and skills) and technical equipment, that is, the means and methods he uses, the level of his rights in relation to the assets of the system, etc.

If the probability assessment is carried out by experts and expressed verbally, then it is necessary to use the Harrington scale to convert this assessment into a numerical format [98]:

"Low probability" – 0.1; "Below average probability" – 0.29; "Average probability" – 0.51;
"Above average probability" – 0.72; "High probability" – 0.98. (14)

The probability of attacks and their destructiveness, i.e., damage to assets, during threats that occur despite the implementation of protective measures are determined by the following formulas:

$$U_{Att_i} = I_i \cdot Inv(Z_{I_i}), \quad (15)$$

$$P_{Att_i} = P_{I_i} \cdot Inv(Z_{P_{I_i}}), \quad (16)$$

where U_{Att_i} - is the level of residual damage after the implementation of the I_i *i -th attack after the protective measure;* - *is the intensity of the* i - *th threat* before the protective measure ; Z_{I_i} its quantity is the effectiveness of the protective measure in reducing the intensity of the i-th threat and is calculated using the formula *Inv(Z* $_{Ii}$ *)* (10); P_{Att_i} - is the residual probability of the i-th attack after the protective measure; - is the probability of the P_{I_i} *i* -th threat before the protective measure ; $Z_{P_{I_i}}$ its quantity is the effectiveness of the protective measure in reducing the probability of the i-th threat and $Inv(Z_{P_{I_i}})$ is calculated using the formula (10).

As mentioned above, one negative event can create a number of threats with different intensities and probabilities of their occurrence. This can lead to a situation where the same value of possible damage corresponds to different probabilities. The values calculated using formulas (15) and (16) U_{Att_i} reflect P_{Att_i} the risks for information assets (the third level of the FCM and allow us to consistently find the risk values for subprocesses (the second level), the main process (the first level of the hierarchy) and the organization as a whole (the zero level of the FCM.

The cost of damage at levels {0;1;2} of the graph G is calculated using the following formula:

$$U_i^{k,j} = \alpha_i^{k,j} U_i^{k+1,j}, \quad (17)$$

where $U_i^{k,j}$ the quantity is the i-th loss of the j-th concept of the k-th level of the QMS; $\alpha_i^{k,j}$ - is the weight coefficient reflecting the impact of the i-th loss of the (k+1)-th level concept on the j-th

concept of the k-th level of the QMS; $U_i^{k+1,j}$ – is the loss affecting the j-th concept of the k-th level brought to the i-th concept of the (k+1)-th level of the QMS; $k \in \{0;1;2\}$.

When k = 2, $U_i^{2,j}$ the values of - reflect the degree of damage to the subprocess, $\alpha_i^{2,j}$ - is the weight of the i-th information asset when supporting the activity of the j-th subprocess. This coefficient is expressed verbally and is estimated using the Harrington scale; $U_i^{3,j}$ - is the amount of damage to the information asset after the threats have passed the protection measure.

When k = 1, $U_i^{1,j}$ the values correspond to the quality reduction levels of the main process, $\alpha_i^{1,j}$ is the weight of the *i -th subprocess* in the execution of the *j -th main process* .

When k = 0, $U_i^{0,0}$ their value reflects the i-th loss to the organization as a whole, $\alpha_i^{0,0}$ the share of the i-th main process in the organization's activities.

remain equal to the probabilities of attacks calculated at level 4 of the FCM . P_{Att_i}

a set of points $i = \overline{1,N}$ characterizing the current indicators of risks arising in the information processing process for the organization as a whole is obtained, where $R^{cur} = \{(U_i; P_i)\}$, so N - is the amount of possible loss values. The total value of the current risk is found by the following formula:

$$R^{cur} = \left\lfloor \sum_{i=1}^{N} (\Delta U_i \cdot P_i) \right\rfloor / U^{critic} - U^{\min or}), \quad (18)$$

where $\Delta U_i = U_i - U_{i+1}$; R^{cur} points are arranged with increasing damage value; $U_0 = U^{\min or}$.

The results of the current risk assessment can be depicted graphically as shown in the figure below (Fig. 3). The diamonds in the figure represent the reference points for constructing the acceptable risk curve, and the squares represent the points characterizing the current risks.

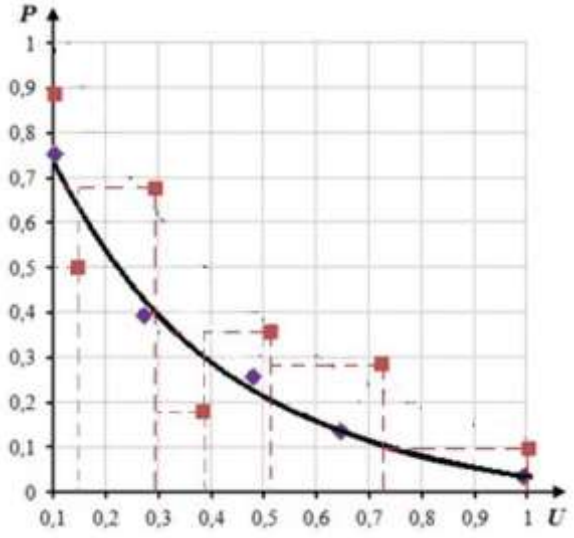


Figure 3: *Results of the current risk assessment*

Note: Damage values in Fig. 3 U^{critic} are normalized.

Thus, the following algorithm can be formulated to assess the current (actual) risks of information processing:

Stage 1. Formation of the risk assessment QMS:

1.1. Identification of the organization's key business processes.

1.2. Separation of sub-processes from the main process (if necessary).

1.3. Identification of information assets that support the activities of the subprocess.

Stage 2 – Risk Calculation:

2.1. Identification of the potential range of possible negative events and assessment of their probability of occurrence.

2.2. Identification of threats that may arise as a result of the identified negative event. Assessment of I_i the intensity of these threats and P_{I_i} the probability of their occurrence.

on the intensity and probability of $Z_{P_{I_i}}$ the occurrence of the hazard Z_{I_i} .

2.4. Calculation of the residual probabilities of attacks on information assets and indicators of damage from them after protective measures, based on formulas (15) and (16), respectively.

2.5. Calculation of the damage, i.e. the degree of damage to the subprocess by attacks, for each subprocess based on the values obtained in step 2.4 using formula (17) for k = 2.

2.6. Determining the damage to key business processes using formula (17) for k = 1. In this case, the attack probabilities calculated in step 2.4 remain unchanged in steps 2.5 and 2.6.

2.7. Calculation of information risks using formula (17) when k = 0 for the organization as a whole.

As a result of the risk assessment, a set of points is obtained that characterize the current indicators of information processing risks for the organization as a whole. In this case, if some information assets participate in more than one main process, the risks for information assets are reconsidered taking into account their weight in the main process. In this case, each such threat on the coordinate plane “harm - probability” corresponds to more than one point.

The total value of the current risk is found by formula (18). In this case, dividing the tolerant risk zone into areas and then obtaining the current values allows classifying the degree of danger of current risks during verbal assessment according to the Harrington scale.

III. Conclusion

The use of a fuzzy cognitive approach allowed the formation of a fuzzy cognitive model for assessing current information processing risks, including information security risks, selected by generalizing information about business processes carried out in the organization. The information assets supporting them were identified. Possible threats and measures to neutralize them, as well as negative situations that could pose a threat to the organization's information assets, were formed. Thus, the use of the proposed model allows determining the set of points on the "harm-probability" coordinate plane, which characterizes the current level of information risks.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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STUDY OF THE EFFECTIVENESS OF CHEMICAL REMEDIATION MEASURES IN DIFFERENT REGIONS OF THE REPUBLIC OF AZERBAIJAN

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Abstract

The article is devoted to the study of the results of leaching amelioration measures using acid solutions on saline and solonetzic soils in the irrigated areas of two major regions of the Republic of Azerbaijan - the Caspian coastal zone and the Karabakh plain. During the scientific research conducted, the characteristics of the soil cover in the studied regions were thoroughly investigated and their current improvement status was comprehensively assessed. Soil samples were collected in the study areas before and after the leaching process and subjected to chemical analysis to evaluate the effectiveness of leaching-based improvement measures. The effect of acid solutions on the properties of the leached soils was also investigated. The results of the research showed that in areas where acid leaching was used, the ameliorative efficacy was significantly higher compared to conventional water-based leaching methods, while the time required for effective leaching was 2 to 3 times shorter, depending on the dose of chemical ameliorant used. Solonetzicity was completely eliminated in all variants of acid leaching. The findings derived from the conducted research leads to the following conclusions: The soils in both regions under investigation exhibit a heavy texture and are highly saline, with moderate levels of sodicity; Chemical amelioration methods should be applied for the improvement of soils in both the Caspian coastal zone and the Karabakh region; During soil amelioration practices, the use of weak acid solutions combined with gypsum as part of the chemical amelioration process is considered optimal; It is recommended that the dosage of chemical ameliorants used in the treatment of regional soils range between 10-15 tons per hectare, with the optimal leaching rate being 15,000 m³/ha.

Keywords: amelioration; salinization; solonetzi ity; acid solution; granulometric composition; leaching

I. Introduction

In recent years, the comprehensive and rapid development across the Republic has become increasingly apparent. The liberation of previously occupied territories, alongside the establishment of new residential settlements and the revitalization of industrial and agricultural sectors in these regions, signifies substantial national progress. This advancement, coupled with a steady increase in population, has brought the issue of food security to the forefront of national priorities.Addressing this challenge necessitates the improvement of soil fertility in irrigated lands and the enhancement of agricultural crop yields. Consequently, the development and implementation of more efficient and cost-eff ctive technologies and agronomic approaches have become imperative. The present scientific investigation is devoted to addressing this pressing concern. [1-4].

The conducted scientific research has also been dedicated to addressing this issue

II. The objective of the research

It involves the development of scientific lly substantiated amelioration technologies for the ecological restoration of saline and variously solonetzic soils, and their implementation in agricultural practice.

III.The research object

The research object is saline and solonetzic soils distributed across the territory of the Republic.

IV.The primary research task

The principal objective of the research is the development of scientific lly grounded ameliorative agents aimed at reducing soil salinity and sodicity to agronomically acceptable thresholds, as well as ensuring their eff ctive integration into agricultural management practices.

V. Research methodology

The scientific investigations were conducted in accordance with standardized methodological frameworks that are currently recognized and widely implemented in land reclamation and soil amelioration practices throughout the Republic.[5]

In the northeastern region of the Republic, an experimental site located within the Caspian coastal zone, covering an area of 20 hectares, was utilized to conduct the study under the following treatment variants.[6]

1. Leaching with ordinary water (control) – 8 ha;
2. Leaching with gypsum application – 8 ha
3. Leaching with 2% dilute sulfuric acid solution – 2 ha
4. Leaching with combined application of gypsum and 2% dilute sulfuric acid solution – 2 ha

Another experimental site, located in the Karabakh plain in the northwestern part of the Republic, encompassed an area of 34.5 hectares and was studied under the following treatment variants. [7]

1. Leaching with ordinary water (control) – 16 ha
2. Leaching with application of 5 tons of gypsum per hectare – 5 ha
3. Leaching with application of 10 tons of gypsum per hectare – 1 ha
4. Leaching with application of 15 tons of gypsum per hectare – 5 ha
5. Leaching with application of 5 tons of gypsum and 10 tons of 1% dilute sulfuric acid solution per hectare – 4.5 ha
6. Leaching with application of 5 tons of gypsum and 10 tons of 0.5% hydrochloric acid (HCl) solution per hectare – 3 ha

The leaching rate was standardized at 15,000 m^3/ha across all treatment variants. To evaluate the effic ncy of the leaching process, soil samples were systematically collected from the experimental site both before and after the treatment, and subjected to relevant chemical analyses.[8;9].

The chemical and mineralogical compositions of the raw materials and substances used in the study were determined using “58 Tiger” and “Muniflex 600” analytical instruments at the Central Laboratory for Shared Instrumentation of the Institute of Geology and Geophysics of the Azerbaijan

National Academy of Sciences (ANAS).

The radioactivity of the raw material was measured at the Institute of Radiation Problems of the Azerbaijan National Academy of Sciences (ANAS), using a Canberra "HP Ge" detector-based gamma spectrometer in the Laboratory of Radiochemistry and Radioprotectors.

The content of calcium carbonate in the soil (according to GOST 26424-85), water-insoluble gypsum (composed of 60% $CaSO_4 \cdot 2H_2O$) (GOST 26487-85), and humus (GOST 26213-91) were determined in accordance with established standards. Soil and groundwater samples were analyzed using the "MW101 PRO" pH meter, following GOST 8.857-2013.

The experimental investigations were conducted in the laboratories of the Institute of Soil Science and Agrochemistry and "Baku Landscaping Service" LLC.

VI. Analysis and Discussion

The results obtained from the studies conducted in the Caspian coastal region are presented in Table 1. As the data indicate, leaching with ordinary water, without the application of chemical ameliorants resulted in a reduction of soil salinity levels (based on total soluble salts) in the 0–50 cm layer from 2.29% to 1.18%, in the 0–100 cm layer from 2.23% to 1.60%, and in the 0–150 cm layer from 2.21% to 1.82%. At this point, the concentration of chloride anions decreased to 0.121%, 0.271%, and 0.331%, respectively, while sulfate anion concentrations were reduced to 0.60%, 0.74%, and 0.78% in the corresponding soil layers. In the treatment variant involving the application of gypsum, the degree of soil salinity, expressed in terms of total soluble salts, was reduced to 0.52% in the upper 0–50 cm layer, to 0.87% in the 0–100 cm layer, and to 1.13% in the 0–150 cm layer. Concurrently, the concentrations of chloride and sulfate anions in the respective layers decreased within the ranges of 0.041–0.025%, 0.095–0.45%, and 0.170–0.55%, indicating a measurable ameliorative effect across all soil depths assessed.

The highest leaching efficiency was observed in the treatment involving the application of a 2% dilute sulfuric acid solution. However, under this variant, effective desalinization was achieved only within the upper 0–50 cm soil layer, reaching permissible salinity thresholds. In the 0–100 cm layer, the salinity level decreased from 2.35% to 0.47%, and in the 0–150 cm layer, it was reduced from 2.33% to 0.74%, based on total soluble salts. These residual concentrations exceed the acceptable limits by nearly twofold in the deeper layers. In this leaching treatment, the amount of chloride ions in the soil was reduced to 0.010% in the 0–50 cm layer, 0.029% in the 0–100 cm layer, and 0.066% in the 0–150 cm layer. Similarly, the sulfate ion concentrations decreased to 0.16%, 0.26%, and 0.41% at the same respective depths. These results demonstrate that the applied treatment was effective in reducing salt content throughout the soil profile.

The leaching variant involving the combined application of gypsum and dilute sulfuric acid demonstrated a high degree of consistency with the results obtained from the treatment using only dilute sulfuric acid (see Table 1).

As a result of the leaching process, notable changes were observed in the concentrations of key soil constituents. In the top 1-meter soil layer subjected to leaching with plain water, the calcium carbonate ($CaCO_3$) content increased slightly from 20.41% to 20.83%, while the gypsum content decreased from 0.442% to 0.283%, and the humus content declined from 0.88% to 0.80%. Additionally, the pH value of the soil solution increased from 8.99 to 9.10.

In the treatment where gypsum was applied at a rate of 20 t/ha, a reduction in calcium carbonate ($CaCO_3$) concentration was observed, reaching 21.15%. Conversely, the gypsum content increased from 0.622% to 0.819%. Additionally, the humus level declined from 0.81% to 0.70%, accompanied by a decrease in soil pH from 9.10 to 8.50.

Table 1: *Dynamics of salinity changes in soil profiles of the Caspian coastal zone before and after leaching treatments (%)*

0-50 cm			0-100 cm			0-150 cm		
Cl	SO_4	Total Soluble Salts (TSS)	Cl	SO_4	Total Soluble Salts (TSS)	Cl	SO_4	Total Soluble Salts (TSS)
leaching with plain water (control treatment)								
0.537 0.121	0.89 0.60	2.29 1.18	0.497 0.271	0.92 0.74	2.23 1.60	0.515 0.331	0.90 0.78	2.21 1.82
Leaching with gypsum (20 t/ha)								
0.378 0.041	0.54 0.25	1.74 0.52	0.743 0.095	0.67 0.45	1.81 0.87	0.509 0.170	0.73 0.55	1.95 1.13
Leaching with dilute sulfuric acid at a rate of 15 t/ha								
0.574 0.010	0.81 0.16	2.19 0.31	0.629 0.029	0.85 0.26	2.35 0.47	0.630 0.066	0.84 0.41	2.33 0.74
Combined leaching treatment: gypsum (5 t/ha) + sulfuric acid (15 t/ha)								
0.392 0.02	0.45 0.019	1.36 0.38	0.463 0.043	0.65 0.30	1.78 0.58	0.496 0.108	0.69 0.42	1.89 0.85

The concentration of exchangeable sodium, which is a primary indicator of sodicity, was considerably lower in the treatments involving chemical ameliorants compared to the control treatment using water leaching. As illustrated in Table 2, the application of gypsum led to a decline in exchangeable sodium levels from 13.30% to 6.12%. In the treatment involving the combined application of gypsum and dilute sulfuric acid, the sodium content was reduced from 18.10% to 3.73%. Similarly, under the treatment where gypsum was applied in conjunction with dilute hydrochloric acid, the concentration dropped from 17.30% to 4.41%.

Table 2: *Chemical composition of gypsum-bearing rocks from various deposits (in %) changes in the main soil components of Caspian coastal soils (0–100 cm) before and after leaching*

Parameters			Leaching methods			
			Water	Gypsum	H_2SO_4	H_2SO_4+gypsum
$CaCO_3$, %			20.41 20.83	21.53 21.15	18.59 16.03	20.43 19.77
Pure gypsum (pure calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$)			0.442 0.283	0.622 0.819	0.677 1.285	0.431 1.168
Ph			8.99 9.10	9.10 8.50	8.95 7.65	9.10 7.50
Humus			0.88 0.80	0.81 0.70	0.74 0.67	0.72 0.63
Sum of exchangeable bases, mg/100eq			35.19 34.90	26.25 36.61	29.11 35.16	29.20 32.66
Percentage composition of individual exchangeable cations:	Ca		66.58 57.05	57.52 61.95	62.59 71.50	64.08 75.90
	Mg		21.26 30.06	29.18 31.33	19.31 24.77	18.63 19.69
	Na		12.16 12.89	13.30 6.12	18.10 3.73	17.30 4.41

The highest ameliorative efficiency in the experiments conducted in the Karabakh plain was achieved through the combined application of gypsum and dilute mineral acid solutions.

Following the completion of the leaching process, chemical analysis of the subsequently collected soil samples indicated that the salinity level in the top 0–40 cm soil layer decreased significantly. In the treatment configuration combining gypsum with 1% sulfuric acid, the total soluble salt content was reduced from 2.00% to 0.20%. Similarly, in the configuration involving gypsum combined with 0.5% hydrochloric acid, the salinity level declined from 2.91% to 0.20%.As a result of leaching, the salinity level in the one-meter soil layer decreased to 0.28% and 0.24% (based on total soluble salts), depending on the treatment configurations applied. In the 0–150 cm layer, the salinity was reduced to 0.30% in both cases. In the configuration combining gypsum with 1% sulfuric acid, the chloride ion concentration across all layers was reduced to 0.02%, while the sulfate ion concentration was recorded at 0.11%, 0.15%, and 0.18%, respectively. In the alternative treatment configuration involving gypsum combined with 0.5% hydrochloric acid, the chloride ion concentrations across the respective soil profile layers were recorded at 0.03%, 0.04%, and 0.04%, while the sulfate ion concentrations were measured at 0.11%, 0.15%, and 0.18%, respectively (Table 3).

The ameliorative effect of leaching with plain water in the Karabakh region was also found to be very low. Specifically, in this treatment approach, the overall salinity level of the soil decreased from 2.50% to 0.78% in the top 40 cm layer, from 2.30% to 1.28% in the one-meter layer, and from 2.15% to 1.50% in the 1.5-meter layer. The chloride ion concentration across the layers was reduced to 0.11%, 0.12%, and 0.12%, while the sulfate ion concentration was approximately 0.42%, 0.74%, and 0.78%, respectively.

When gypsum was used in combination with mineral acids, the salinity level in the soil profile was reduced to an acceptable threshold of 0.3% up to a depth of 150 cm. However, when applied alone at rates of 5, 10, and 15 tons per hectare, the ameliorative effect was observed only in the top 40 cm layer, where the salinity levels decreased to 0.47%, 0.36%, and 0.29%, respectively, in line with the application rates. In the top layer, the chloride ion concentration was reduced to 0.11%, 0.08%, and 0.05%, while the sulfate ion concentration decreased to 0.29%, 0.21%, and 0.18%, respectively, according to the applied treatment rates (Table 3).

The effectiveness of the leaching process with gypsum diminished in the deeper soil layers. The remaining salt content in the top 0–100 cm layer decreased to 0.67%, 0.58%, and 0.60%, while in the 0–140 cm layer, it was reduced to 0.74%, 0.70%, and 0.69%. For the treatment with 5 tons of gypsum per hectare, the chloride ion concentration in the 0–140 cm soil layer dropped to 0.11%, and the sulfate ion concentration decreased to 0.29%. In the 0–140 cm depth, the reduction was observed at 0.13% and 0.86%, respectively. When 10 tons of gypsum per hectare were applied, the chloride concentration in the one-meter layer was reduced to 0.10%, and the sulfate concentration was reduced to 0.24%. For the 0–140 cm depth, these values were 0.12% and 0.29%, respectively. Finally, in the treatment with 15 tons of gypsum per hectare, the remaining salt content in the one-meter soil layer was 0.60%, and in the 0–140 cm layer, it was 0.69% (Table 3).

During the experiments conducted in the Karabakh plain, the impact of leaching on the primary chemical elements of the soil was also investigated. The results of the study indicated that after leaching with plain water, the calcium carbonate content in the top one-meter soil layer increased from 10.34% to 11.20%, while the gypsum content decreased from 0.27% to 0.21%. The amount of exchangeable calcium (Ca) cations decreased from 64.27% to 55.70%, while the magnesium (Mg) cation concentration increased from 27.13% to 34.80%, and the sodium (Na) cation concentration rose from 8.60% to 9.50%. During the experiments conducted in the Karabakh plain, the impact of leaching on the primary chemical elements of the soil was also investigated.

Table 3: *The dynamics of salinity variation across soil horizons in the Karabakh plain following leaching, expressed as percentage values.*

Depth, cm	Parameters	Without ameliorants	Meliorantla				
			Gypsum			Gypsum +H_2SO_4	Gypsum +HCl
			5	10	15	5+10	5+10
0-40	Total Soluble Salts (TSS)	2.50 0.78	2.00 0.47	2.36 0.36	2.72 0.29	2.00 0.20	2.91 0.20
	Cl	0.50 0.11	0.88 0.11	0.32 0.08	0.51 0.05	0.56 0.02	0.87 0.03
0-100	SO_4	0.70 0.42	0.90 0.29	0.70 0.21	1.28 0.18	0.63 0.09	0.30 0.11
	Total Soluble Salts (TSS)	2.30 1.28	1.993 0.67	2.32 0.58	2.32 0.60	2.10 0.28	2.65 0.24
0-140	Cl	0.48 0.12	0.86 0.12	2.64 0.10	0.38 0.06	0.54 0.02	0.70 0.04
	SO_4	0.66 0.47	0.82 0.83	0.80 0.24	1.25 0.32	0.74 0.15	0.98 0.15
	Total Soluble Salts (TSS)	2.15 1.50	1.90 0.74	2.52 0.70	2.11 0.69	2.11 0.30	2.50 0.30
	Cl	0.43 0.12	0.35 0.13	0.76 0.12	0.33 0.07	0.50 0.02	0.62 0.04
	SO_4	0.73 0.78	0.80 0.86	0.65 0.29	1.12 0.39	0.79 0.18	1.00 0.18

Table 4: *The Change in the Main Elemental Composition of Karabakh Saline Soils After Leaching (0-100 cm Layer)*

Parameters	Without ameliorants	With ameliorant				
		Gypsum			gypsum+H_2SO_4	gypsum +HCl
		5	10	15	5+10	5+10
CaCO3, in %	10.34 11.20	12.38 12.48	12.56 13.66	11.91 12.90	12.90 9.75	13.00 10.36
Pure gypsum (pure calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$)	0.27 0.21	0.24 0.20	0.25 0.237	0.33 0.36	0.134 0.91	0.28 0.53
Sum of exchangeable bases, mg/100eq	31.14 31.65	25.42 28.18	30.87 28.61	21.37 27.47	29.20 29.37	25.37 28.80
percentage of the total						
Ca	64.27 55.70	59.57 61.02	57.05 61.58	55.07 59.17	57.72 71.17	60.15 67.05
Mg	27.13 34.80	32.13 30.88	32.95 31.98	34.47 34.23	28.93 23.80	27.70 26.95
Na	8.60 9.50	8.30 8.10	10.00 7.14	10.46 6.60	13.35 5.03	12.15 6.00

The results of the study indicated that after leaching with plain water, the calcium carbonate content in the top one-meter soil layer increased from 10.34% to 11.20%, while the gypsum content decreased from 0.27% to 0.21%. The amount of exchangeable calcium (Ca) cations decreased from 64.27% to 55.70%, while the magnesium (Mg) cation concentration increased from 27.13% to 34.80%, and the sodium (Na) cation concentration rose from 8.60% to 9.50%. As a result of leaching, the

indicators of the primary chemical elements in the soil showed that treatment configurations involving the combined application of ameliorants were more effective than those using gypsum alone. According to the analysis data, when gypsum was used in combination with a sulfuric acid solution, the concentration of exchangeable sodium (Na) decreased from 13.35% to 5.03%, while in the treatment with a 0.5% hydrochloric acid solution, the concentration of sodium was reduced from 12.15% to 6.00%. This resulted in nearly complete elimination of salinity (Table 4).

VII. Conclusion

The findings derived from the conducted research leads to the following conclusions.

1. The soils in both regions under investigation exhibit a heavy texture and are highly saline, with moderate levels of sodicity.
2. Chemical amelioration methods should be applied for the improvement of soils in both the Caspian coastal zone and the Karabakh region.
3. During soil amelioration practices, the use of weak acid solutions combined with gypsum as part of the chemical amelioration process is considered optimal.
4. It is recommended that the dosage of chemical ameliorants used in the treatment of regional soils range between 10-15 tons per hectare, with the optimal leaching rate being 15,000 m^3/ha.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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RISK OF SOIL AND WATER CONTAMINATION BY INDUSTRIAL TOXIC WASTE IN THE KAZRETI AND ZESTAFONI REGIONS OF GEORGIA

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Abstract

This paper analyses soil and water pollution issues in the Kazreti and Zestafoni regions of Georgia, where industrial activities have led to significant environmental contamination by heavy metals and other toxic compounds. It discusses the causes and scale of chemical contamination of soil and water, and its ecological and social impacts. The paper emphasizes the detrimental impact of soil pollution on ecosystems and human health. It also explores potential solutions to this problem, such as environmental monitoring, the regulation of industrial activities and the implementation of new technologies. The importance of preventive measures and sustainable development strategies for maintaining ecological balance and public health is emphasized.

Keywords: soil contamination, industrial activities, toxic waste, mining activity

I. Introduction

Contamination of soils and water from toxic industrial waste is one of the most significant global environmental challenges, often causing long-term and sometimes irreversible consequences. This issue is severe in Georgia's industrial regions, such as the surrounding areas of Kazreti and Zestafoni towns. Kazreti (in Southeast Georgia) is affected by mining activities related to the extraction of polymetals, while Zestafoni (in West Georgia) faces problems due to its ferroalloy manufacturing plant. In both regions, industrial activities have significantly degraded soil and water quality and disrupted the stability of the ecosystems through interactions between metals and chemical compounds.

There are a lot of publications in the world scientific literature concerning the pollution of the environment, particularly soil, water, air, and plants, both by radionuclides and heavy metals. Relatively recent studies in this area concerning the intake and impact of radionuclides and heavy metals into the environment [1-6], their transfer and behavior factors in soil, monitoring in agroecosystems and restoration [7-9], spatial distribution and ecological risk assessment [10-13], etc. Similar questions have been studied specifically in the soils and waters of Georgia [14-20]. This

work paid special attention to industrial soil and water pollution and the comparative analysis of data from these regions.

Toxic wastes generated by industrial activities, including radionuclides (such as Cs-137 and Sr-90) and heavy metals like lead, chromium, and cobalt, are the primary pollutant source of soil, groundwater, and vegetation. Compounding this issue is the persistence of these toxic substances in the soil for a long time, which enables them to maintain their harmful effects over extended periods. Consequently, they impact both the structure of local ecosystems.

This paper explores the issue of soil pollution caused by industrial toxic waste in Georgia, focusing precisely on Kazreti and Zestafoni. It analyzes the forms and impacts of contamination, the associated ecological and health risks, and offers recommendations to improve soil conditions.

Implementing a combination of global and local environmental policies, scientific research, and technological innovations is essential to mitigating this problem and reducing ecological damage (UNEP). However, the current situation in the Kazreti and Zestafoni regions reflects ineffective waste management practices and high environmental risk (GEOSTAT).

The study aims to comprehensively analyze the problem of industrial pollution of soils and water and develop appropriate recommendations for improving the environment's state.

The study regions exemplify the environmental challenges associated with industrial pollution. Although differing in industrial profile, both regions face similarly acute ecological problems. Hence, the scale, causes, and impacts of soil contamination in these two regions are compared.

The Zestafoni Ferroalloy Plant is one of Georgia's largest industrial enterprises, primarily producing silicomanganese and other ferroalloys. The production process generates substantial quantities of dust and waste containing heavy metals, accumulating in the soil and contributing to its degradation. Research indicates that concentrations of manganese, lead, and cadmium in the soils of the Zestafoni region significantly exceed established sanitary norms. The primary contamination sources include emissions from industrial processes and the uncontrolled disposal of industrial waste. These factors alter the soil’s physical and chemical properties, reduce fertility, and hinder essential biological processes.

Kazreti is one of Georgia’s key mining centers that is involved in extracting and processing non-ferrous and precious metals. Extensive mining operations introduce hazardous elements such as arsenic, lead, and mercury into the soil and water, posing long-term ecological and health risks. Of particular concern are the tailings storage facilities, from which toxic substances frequently leak into the surrounding soil and groundwater.

II. Methods

Soil samples were collected from selected sites in the Kazreti and Zestafoni regions using a grid sampling method to ensure spatial representativeness. Sampling was performed at 0–30/40 cm depth, corresponding to the biologically active soil layer most affected by anthropogenic activities. Samples were placed in sealed plastic containers and labeled with precise geographic coordinates for traceability. Laboratory analyses were conducted at the Laboratory of the Scientific-Research Institute of Agriculture and Soil Fertility of Georgia. The concentration of heavy metals—specifically lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), manganese (Mn), nickel (Ni), and zinc (Zn)—was determined using Atomic Absorption Spectroscopy (AAS), a highly sensitive and reliable method for detecting trace metal elements in soil matrices.

Data were compared against both national soil quality standards and international environmental benchmarks, including those set by the World Health Organization (WHO) and the European Union (EU). Results were analyzed to identify spatial variation, assess exceedances of permissible limits, and evaluate potential ecological and health risks. The methodology also included cross-referencing soil contamination patterns with proximity to industrial sites and local hydrographic networks to assess potential leaching and downstream dispersion of contaminants.

The research is based on analyses of soil and water samples collected from the Kazreti and Zestafoni regions. Radionuclide concentrations were determined using high-resolution gamma spectrometry, ensuring precise Cs-137 and Sr-90 levels were measured.

The data used in this study encompass over 150 samples collected between 2022 and 2024 from the Kazreti and Zestafoni regions.

III. Results and Discussion

Environmental radionuclides pose a significant challenge from ecological and public health perspectives. Their distribution and concentration in the environment—especially in soil and water—substantially impact agricultural productivity, the safety of water resources, and human health. In Georgia, radionuclide levels vary across different regions and are influenced by natural and anthropogenic factors.

The Kazreti region, located in a mountainous area, is notable for its intensive mining, metallurgical activities, and abundant naturally occurring radioactive minerals. Research has shown that concentrations of Cs-137 and Sr-90 in Kazreti's soil and water are among the highest in Georgia (Cs-137 in soil: 15.0–25.0 Bq/kg; Sr-90: 7.5–12.0 Bq/kg). These elevated levels are closely linked to mining operations, metallurgical industries, and the natural geochemical composition of the area.

In Zestafoni, radionuclide levels are, on average, lower than in Kazreti; however, they still exceed those recorded in some other regions of Georgia. This is particularly evident in the average activity of Cs-137 in both soil and water.

If in the Kazreti region, high concentrations of radionuclides are geographically closely associated with zones of active mining operations, where elevated radiation levels are observed, in the case of Zestafoni, the distribution of radionuclides is more horizontal and is associated both with anthropogenic activities, particularly the technogenic emissions from the ferroalloy plant, and with natural processes such as surface runoff and wind-driven transport.

The data indicate that Cs-137 and Sr-90 concentrations in Kazreti are significantly higher than those in Zestafoni, particularly in soil samples (**Table 1**). In Kazreti, Cs-137 activity in soil was measured at 21.5 ± 3.8 Bq/kg and Sr-90 at 9.5 ± 1.8 Bq/kg, whereas in Zestafoni the corresponding values were 12.8 ± 2.5 Bq/kg for Cs-137 and 5.4 ± 1.1 Bq/kg for Sr-90. Water samples followed a similar pattern: in Kazreti, Cs-137 activity reached 2.0 ± 0.5 Bq/L and Sr-90 1.0 ± 0.3 Bq/L, while in Zestafoni these levels were 1.1 ± 0.3 Bq/L and 0.5 ± 0.2 Bq/L, respectively.

Table 1: *Average Concentrations of Cs-137 and Sr-90 in Soil and Water Samples from Kazreti and Zestafoni, 2022*

Region	Sample Type	Cs-137 (Bq/kg or Bq/L)	Sr-90 (Bq/kg or Bq/L)
Kazreti	Soil	21.5 ± 3.8	9.5 ± 1.8
	Water	2.0 ± 0.5	1.0 ± 0.3
Zestafoni	Soil	12.8 ± 2.5	5.4 ± 1.1
	Water	1.1 ± 0.3	0.5 ± 0.2

These results support the hypothesis that elevated radionuclide levels in Kazreti are associated with intensive mining and metallurgical activities. In contrast, Zestafoni, although less pollution, still exhibits radionuclide levels above baseline values observed in other regions of Georgia. The results confirm that the Kazreti region remains a radionuclide contamination hotspot in Georgia, with the primary risk factors associated with mining and metallurgical processes. The newly obtained data indicate that the current situation partially aligns with international findings in similar industrial regions.

Statistical average generalized data for 2022, 2023, and 2024 show that the average activity of Cs-137 in soil samples from Kazreti is approximately 2.8 times higher than in Zestafoni, while Sr-90 levels are about three times greater (**Figure 1**). Similar trends are observed in water samples,

where radionuclide concentrations are consistently higher in Kazreti than Zestafoni. These differences highlight the elevated environmental burden of artificial radionuclides in the Kazreti region, further supporting the hypothesis that mining and metallurgical activities significantly contribute to local contamination. Figures below show the average concentrations of radionuclides (Cs-137 and Sr-90) in soils and water in the areas of Zestafoni and Kazreti in 2022 (Fig. 2) and 2023-2024 (Fig. 3).

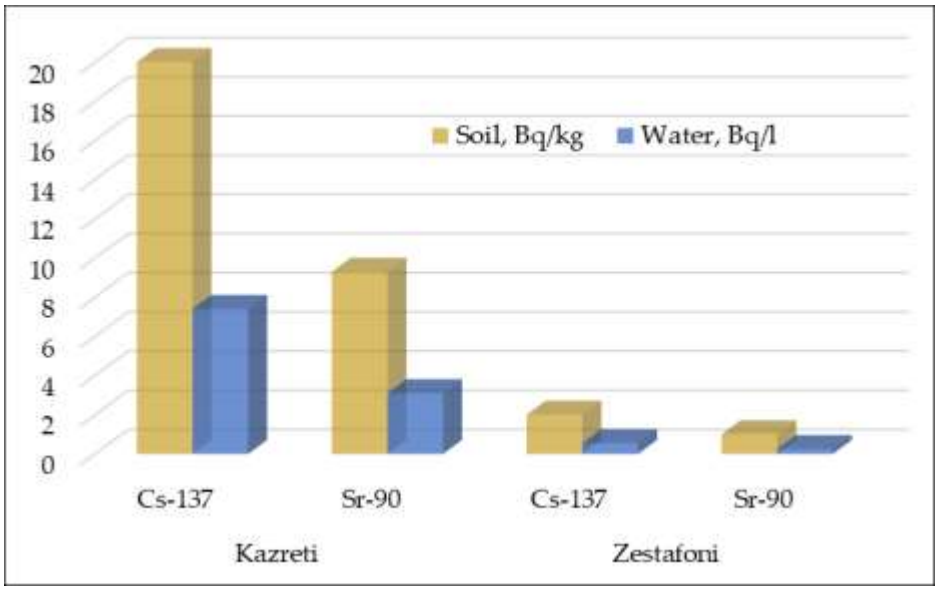


Figure 1: *Average Activity of Cs-137 and Sr-90 in Soils and Water in Kazreti and Zestafoni (2022-2024)*

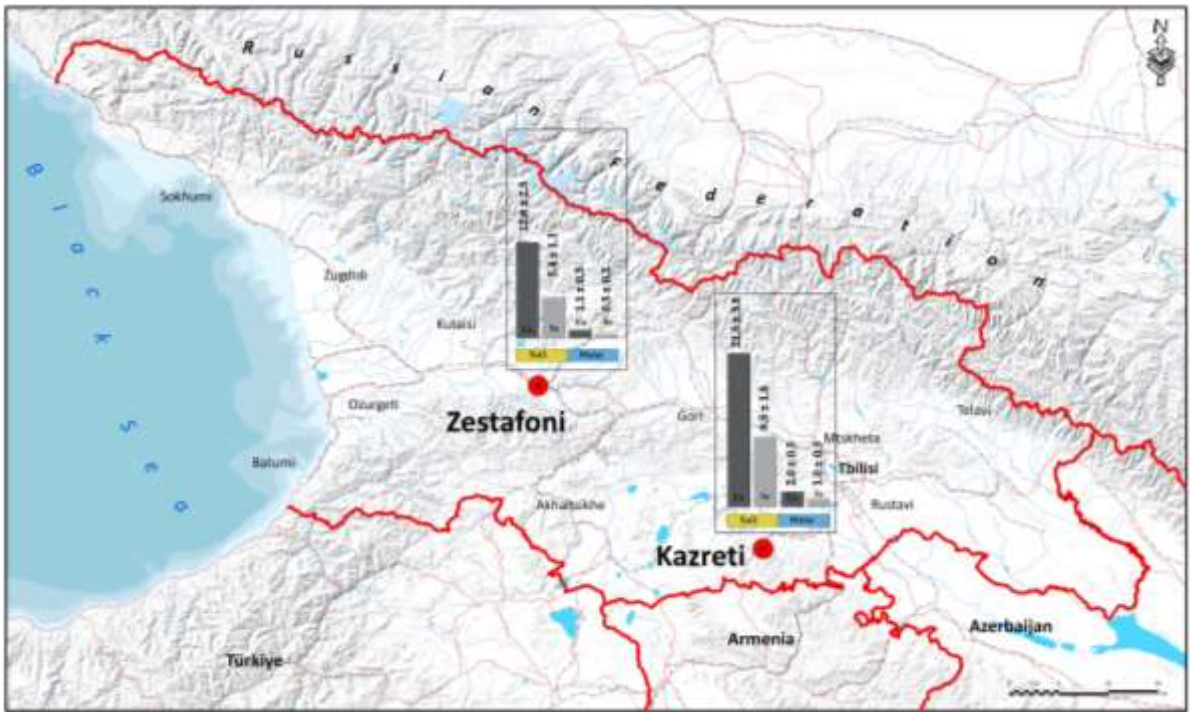


Figure 2: *Average concentrations of radionuclides in soils and water in the Zestafoni and Kazreti regions, 2023-2024*

The study highlights the necessity of regular monitoring and control of radionuclide levels in the Kazreti and Zestafoni regions to accurately assess the extent of environmental contamination

and to develop appropriate safety standards.

The heavy metals were also assessed in the soil and water of the research sites, focusing primarily on elements such as Manganese (Mn), Mercury (Hg), Cadmium (Cd), Zinc (Zn), Arsenic (As), Nickel (Ni), and Lead (Pb). The graphs below illustrate the concentrations of mercury, zinc, arsenic, nickel, and lead over three years in Kazreti (Fig. 4) and two years in Zestafoni (Fig. 5).

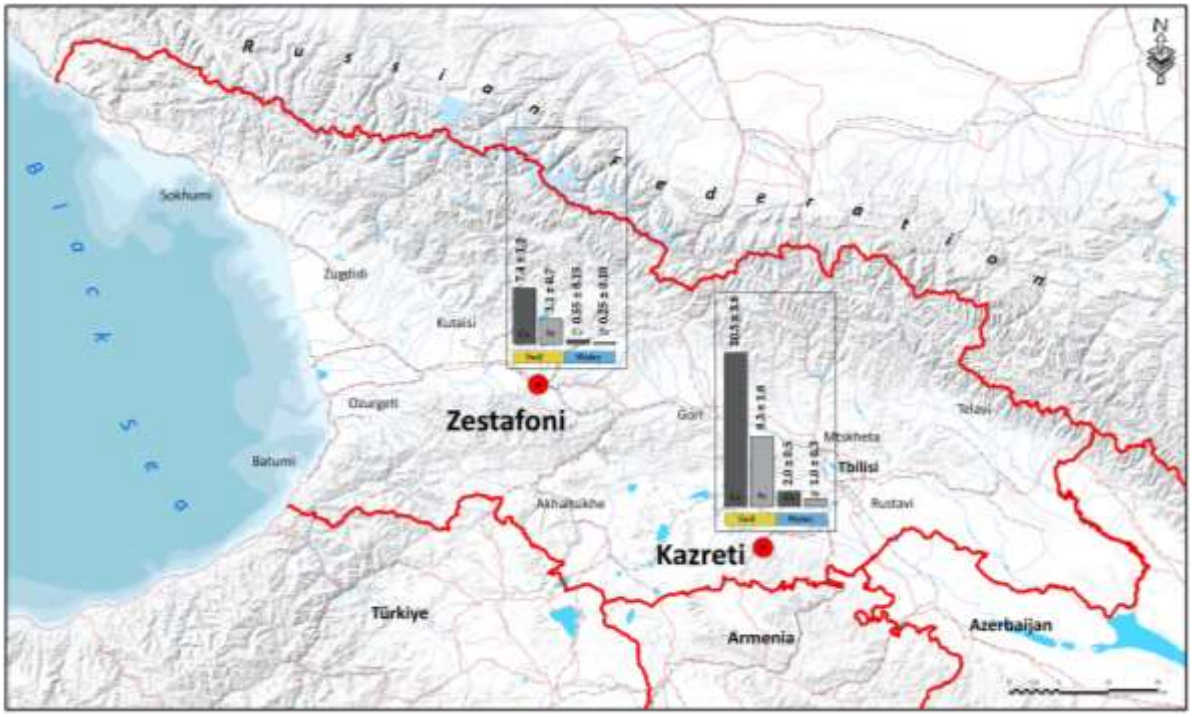


Figure 3: *Average concentrations of radionuclides in soils and water in the Zestafoni and Kazreti regions, 2022*

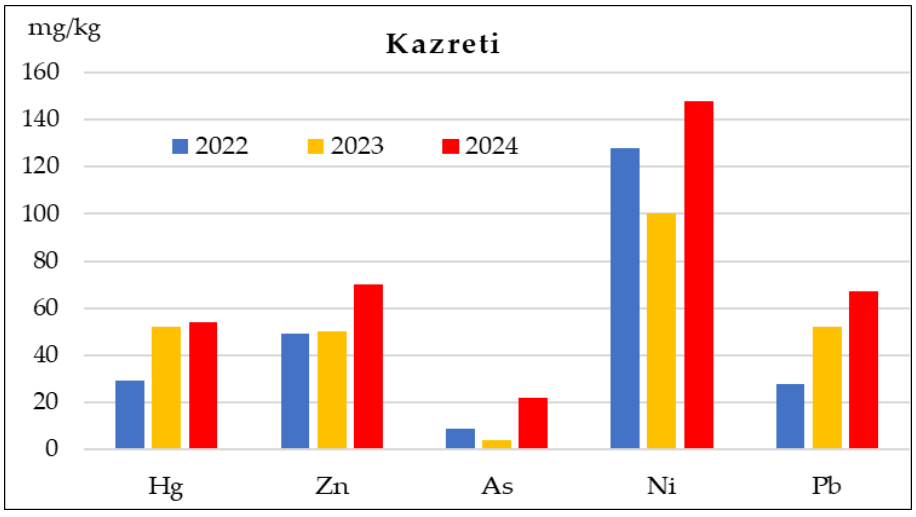


Figure 4: *Concentrations of Hg, Zn, As, Ni, Pb in soils of Kazreti (2022, 2023, 2024)*

It is worth noting that if, in the case of radionuclides, the territory of Kazreti is characterized by a markedly increased content of Cesium and Strontium, then the opposite picture is observed concerning heavy metals. Most of the studied chemical elements are clearly distinguished by a higher concentration in the soils of the Zestafoni territory, especially nickel, where, according to

data for 2023, it exceeded 750 mg/kg (Fig. 5). It is evident that the concentration of manganese in the Zestafoni area, which is the region of extraction and processing of this raw material, prevails (in 2024 it reached 16'500 mg/kg) and significantly exceeds the Kazreti indicator (Fig. 6). Its concentration in both areas exceeds the maximum permissible concentration (500 mg/kg) several times. The cadmium and lead content in both places is within the normal range (the maximum allowable concentration is 0.5-2 mg/kg for Cd and 300 mg/kg for Zn), with a minimum content in Kazreti (Fig. 7).

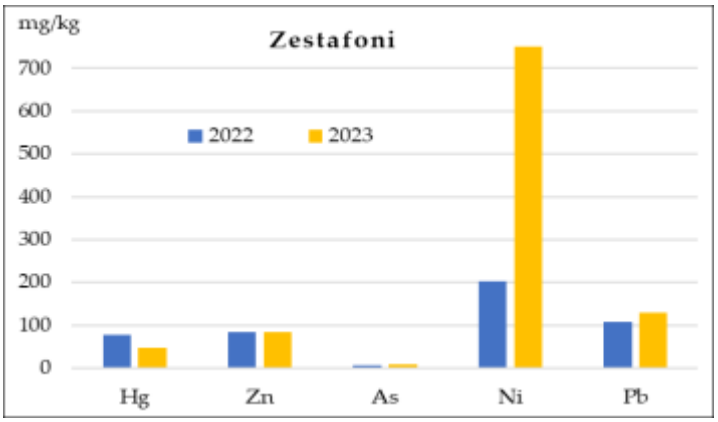


Figure 5: *Concentrations of Hg, Zn, As, Ni, Pb in soils of Zestafoni (2022, 2023)*



Figure 6: *Concentrations of Mn in Soils (2022-2024)*

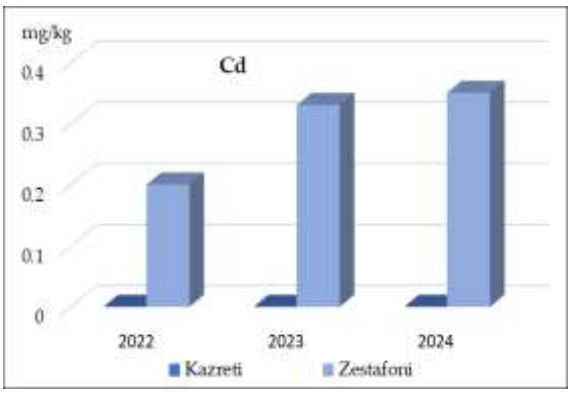


Figure 7: *Concentrations of Cd in Soils (2022-2024)*

Based on the evaluation data presented, there is an apparent disparity in the degree of environmental impact between Kazreti and Zestafoni. According to four key ecological criteria, Kazreti consistently qualifies as a high-risk zone, while Zestafoni can be categorized as a moderately impacted area, where contamination remains more localized (Table 2, Fig. 8).

Table 2: *Rating Scale of Statistical Data on Environmental Impact*

Criterion	Kazreti	Zestafoni	Rating scale (1-5)
Heavy metal concentration	Very high (Pb, As, Cd, Hg)	Medium-high (Mn, Ni, Zn)	Kazreti-5 Zestafoni-3
Soil contamination level	Large-scale, acute	Local, partial	Kazreti-5 Zestafoni-3
Pollution of water resources	Heavy metal pollution of rivers and reservoirs	Minor impact only on nearby waters	Kazreti-4 Zestafoni-2
Environmental risk	Extremely high	Moderate	Kazreti-5 Zestafoni-3

1. Heavy Metal Concentration. Kazreti shows a very high concentration of heavy metals (Pb, As, Cd, Hg), indicating widespread and chronic pollution of soil and environment as a result of intensive mining activities. In contrast, Zestafoni presents medium to high levels of metals (Mn, Ni, Zn), largely due to metallurgical industry operations. Kazreti scores the maximum – 5 on the rating scale, and Zestafoni – 3.

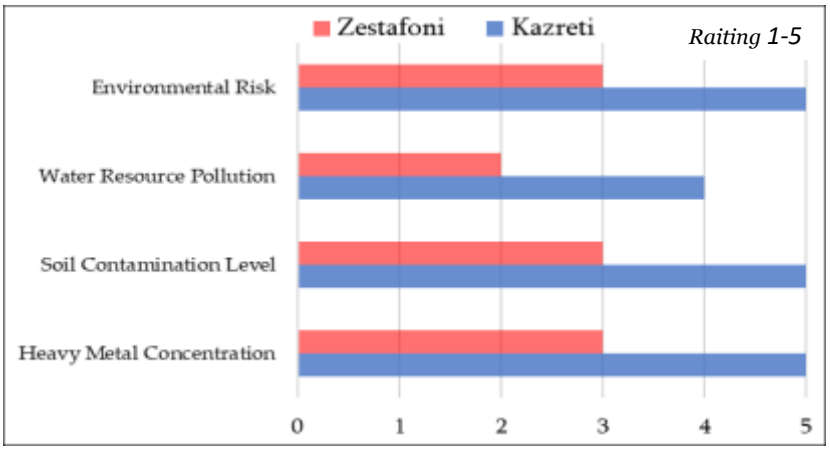


Figure 8: *Environmental Impact Comparison: Kazreti vs Zestafoni*

2. Soil Contamination Level. Soil pollution in Kazreti is large-scale and acute, suggesting that contaminants penetrate deeper soil layers and severely hinder natural recovery. In Zestafoni, the contamination is localized and partial. Kazreti once again scores 5, while Zestafoni scores 3.

3. Water Resource Pollution. Kazreti suffers from significant heavy metal pollution in rivers and reservoirs, which poses a serious threat to aquatic ecosystems. In Zestafoni, the impact is minor and limited to nearby waters. Therefore, the ratings are Kazretiasd – 4, Zestafoni – 2.

4. Environmental Risk. Kazreti is considered an area of extremely high environmental risk, with pollution affecting soil, water, and potentially biota. Zestafoni, meanwhile, poses a moderate risk, mainly due to localized industrial activity. Rating scores: Kazreti – 5, Zestafoni – 3.

IV. Conclusions

The cases of Zestafoni and Kazreti show that inadequate environmental safety measures lead to severe contamination and ecosystem degradation, and the type of industrial activity determines the nature and scale of soil contamination. Despite differences in industrial processes, both regions share the common issue of excessive heavy metal and radionuclide accumulation, which results in significant ecological and public health consequences.

The study of both regions faces a common notable environmental challenge — the ongoing soil degradation and water pollution. Addressing this issue requires a systemic approach: strengthening environmental monitoring, developing remediation programs, tightening environmental regulations, and raising public awareness.

To address these challenges, it is essential to implement the following measures:

- Regular environmental monitoring;
- Introduction of soil remediation programs;
- Effective management of industrial waste;
- Enforcement of environmental legislation.

A comprehensive and systematic approach can improve soil quality and protect the health of local populations.

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ENVIRONMENTAL RISK ASSESSMENT OF MANGANESE (Mn) ACCUMULATION IN GEORGIA'S BLACK SEA BASIN RIVERS: A CASE STUDY OF THE KVIRILA RIVER

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Abstract

The accumulation of manganese (Mn) in freshwater systems has become a significant environmental and public health concern, especially in areas impacted by intensive mining activities. This study examines the temporal dynamics and regulatory compliance of manganese concentrations in the Kvirila River in Georgia between 2017 and 2023. Analysis of monthly maximum concentration data obtained from Georgia's National Environmental Agency (NEA) reveals widespread and persistent exceedances of the national regulatory threshold of 0.1 mg/L. Almost 80% of the recorded measurements exceeded the permitted limit, with particularly high concentrations observed near the cities of Zestaponi and Chiatura — regions that have been heavily impacted by manganese mining in the past. Seasonal patterns were evident, with peak concentrations typically occurring during the summer and autumn months. Linear trend analysis revealed no significant decline in manganese levels over time, suggesting that natural attenuation processes are insufficient to achieve compliance. These findings emphasise the urgent need for enhanced monitoring, source control measures and targeted remediation strategies to mitigate the environmental and public health risks posed by elevated Mn concentrations in the Kvirila River system.

Keywords: mining, manganese, Kvirila River, Georgia, Zestaponi, Chiatura

I. Introduction

Manganese (Mn) is a naturally occurring element commonly found in the Earth's crust and surface waters. While it is an essential micronutrient for biological systems at trace levels, elevated concentrations of manganese (Mn) in water bodies can pose significant risks to human health and aquatic ecosystems [1]. Elevated Manganese (Mn) levels that are often driven by anthropogenic activities such as mining and industrial discharge pose significant environmental and public health threats [2], [3]. In aquatic systems, manganese (Mn) exists in multiple redox states and interacts dynamically with other biogeochemical cycles, including those of iron (Fe), sulfur (S), and carbon (C), influencing nutrient availability, microbial community structures, and oxygen regimes [2], [4].

Long-term exposure to manganese (Mn), especially in drinking water, has been linked to neurodevelopmental effects in children and other health risks in vulnerable populations [11]. Consequently, many countries, including Georgia, have established strict regulatory thresholds for manganese (Mn) concentrations in water resources; in Georgia, the permissible limit is set at 0.1 mg/L.

In Georgia, the Black Sea Basin rivers, especially the Rioni and its tributary the Kvirila, are profoundly impacted by manganese (Mn) mining activities centered in the Chiatura region.

Historical and ongoing mining operations have led to the release of hundreds of thousands of tons of Manganese (Mn)-rich tailings into the river system annually [5]. These discharges result in widespread contamination of both water and sediments, which poses long-term ecological risks, including toxicity to aquatic life, bioaccumulation, and disruption of sediment-water interactions [5].

This study aims to assess the temporal and spatial patterns of manganese (Mn) concentrations in the Kvirila River over the period from 2017 to 2023. Utilizing official data provided by the National Environmental Agency (NEA) of Georgia, the study evaluates compliance with regulatory standards, identifies seasonal and annual trends, forecasts future concentration levels, and highlights areas requiring urgent environmental management interventions. By understanding the dynamics of manganese (Mn) contamination in the Kvirila river, this research seeks to support more effective policy responses and remediation strategies to protect public health and the environment.

Beyond local impacts, manganese (Mn) contamination intersects with broader environmental issues such as climate change. Rising global temperatures, altered precipitation regimes, and sea level rise are modifying hydrological processes, thereby intensifying manganese (Mn) mobilization and transport. For instance, increased storm intensity enhances erosion of manganese (Mn)-laden soils, while warming and hypoxic conditions favor the release of soluble manganese (Mn) from sediments [6]. This interaction not only exacerbates the spread of manganese (Mn) pollution, but also contributes to feedback loops in global carbon and nutrient cycles, with implications for greenhouse gas emissions and ecosystem resilience [7]. Climate-induced salinization and sea-level rise accelerate heavy metal release, particularly in coastal and estuarine environments [8] [9].

The Kvirila River Basin, located in western Georgia, is an area of particular concern for manganese (Mn) contamination due to its geological characteristics and extensive historical mining activities, especially around the cities of Chiatura and Zestaponi [5]. Chiatura is renowned for its manganese (Mn) ore deposits and has been a center of mining and industrial activity for over a century, contributing to elevated levels in nearby watercourses [5]. The environmental impact of such activities, combined with natural mineralization processes, makes the Kvirila River a critical focus for water quality monitoring and management efforts [5].

Mining and industrial discharge are the dominant drivers of manganese (Mn) pollution in polymetallic belts [10],[7], [11]. Given the scale and complexity of the issue, there is a critical need for interdisciplinary research that integrates geochemical analysis, ecological risk assessment, and climate science. This paper aims to evaluate the environmental risks associated with manganese (Mn) accumulation in Georgia's Black Sea Basin rivers using long-term monitoring data, pollutant modeling, and health risk indices. In doing so, it contributes to a broader understanding of how regional pollution challenges relate to global environmental implications.

II. Methods

2.1. Study Area

This study focuses on the Kvirila River Basin, located in the western region of Georgia, specifically in the areas surrounding the cities of Zestaponi and Chiatura. The Kvirila River is a major tributary in the region, flowing through zones characterized by both natural mineral deposits and significant anthropogenic activities, particularly related to mining and industrial operations.

The majority of the manganese (Mn) concentration measurements were collected from the upper section of the Kvirila River near Zestaponi. This area is influenced by both natural geological formations rich in manganese (Mn) and the impacts of urban and industrial activities. Additionally, significant sampling and analysis were conducted at the lower section of the Kvirila River near Chiatura, a city historically known for its intensive manganese (Mn) mining and ore processing industries.

In both monitoring locations, manganese (Mn) concentrations frequently exceeded the national regulatory threshold of 0.1 mg/L. Exceedances were particularly prominent downstream of

Chiatura, reflecting the cumulative impact of industrial discharges and possible leaching from mining-related activities. The selected monitoring sites thus represent critical control points for understanding the spatial variability and severity of manganese (Mn) contamination within the Kvirila River system.

Due to the strategic environmental and economic relevance of the Kvirila River and its proximity to manganese (Mn) mining operations, this region serves as a valuable case study for evaluating interactions among natural mineralization, human activity, and water quality.

2.2. Data Source

The manganese (Mn) concentration data utilized in this study were obtained from the National Environmental Agency (NEA) of Georgia, accessible via https://nea.gov.ge/. The dataset comprised monthly maximum manganese (Mn) concentration measurements collected from January 2017 through December 2023. All concentration values were reported in milligrams per liter (mg/L) and reflect the highest recorded manganese (Mn) levels for each month within the respective year.

The data were sourced from official monitoring programs conducted by the NEA, which are designed to ensure compliance with national environmental standards and support the assessment of water quality trends across Georgia. According to national regulations, the permissible limit for manganese (Mn) concentration in water is 0.1 mg/L.

2.3. Data Processing

The raw dataset was structured into a matrix format with months as rows and years as columns. To facilitate analysis:

- The data were reshaped into a long-form structure to allow chronological ordering and time-series visualization.
- Months were treated as categorical variables to preserve the natural calendar order.
- Concentrations were evaluated against the regulatory limit to classify each monthly measurement as either compliant or non-compliant.
- Descriptive statistics, including annual averages and monthly trends, were calculated to assess the temporal distribution of manganese (Mn) concentrations.

2.4. Analytical Methods

Several statistical and visualization techniques were employed:

- **Time-Series Plotting**: Monthly manganese (Mn) concentrations were plotted over time to visualize temporal patterns and highlight exceedances relative to the permissible limit.
- **Exceedance Analysis**: The number of months exceeding the regulatory threshold was calculated annually to evaluate compliance trends.
- **Heatmaps**: A heatmap was generated to visualize concentration intensities across different months and years.
- **Trend Forecasting**: A simple linear regression model was applied to annual mean concentrations to project future manganese (Mn) levels up to 2025 under the assumption of continued current conditions.

III. Results

The comprehensive analysis of manganese (Mn) concentration data from 2017 to 2023 indicates persistent and widespread exceedances of the national regulatory threshold of 0.1 mg/L. Across the 84 monthly maximum concentration records, a total of 66 measurements (78.6%) surpassed the permissible limit. The year 2017 exhibited full non-compliance, with manganese (Mn) concentrations exceeding regulatory standards in all 12 months. Other years, including 2019, 2020,

and 2023, also showed elevated non-compliance rates, each recording exceedances in more than two-thirds of the monitored months (See Figure 1).

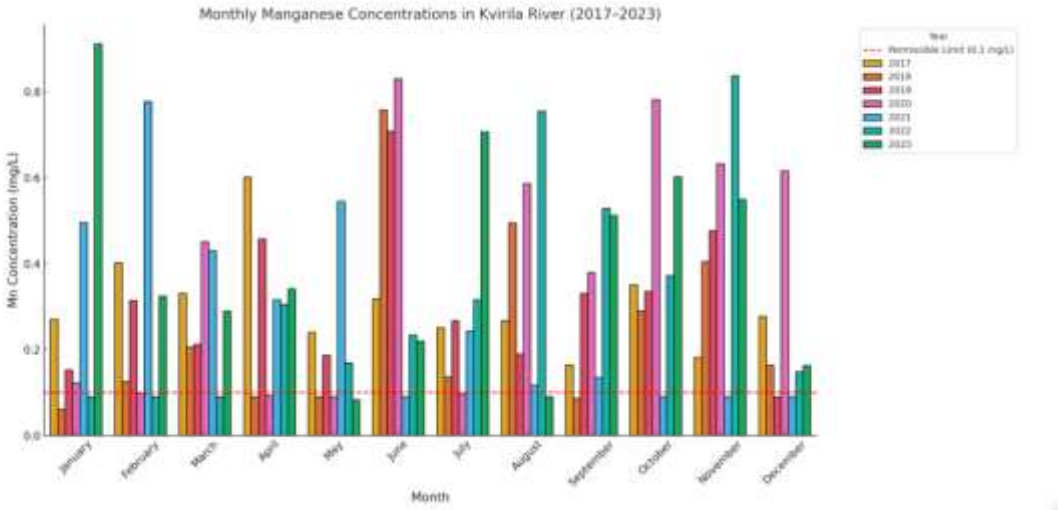


Figure 1:*Combined monthly manganese (Mn) concentrations in the Kvirila River from 2017 to 2023. Bars are grouped by month and color-coded by year. The red dashed line indicates the regulatory limit of 0.1 mg/L.*

The annual mean manganese (Mn) concentrations reflected notable fluctuations over the observed period. Average concentrations were 0.305 mg/L in 2017, decreased slightly to 0.243 mg/L in 2018, and then rose again to 0.310 mg/L in 2019. The most pronounced peak was recorded in 2020, with an average concentration of 0.398 mg/L, followed by a minor decline in 2021 to 0.285 mg/L. A resurgence was observed in subsequent years, with 2022 and 2023 recording average concentrations of 0.328 mg/L and 0.400 mg/L, respectively. These results underscore persistent exceedances and a concerning upward trend in recent years, notably in 2020 and 2023 (Refer to Figure 2).

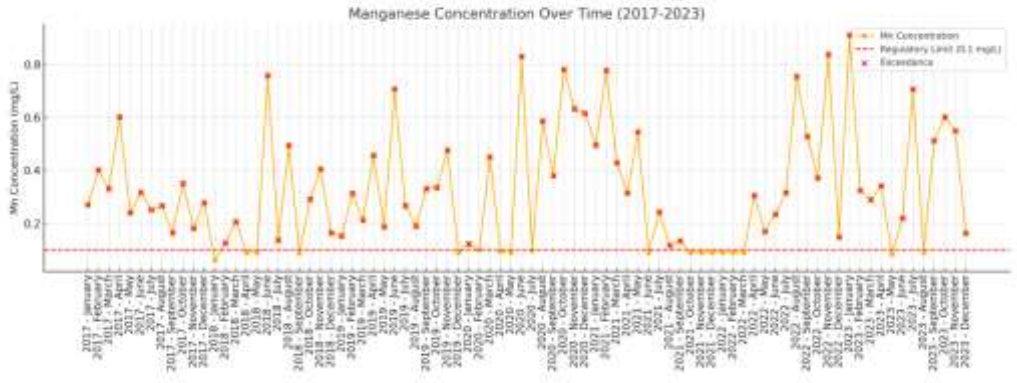


Figure 2:*Monthly Manganese (Mn) Concentrations in the Kvirila River Basin Compared to Regulatory Limit (2017–2023)*

Monthly trends revealed consistent seasonal variations in manganese (Mn) levels. Elevated concentrations were most frequently observed during the summer and autumn months. June and November exhibited the highest average concentrations, each exceeding 0.45 mg/L, significantly surpassing the regulatory threshold. In contrast, May and December generally recorded lower manganese (Mn) concentrations; however, even during these months, exceedances were common, with four to five months per year still surpassing the permissible limit. This pattern suggests potential environmental or operational factors contributing to manganese (Mn) mobilization during specific periods of the year (Refer to Figure 3).

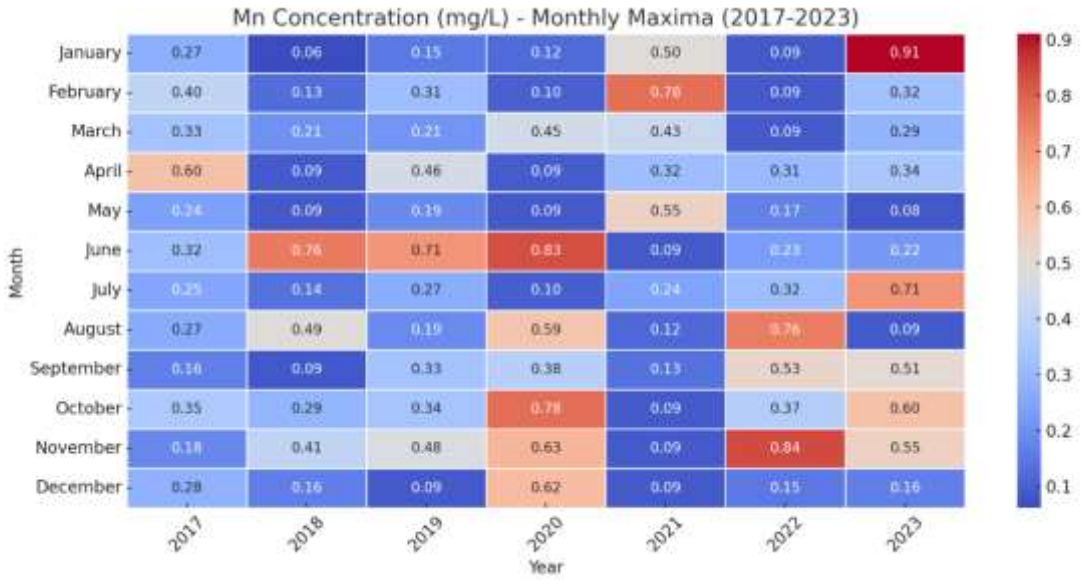


Figure 3: *Heatmap of Monthly Maximum Manganese (Mn) Concentrations (mg/L) in the Kvirila River Basin (2017–2023)*

Visualization through a heatmap of monthly data confirmed that high manganese (Mn) concentrations were not isolated events but were distributed consistently across months and years. Particularly noteworthy were the extreme values recorded in November 2020 and January 2023, with the latter reaching a peak concentration of 0.9114 mg/L — nearly nine times the regulatory limit. Analysis of exceedance frequency across individual months showed that March, June, July, August, September, October, and November had six exceedances out of seven years, corresponding to an exceedance rate of approximately 86%.

A linear regression model was applied to assess potential temporal trends in manganese (Mn) concentrations. The model indicated a weakly increasing trend in average manganese (Mn) concentrations over time, with predictions suggesting that, under current conditions, exceedances will persist at least through 2025. No statistically significant declining trend was observed, emphasizing that manganese (Mn) levels are unlikely to improve without deliberate intervention.

In summary, the dataset reveals a severe and persistent manganese (Mn) contamination issue within the monitored system. The high frequency of exceedances across years and months, coupled with increasing average concentrations in recent years, indicates that natural attenuation or incidental improvements are insufficient to achieve compliance. The results strongly highlight the necessity for immediate and sustained remediation efforts, improved monitoring practices, and further investigation into the underlying causes of seasonal variability to develop effective management strategies.

IV. Discussion

Elevated manganese (Mn) levels in Georgian rivers are predominantly due to mining operations lacking adequate environmental monitoring [5]. Redox-sensitive manganese (Mn) cycling, driven by hydrological variability and sediment dynamics, facilitates its mobility and bioavailability [2]. Once mobilized, manganese (Mn) alters aquatic redox conditions, displaces other trace metals, and supports eutrophic conditions through phosphorus mobilization [2].

The ecological consequences are severe. Manganese (Mn) affects aquatic organisms at sub-lethal levels, impairing growth and reproduction, as demonstrated by studies in the Selangor and Barnoi rivers [6], [8]. Long-term exposure to manganese (Mn) has been associated with neurological

deficits in fish and biomagnification up the food web [1]. Health risk modeling in this study corroborates similar findings in China [10].

Climate variability acts as a critical modifier of manganese (Mn) risk. Rising temperatures enhance microbial manganese (Mn) cycling, while extreme rainfall accelerates erosion and runoff [6]. Sea-level rise and saline intrusion, particularly in the Rioni river, may shift sediment redox profiles and promote manganese (Mn) release [9]. Integrating climate factors into heavy metal contamination environmental risk assessment frameworks is crucial for anticipating future risks [9].

The results of the temporal analysis highlight a significant and persistent manganese (Mn) contamination problem that poses substantial regulatory and environmental challenges. The exceedance of the national permissible limit of 0.1 mg/L in nearly 80% of the recorded observations between 2017 and 2023 indicates systemic issues rather than isolated or anomalous events. The particularly high levels recorded in 2020 and 2023, coupled with the absence of any clear declining trend, suggest that natural attenuation processes are ineffective in this system or that external inputs of manganese (Mn) continue unabated.

Various environmental and operational factors likely contribute to the seasonal and annual fluctuations observed in manganese (Mn) concentrations. Elevated levels during the summer and autumn months could be attributed to increased temperatures, which enhance the microbial activity responsible for manganese (Mn) mobilization from sediments. Additionally, periods of high rainfall during late spring and early summer may facilitate the leaching of manganese (Mn) from soils into groundwater and surface water systems, contributing to elevated concentrations. In contrast, lower concentrations in winter months such as December may reflect reduced microbial activity, lower rates of geochemical weathering, and diminished hydrological transport processes.

The extremely high peak concentration recorded in January 2023 (0.9114 mg/L) suggests the possibility of point source pollution events, such as industrial discharges, mining activities, or failures in water treatment processes. Although background geochemical conditions can sustain elevated manganese (Mn) levels naturally, such acute spikes are often indicative of anthropogenic influences. Therefore, a more detailed investigation into potential local sources of manganese (Mn) contamination is warranted.

Chronic exceedances of manganese (Mn) present serious implications for public health and ecological stability. Elevated manganese (Mn) concentrations in drinking water are associated with neurological effects, particularly in children, while aquatic ecosystems can suffer from altered species compositions and reduced biodiversity [8]. Given these risks, the current trends represent not only a regulatory compliance issue but also a broader environmental and public health concern.

Given the absence of natural recovery trends, proactive intervention is necessary. Potential mitigation measures include:

- Enhanced water treatment technologies such as oxidation-filtration, ion exchange, or biological filtration systems specifically targeting manganese (Mn) removal.
- Source control strategies, including the regulation and monitoring of industrial discharges.
- Restoration of natural hydrological conditions to stabilize redox environments and minimize manganese (Mn) mobilization.
- Seasonal monitoring adjustments to better capture peak concentration periods and inform management decisions.

In conclusion, the evidence strongly supports the need for immediate, comprehensive, and sustained action to address manganese (Mn) contamination. Future studies should focus on identifying specific contamination sources, understanding seasonal geochemical dynamics, and assessing the effectiveness of mitigation efforts through adaptive monitoring frameworks.

V. Conclusion

Manganese (Mn) accumulation in Georgia's Black Sea Basin rivers is a multi-dimensional environmental challenge, driven by industrial, geochemical, and climatic processes [5], [9]. Its impacts on aquatic ecosystems, public health, and climate feedbacks necessitate immediate intervention [7].

Mitigation strategies should include microbial-induced calcite precipitation, phytoremediation, and sediment dredging in hotspots [6]. Implementation of real-time monitoring technologies and data-driven public health advisories is essential [3]. At the policy level, Georgia should align its water management framework with EU directives and collaborate regionally to address transboundary pollution [11].

An interdisciplinary approach combining environmental science, public health, and policy is critical to managing manganese (Mn) pollution sustainably [7]. Future research should focus on temporal monitoring, advanced remediation technologies, and socioeconomic risk communication [1].

The comprehensive analysis of manganese (Mn) concentration data from 2017 to 2023 clearly demonstrates a persistent and significant pattern of non-compliance with the national regulatory limit of 0.1 mg/L. Nearly 80% of monthly maximum measurements exceeded the permissible level, with certain years, notably 2017 and 2023, showing particularly widespread exceedances. Seasonal trends indicated that manganese (Mn) concentrations typically peak during the warmer months, suggesting environmental factors such as temperature-driven redox reactions and hydrological dynamics may play a critical role in manganese (Mn) mobilization.

The increasing trend in annual average concentrations, especially in recent years, highlights an urgent need for intervention. Forecasting analysis suggests that, without targeted remediation, manganese (Mn) levels will continue to exceed regulatory limits in the coming years. The sporadic occurrence of extremely high concentrations further suggests the potential influence of anthropogenic activities, warranting more detailed investigation into possible industrial or land-use sources.

Given the human health and ecological risks associated with elevated manganese (Mn) levels, immediate and sustained management actions are necessary. Future efforts should prioritize source identification, seasonal monitoring enhancements, and the implementation of effective treatment technologies to ensure both regulatory compliance and the protection of public health and the environment.

Ultimately, managing manganese (Mn) contamination demands an interdisciplinary approach that integrates environmental science, public health, and policy. Future research should prioritize the identification of pollution sources, the refinement of remediation strategies, and the development of adaptive monitoring frameworks to ensure long-term water safety and ecosystem resilience.

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THE IMPACT OF THE METAMODERN CONCEPT ON THE ECONOMIC BEHAVIOR OF INFRASTRUCTURE ORGANIZATIONS AND THE TRANSFORMATION OF THEIR BUSINESS STRATEGIES IN CONDITIONS OF UNCERTAINTY

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Abstract

This article examines how the concept of metamodernizm influences the economic behavior of infrastructure organizations and how their business strategies transform in uncertain conditions. Characterized by an oscillation between modernist optimism and postmodernist scepticizm, metamodernizm provides a unique basis for understanding how organizations adapt to changing environments by selecting and transforming their economic behavior and business strategies. This study aims to analyze the interaction between metamodernizm and organizational behavior, paying particular attention to the challenges and opportunities this creates for infrastructure organizations. It identifies key metamodernist features, such as an emphasis on flexibility, emotional depth and pragmatic idealism, and examines how these features influence decision-making and strategic planning processes. Based on a review of recent scientific publications, the study highlights issues with existing approaches to economic behavior in uncertain conditions and proposes a new classification of organizational strategies influenced by metamodernizm. The results obtained show that, while metamodernizm encourages innovative and adaptive business strategies, it also creates challenges in managing organizational stability. The study concludes with practical recommendations for managing infrastructure organizations in uncertain times, emphasising the need for a balanced approach that integrates metamodern principles with traditional strategic frameworks.

Keywords: metamodernism, economic behavior, infrastructure organizations, business strategies, uncertainty, organizational transformation

I. Introduction

The modern economic reality is characterized by a high degree of uncertainty caused by global crises, technological changes and shifts in cultural paradigms. In such conditions, infrastructure organizations are faced with the need to review and transform their business

strategies and economic behavior. One of the key factors influencing these processes is the concept of metamodernism, which combines elements of postmodern irony and modernist sincerity. In general, metamodern means fluctuations between two opposite concepts and the simultaneity of their use.

The economic behavior of organizations under uncertainty has long been the focus of academic and practical research. Traditional approaches such as risk management systems (Kaplan & Mikes, 2012) [9] that emphasize the importance of categorizing risks and implementing individual mitigation strategies, adaptive strategies or dynamic capabilities (Teece et al., 1997) [10], that allow organizations to reconfigure resources in response to changing conditions, and resilience theory by Folke et al. (2010) [8] that emphasizes the role of resilience in maintaining organizational stability during disruptions have traditionally dominated the discourse. However, the emergence of metamodern as a cultural and philosophical concept has brought new dimensions to this debate. Metamodernism, defined by Timotheus Vermeulen and Robin van den Akker (2010) [11] as an oscillation between modernist progressivism and postmodernist relativism, offers a fresh perspective on the analysis of organizational behavior in uncertain environments.

In Russia, the theoretical foundations of the behavior of economic agents were developed by B. H. Erznkyan, O. S. Ponomareva [2], G.B. Kleiner [3], S.L. Sazanova [5]. Modern domestic researchers present scientific works on various issues related to metamodernism. Thus, E. V. Khlyshcheva considered metamodern as a new worldview [7]. D. P. Frolov investigated post-institutionalism in the 21st century [6]; G. N. Ryazanova studied the features of consumer behavior management in a metamodern organization [4].

The analysis of scientific works on metamodernism and uncertainty showed insufficient application of these trends in the study of the features of economic behavior and business strategies of infrastructure organizations.

The concept of metamodernism is a philosophical and cultural paradigm that seeks to overcome the limitations of postmodernism. It suggests a cyclical movement between enthusiasm and irony, hope and melancholy, striving for sincerity and meaningfulness in an era of uncertainty. The main features of metamodernism are oscillation (fluctuations) between opposites, informed naivety, empathy, and the desire for transcendence. Metamodernism rejects the relativism and nihilism of postmodernism, while recognizing its contribution to critical thinking.

In conditions of uncertainty caused by global economic and political factors, infrastructure organizations that are guided by metamodern principles demonstrate greater resilience and adaptability. They more effectively exploit the opportunities that arise from change and minimize the risks associated with it. Thus, metamodernism has a significant impact on the economic behavior of infrastructure organizations, stimulating them to transform business strategies and increase resilience under uncertainty.

The need to study the economic behavior of infrastructure organizations and the transformation of their business strategies in conditions of uncertainty is due to the growing complexity of the external environment. In Russia, these processes have their own characteristics associated with the historical and cultural context, as well as with current economic and political conditions.

The study is motivated by the need to integrate metamodern principles into the economic behavior of infrastructure organizations. In modern Russia, where uncertainty is exacerbated by geopolitical and economic challenges, such integration is especially relevant. Using the features of metamodernism and their impact on organizational behavior, the study aims to provide practical information for the effective management of infrastructure organizations under uncertainty.

II. Methods

The theoretical and methodological basis of the study was the concepts and regulations of economic science, including the concepts of modernism, postmodernism and metamodernism, set out in the scientific works of foreign and domestic scientists. The following general scientific methods, ways of studying and processing data were used: logical, comparative, systemic, strategic, index analyses, methods of generalization and expert assessments, synthesis, classification and typology.

III. Results

In conditions of uncertainty, the economic behavior of infrastructure organizations is studied using several scientific approaches.

First, the neoclassical approach assumes that organizations seek to maximize profits by making decisions based on rational cost-benefit analysis. However, this approach is often criticized for ignoring behavioral factors and bounded rationality.

Second, the behavioral approach considers cognitive distortions, emotions, and social norms that influence decision making under uncertainty. This approach includes prospect theory, bounded rationality theory, and social network theory.

Third, the institutional approach focuses on the role of formal and informal institutions that define the rules and norms of organizational behavior. Institutions can reduce uncertainty by providing stability and predictability to the environment in which organizations operate.

Fourth, the evolutionary approach considers organizations as adaptive systems that learn and change in response to changing conditions. This approach emphasizes the importance of innovation, experimentation, and the selection of the most successful strategies.

The concept of metamodernism is a cultural and philosophical phenomenon that arose as a reaction to the crisis of postmodernism. The content of metamodernism is reflected in a number of the following features.

1. An oscillation between irony and sincerity, according to which organizations and individuals are simultaneously skeptical of grand narratives and eager to express their values sincerely. It may also be represented by a switch in the approaches between optimism and skepticism.

2. Plurality of identities –means the subject's rejection of rigid categories and the acceptance of hybrid forms. At the same time, it can also be perceived as a balancing of idealistic goals or ideas with practical limitations.

3. The rejection of binary oppositions – metamodernism clearly rejects dichotomies such as "tradition or innovation", "global or local", etc.

The directions of modern metamodernism are quite diverse and cover culture, economics, technology, sustainable development, and the social sphere.

Metamodernism influences cultural narratives by shaping how organizations perceive and respond to uncertainty.

The economic behavior of infrastructure organizations in modern Russia is characterized by a high degree of dependence on government regulation and rate policy. In conditions of uncertainty caused by geopolitical factors and changes in the economic situation, ensuring the stability of operation and maintaining the reliability of infrastructure systems becomes a priority.

The transformation of business strategies of infrastructure organizations is aimed at optimizing costs, increasing operational efficiency and diversifying funding sources. Digital technologies and innovative solutions are being actively implemented to improve the quality of services provided and reduce costs.

Particular attention is paid to the development of public-private partnerships as a mechanism for attracting investment in the modernization and expansion of infrastructure facilities. An important aspect is adaptation to changing consumer needs and sustainable development requirements.

Under uncertainty, infrastructure organizations are seeking to increase the flexibility and adaptability of their business models, as well as to strengthen their interactions with government authorities and other stakeholders. This helps minimize risks and ensure sustainable development in the long term.

Metamodernism, with its emphasis on oscillations between enthusiasm and skepticism, sincerity and irony, has a significant impact on the formation of cultural narratives. Organizations functioning in metamodernism are faced with the need to adapt their strategies and communication approaches to the perception of uncertainty that is becoming a dominant feature of contemporary culture. The impact of metamodernism on culture is manifested in the rejection of universal truths and the recognition of multiple perspectives. This forces organizations to develop more flexible and context-sensitive narratives that can accommodate a diversity of perspectives and values.

Cultural narratives in the metamodern era are characterized by increased reflexivity and self-criticism. Organizations strive for greater transparency and openness, recognizing their own limitations and shortcomings. This allows them to build more trusting relationships with audiences and enhance their reputation. Moreover, metamodernism stimulates the search for new forms of expression and communication. Organizations experiment with different media formats and platforms, seeking to establish a deeper and more meaningful connection with the target audience.

The economic aspect of metamodernism is manifested in the introduction of integrative (hybrid) business models that synthesize market and socio-centric tasks. Such models combine elements of entrepreneurship aimed at eliminating current social imbalances with commercialization mechanisms that ensure financial stability. In contrast to classic non-profit organizations, which focus on maximizing social effect, and commercial structures, which are focused on making a profit, hybrid formats assume a synergy of both vectors. The companies, producing biodegradable package, can serve as an example, since their activities not only minimize environmental damage, but also create jobs for vulnerable groups (for example, migrants or disabled persons). Similarly, technology startups that develope low-cost medical gadgets for the poor (including the elderly), combine a social mission with investor attraction and profitability. The effectiveness of such models is due to the ability to quantitatively and qualitatively assess the dual result – social impact and economic return. This requires the creation of specialized metrics that integrate indicators of the ecological footprint, the level of employment of target groups, ROI (return on investments) and EBITDA (earnings before interest, taxes, depreciation and amortization). The monitoring system should reflect both short-term financial results and long-term changes in society.

Thus, the metamodern economic paradigm proposes to overcome the conflict between profit and social values, proving their mutual complementarity. This is confirmed by cases where the improvement of the quality of life of the population correlates with the growth of customer loyalty and brand sustainability.

Digital transformation is a key element of metamodernism, implementing its principles of adaptability and nonlinearity. The introduction of cloud platforms, AI and IoT allows organizations to quickly restructure processes, test innovations and respond to market fluctuations. Decentralization of management, replacing rigid hierarchies with agile approaches, accelerates communication between departments and stimulates creativity. For example, the transition to blockchain document management systems reduces bureaucratic costs, and the use of big data optimizes logistics.

A culture of continuous learning is becoming a must: employees master digital tools (e.g. low-code platforms), which increases their competitiveness in a VUCA world. However, risks include dependence on IT infrastructure and cyber-attacks, which require investments in cybersecurity.

Sustainable development in metamodernism is interpreted as a triune system that balances economic, environmental and social KPIs. Investments in "green" technologies (solar power plants, waste recycling) and ethical supply chains (fair trade) are transformed from optional practices into mandatory standards. For example, ESG reporting by companies now influences stock quotations, and the carbon footprint of a product influences consumer choice.

The critical difference between metamodernism and postmodernism is the recognition of the conventionality of "grand narratives" while maintaining attempts to use them constructively. Unlike the modernist belief in linear progress, metamodernism allows for cyclical development, where innovations are combined with a rethinking of traditions (for example, the use of AI in ethnographic research).

Analysis of the economic behavior of organizations in conditions of instability reveals a correlation between the level of environmental uncertainty and the choice of strategies. The introduction of metamodern principles (flexibility, multidisciplinarity) can generate both positive effects (reduction of transaction costs, growth of innovative potential) and risks (overload of resources, imbalance of short- and long-term goals). The proposed classification of strategies (Table 1) demonstrates that the synthesis of adaptability and sustainability increases the resilience of organizations in crisis scenarios.

Table 1: *Classifications of economic behavior and business strategies of infrastructure organizations under uncertainty*

Type of economic behavior and business strategy	Characteristic
1. Adaptive behavior (business strategy)	Use of flexibility and adaptability
2. Sustainable behavior (business strategy)	Ensuring stability during disruptions
3. Innovative behavior (innovative business model)	Implementation of new technologies and business models
4. Socially oriented behavior (business strategy)	Taking the interests of stakeholders and society into account

The choice of the type of economic behavior and business strategy by each infrastructure organization is largely determined by the indicators of uncertainty of the environment of its operation. The orientation of economic behavior and business strategies of infrastructure organizations on the use of the principles of metamodernism can lead to positive and negative effects.

The positive effects of the application of the concept of metamodernism consists in the fact, that as a cultural and intellectual paradigm, it has a significant influence on various spheres of human activity, stimulating progress and development. For example, in relation to infrastructure organizations, one of the positive aspects of its use is the orientation of economic behavior and business strategies towards stimulating and encouraging innovation. The oscillations between opposite poles, that characterize metamodernism, create fertile ground for the emergence of new ideas and approaches, as they stimulate critical thinking and the search for compromises between traditional and modern concepts. In addition, emotional involvement, which is an integral part of metamodernism, helps to form deeper connections between employees of infrastructure organizations and the world around. Awareness of the complexity and multifaceted reality of the external environment causes empathy and sympathy in employees, which, in turn, motivates them to actively participate in solving economic, social and environmental problems on an innovative basis. Pragmatic idealism, which combines the pursuit of high ideals and a realistic assessment of possibilities, allows us to find new effective solutions to achieve our goals.

Metamodernism encourages constructive dialogue and collaboration between different stakeholders, which contributes to the development and implementation of innovative projects aimed at improving the quality of life and sustainable development.

Metamodern as a whole contributes to infrastructure organizations becoming more open to change, adopting various hybrid business strategies, and increasing staff attention to corporate social responsibility.

The study also revealed negative effects from the application of the concept of metamodernism in infrastructure organizations. For example, it introduces complexity and instability in management decision-making processes. This can largely be explained by the fact that metamodernism, characterized by oscillations between enthusiasm and skepticism, creates additional levels of uncertainty. In the context of constant paradigm shifts and the absence of clear guidelines, decision-making by management systems becomes more labor-intensive and error-prone. Such complexity is exacerbated by the fragmentation of information and the pluralism of development prospects. The lack of a single, widely accepted narrative means that decision makers are forced to consider a multitude of conflicting points of view, making it difficult to formulate a coherent line of economic behavior or business strategy.

It is necessary to specifically highlight the problems that arise when using the concept of metamodernism in infrastructure management systems, which include the complexity of managing hybrid types of economic behavior and business strategies, the risk of identity loss, and uncertainty in long-term planning.

The complexity of managing hybrid types of economic behavior and business strategies is associated with the need to simultaneously combine and alternate opposite approaches, such as sustainable development and innovation, centralization and decentralization. Effective management requires decision makers to have a deep understanding of the context, the ability to assess risks and flexibly adapt strategies to changing circumstances. Insufficient development of coordination and control mechanisms can lead to contradictory actions and a decrease in the overall efficiency of the system. In addition, the problem of assessing the effectiveness of metamodernist strategies arises. Traditional assessment methods, focused on achieving specific, measurable goals, turn out to be ineffective under conditions of constant variability and uncertainty characteristic of metamodernism. There is a need to develop new approaches to assessment that consider both quantitative and qualitative indicators and are capable of reflecting the dynamics of change and the long-term consequences of decisions made.

The next problem is the risk of identity loss, which means that when trying to balance between the opposite poles characteristic of metamodernism (e.g. between utopia and pragmatism, knowledge and faith), the infrastructure management system may lose a clear idea of its main goals and values. This may lead to a lack of coordination in decision-making and strategic planning. The uncertainty in long-term planning and the complexity, inherent in metamodernism, can make it difficult to predict future states of infrastructure systems. In the context of rapidly changing technological, economic, and social factors, attempts to adapt to metamodern trends can lead to short-term decisions that ignore long-term consequences for the sustainability and reliability of infrastructure.

Taking into account the positive and negative effects of the concept of metamodernism in infrastructure organizations, it is proposed to focus on the following management principles:

- operational flexibility, which implies the ability of infrastructure management systems to quickly adapt to changes;

- ensuring sustainable development, which means the transition to sustainable and stable styles of economic behavior and business strategy (for a certain period) during changes;

- interaction means the organization's readiness for cooperation, exchange of knowledge, technologies and experience, transparency in communications and decision-making;

- balance – the feasibility of integrating meta-modern principles with traditional frameworks.

IV. Discussion of the results

The obtained results indicate that the concept of metamodern has a significant impact on the economic behavior of infrastructure organizations.

In conditions of uncertainty, companies are forced to change their economic behavior and business strategies, leading to the emergence of hybrid strategies. The findings also highlight the role of cultural narratives and digital transformation in shaping the organizational behavior of infrastructure companies. The study extends these ideas by offering a new classification of strategies influenced by metamodernism. The emphasis on emotional depth and pragmatic idealism represents a significant deviation from traditional approaches, offering new possibilities for research and practice.

V. Conclusions

1. Metamodernism provides a unique framework for understanding the economic behavior of infrastructure organizations under uncertainty.

2. The concept encourages innovative and adaptive strategies, but also introduces complexity into the decision-making process.

3. Organizations must balance between metamodern principles and traditional structures to achieve stability and growth.

4. Key challenges include the complexity of managing hybrid strategies and the risk of identity loss.

5. Future research should examine the long-term implications of metamodernism for organizational behavior and strategic planning.

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MODELLING EXTREME METEOROLOGICAL PROCESSES POSING A RISK TO AGRICULTURE UNDER MODERN CLIMATE CHANGE

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Abstract

The phenomena associated with modern climate change have currently become an urgent problem in the South Caucasus region (Georgia), where frequent heavy rainfall, hail and flooding cause landslides that seriously endanger human safety and damage production and agriculture. To promptly control and prevent torrential rain, heavy hail and their consequences, it is necessary to provide environmental authorities, the scientific community and the population with scientific information on upcoming extreme regional and local events. This article emphasizes the importance of studying the thermodynamic state of the atmosphere during the formation of convective clouds in areas with complex orography. To this end, the Real-Time Environmental Applications and Display (READY) system, comprising the Meteor 735CDP10 meteorological radar and the Weather Research Forecast (WRF) v.4.5 model, was employed. The numerical values of instability energy throughout the day were determined and analyzed by carefully studying observational data and meteorological radars in certain regions of eastern Georgia. Analysis of the calculation results showed that, in some cases, the WRF model (using various microphysical parameterization schemes) did not correctly forecast showers and hail in some of the studied local territories. However, the thermodynamic state of the atmosphere was satisfactorily forecast by the ARL READY system compared with the meteorological radar data. Furthermore, the ARL READY system satisfactorily forecasted the stratification of the atmosphere (CAPE values) for the time interval between 13:00 and 19:00 local time in most cases.

Keywords: modelling, risk analysis, extreme processes, forecasting methods, climate change

I. Introduction

Modern climate change is caused mainly by an increase in anthropogenic environmental pollution, and this change in many regions of the Earth is expressed in frequent heavy rains and hail with destructive floods, accelerated melting of glaciers with avalanches and landslides, long-term droughts with increased desertification processes [1]. Climate change is in full swing in the Caucasus region and is well expressed in Georgia too [2]. Namely, climate change in Georgia is manifested, at a minimum, as a result of a pronounced accelerated melting of Georgian glaciers in the Caucasus with frequent avalanches and devastating landslides, an increase in the frequency of short-term heavy rains and hail with destructive floods and prolonged droughts in the summer [3,4]. Research has shown that over the past four decades, the number of extreme weather events

and natural disasters (floods, landslides, storms, heavy rains, hail) has increased approximately two to three times compared to the 60-year period of the last century [4]. It should be noted that extreme meteorological processes in the Caucasus are largely due to the complex orography of the Caucasus and the consequences of regional climate specifics. Moreover, on the territory of Georgia, they are of a local nature and generally proceed differently due to the wide variety of features of the regional climate and locations [5]. Of particular importance among the frequent extreme meteorological processes in Georgia are heavy rains, hail, and subsequent floods and landslides. Frequent heavy rains and hail cause serious damage to agriculture (hundreds of vineyards in the Kakheti wine region in southeastern Georgia are especially destroyed) and also harm the population. To protect the entire Kakheti region, 85 anti-hail missile systems have been installed since 2015, but their effectiveness is not yet entirely satisfactory [6,7]. To effectively use a modern anti-hail system, it is necessary to timely predict extreme weather events, forecast local convective processes, and assess the thermodynamic state of the atmosphere and, accordingly, its stratification. It is clear that to warn operational authorities about the vagaries of nature and prevent extreme weather events, it is necessary to more effectively use modern scientific tools, such as ARL READY and Radar Meteor 735CDP10. At the same time, the Atmospheric Sounding Program (ASP) is a useful tool for assessing the state of the atmosphere, since ASP aerialgrams are the most useful means of displaying vertical profiles of thermodynamic quantities (temperature, humidity, and pressure profiles), for forecasting precipitation, boundary layer, clouds and the type of atmospheric convection [8]. In addition, fully automated ASP reduces operating costs and provides full coverage of upper-air meteorological observations, making it possible to compare convective available potential energy (CAPE) with standard instability indices for estimating convective atmospheric potential, such as lift index [9,10]. Over the past few decades, convective available potential energy (CAPE) has become a widely used variable to assess atmospheric instability, and atmospheric convective potential, since CAPE is independent of one specific atmospheric level (calculated using the integral of the atmospheric vertical profile). CAPE is widely used to model the developing thunderstorms (strength within a thunderstorm), showers, and hail [11, 12]. To improve the hail forecast model developed by the Laboratory of Atmospheric Physics of the University of León, the differences between groups of days with different levels of convective activity and the corresponding CAPE values were studied using morning radiosonde data [11]. The hail forecast results showed that CAPE should not be used as a single variable, but in combination with other parameters: in Leon, the maximum CAPE values were reached in the afternoon and did not exceed 2000 J/kg, while the average value of the entire sample was 132 J/kg.[11]. By systematically varying CAPE in a horizontally homogeneous reference environment, Lin and Koumdjian in [12] simulated hail formation under highly unstable supercell storms using a cloud1 model and a detailed 3D hail growth trajectory model. The results showed a non-monotonic relationship between hailstone residence time and CAPE due to changes in the upwelling wind field [12]. It should be noted that sometimes storms in high CAPE environments may produce smaller hail because the horizontal wind speed in the updraft becomes too high and the hailstones are prematurely thrown out of the optimal growth area [13]. Therefore, it is important to know the types of storm conditions that can cause large hail [14]. Therefore, it is important to know the types of storm conditions that can cause large hail. Among extreme meteorological processes for Eastern Georgia with complex orography, short-term, local, heavy hail and rain are of particular importance [4]. The strength and characteristics of the development of such processes are largely determined by the stratification of the atmosphere [10]. Besides, it is important to know temperature variability between the study regions. Therefore, when considering such processes, it is important to assess the thermodynamic state of the atmosphere in a local area and, accordingly, stratification [15-17]. The purpose of this article is to obtain additional information on extreme events (hail, and rain) in an area with complex orography (Georgia) to further develop an approach for predicting strong convection with hazardous precipitation and hail using modern forecasting tools.

II. Methodology and data

To assess the state of convection in the atmosphere, the particle method is used, where it is assumed that initially the particle and the surrounding atmosphere have the same temperatures, and if the particle moves upward, it moves dry adiabatically up to the condensation level. In the case of rising above the condensation level due to condensation and the release of latent heat of condensation, the particle temperature drops more slowly and the particle moves along a humid adiabata [9, 11, 12]. From the level of free convection (LFC) to the equilibrium level (EL) during the adiabatic rise of a unit volume of air, the work done by the particle is called convective available potential energy (CAPE), which can be represented as follows [9, 12,17],

$$CAPE = \int_{LFC}^{EL} g \frac{T_{parcel} - T_{env}}{T_{env}} dz, \quad (1)$$

where *Tparcel* is the temperature of the parcel and *Tenv* is the temperature of the environment, g is gravity acceleration.

It should be noted that LFC is the level above which the temperature of the environment falls faster than the temperature of the particle and EL is the level at which the temperature of the environment equals the temperature of the particle. The velocity W of an air particle at the level Zmax, where the temperature of the environment is equal to the temperature of the air particles is maximum and has the following from [9, 12,17],

$$W(Zmax)=(CAPE)1/2 \quad (2)$$

Formula (2) can be used to account for the relationship between instability energy and peak wind speed at maximum height. Theoretically, it is known that the state of the atmosphere can be divided into several stages depending on the energy of instability and the speed of the upward flow. When the instability energy CAPE>0 J/kg, the state of the atmosphere becomes unstable, and when CAPE>1000 J/kg, the state of the atmosphere changes from medium instability to extreme.

As already mentioned, to assess the degree of instability of the atmosphere, it is necessary to study its vertical structure and the processes developing in it. Today, the operation of a radiosonde is associated with certain financial costs, and its use in some developing countries is practically not carried out (including Georgia). To enable efficient and timely forecasting of atmospheric processes, the National Oceanic and Atmospheric Administration's (NOAA) Atmospheric Research Laboratory (ARL) has created the Real-time Environmental Applications and Display System (READY) (http://www.ready.noaa.gov). To study the thermodynamic state of the atmosphere on the days under consideration, we used data from the ARL archive with a horizontal resolution of 0.5^0 and constructed a particle state curve for each day under consideration. Numerical instability energy values were also taken from the ARL READY system archive with a horizontal resolution of 1.0^0 (~111 km)) [15]). The calculation results were compared with real data obtained from the Sighnaghi meteorological radar (Meteor 735CDP 10-Doppler Weather Radar), controlled by the Military Scientific and Technical Centre "DELTA", located in the village of Chotori, Sighnaghi municipality, through which the state of the atmosphere was studied throughout Kakheti.

III. Results and discussion

On June 13, 2023, torrential rain and heavy hail caused damage to the villages of Samtskhe-Javakheti (southern Georgia), in particular, the villages of Shoraveli, Pkhero, and Zemo Enteli of the Adigeni municipality were affected. The disaster destroyed crops and a large harvest. Heavy hail occurred in six villages of the Akhalkalaki municipality. The hail began at 13:49 on 13/06/2023

and lasted 20 minutes but large hail caused significant damage to potato and barley crops, as well as destroying plantings. Fig. 1 shows forecast maps of convective accumulated precipitation in mm (Fig. 1, a), atmospheric temperature, and geopotential heights at 500 hPa at 12 UTC (Fig. 1, b), taken from the Wettercentrale NCEP Climate archive Forecast System Reanalysis (CFSR) at 0.5 resolution. Figure 2, a - shows that strong convective precipitation (20-25 mm) is recorded almost throughout the entire territory of Georgia at 12 UTC, while as can be seen from Figure 2, b, Georgia is located in an area of relatively low pressure (1005 hPa), therefore frontal processes are activated from the west, which caused strong convective precipitation throughout Georgia.

Testing of the physical parameterization schemes of the model WRFv.4.5.1 under conditions of strong convection that occurred on June 13, 2023, against the backdrop of the complex orography of Georgia showed a scatter in the values of the calculation results. The format of the

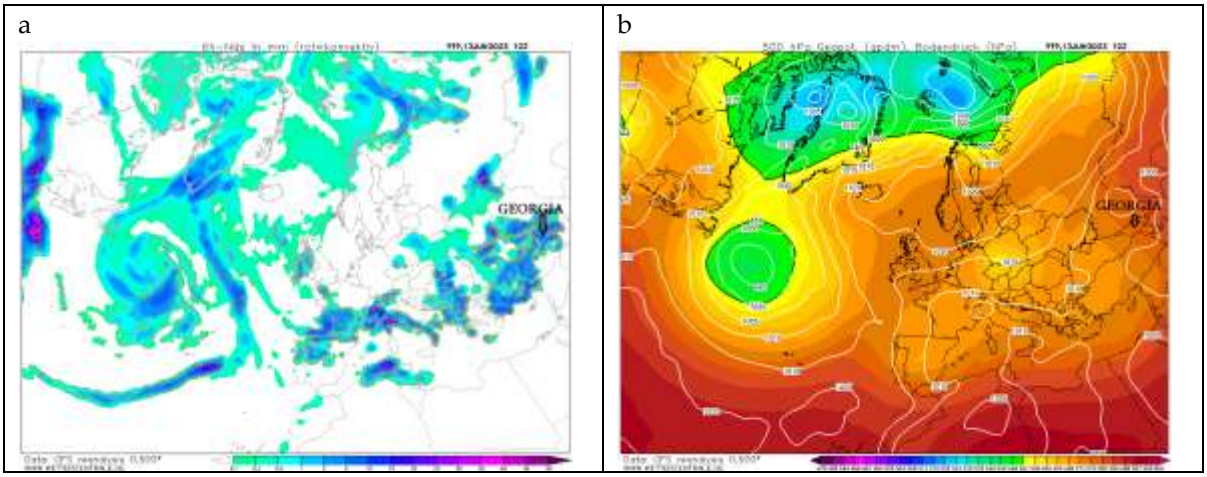


Figure 1: *CFSR 0.5 resolution forecast maps for 12 UTC (**a** - rainfall intensity in mm; **b** - 500 hPa geopotential heights contours).*

article does not allow us to consider in detail all the results of the calculations (we are going to discuss this issue in a separate article), but in a nutshell, it should be noted that the calculations showed that none of the combinations of the Physical and Cumulus parameterization schemes were able to fully reproduce the deep convection that occurred on June 13 2023 in the Akalkalaki and Kakheti regions. According to ARL's READY system, the maximum value of instability energy for Akhalkalaki was (CAPE=1950 J/kg) at 12 UTC on June 13, 2023. Figure 2 shows radar data of cloud intensity in Eastern Georgia on June 13, 2023, the legend shows cloud reflectivity and the right and upper parts of the image show cloud height in km. According to radar data, on the same day a cold atmospheric front spread across the territory of Eastern Georgia and, as a result of local convective processes, the cloud system intensified even more throughout almost the entire territory of Kakheti (Sagarejo, Telavi, Akhmeta, Kvareli, Gurjaani, Lagodekhi, and Dedoplistskaro) (Fig. 2). For example, the maximum value of instability energy in Gurjaani was CAPE=2020 J/kg. According to Fig. 2, a cloud with a reflectivity of 55-60 dB, which corresponds to the dark red color in the image, was observed at 19:54 (local time) mainly in the territory of the municipalities of Sagarejo and Akhmeta and after that, the atmospheric front expanded and intensified in other regions and the upper the cloud boundary reached 10 km (in Fig. 2, the upper boundary of the cloud is clearly visible from the vertical section of the cloud, which corresponds to the upper and right parts of the picture).

Fig. 3 shows the thermodynamic state of the atmosphere on June 13, 2023, in the period 09-12 UTC for geographic coordinates 41.73'N, and 45.33'E. (Gurjaani). As can be seen from Figure 4, the green area in Figure 3 accurately represents the numerical value of CAPE and shows that the Gurjaani region experiences strong instability between 09 and 12 UTC.

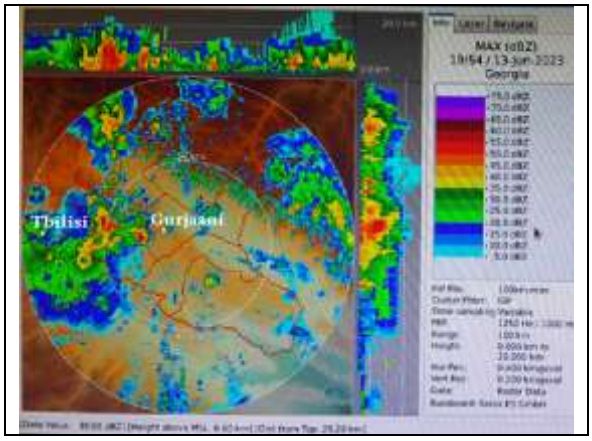


Figure 2: *Cloud intensity in Kakheti according to meteorological radar data (June 13, 2023).*

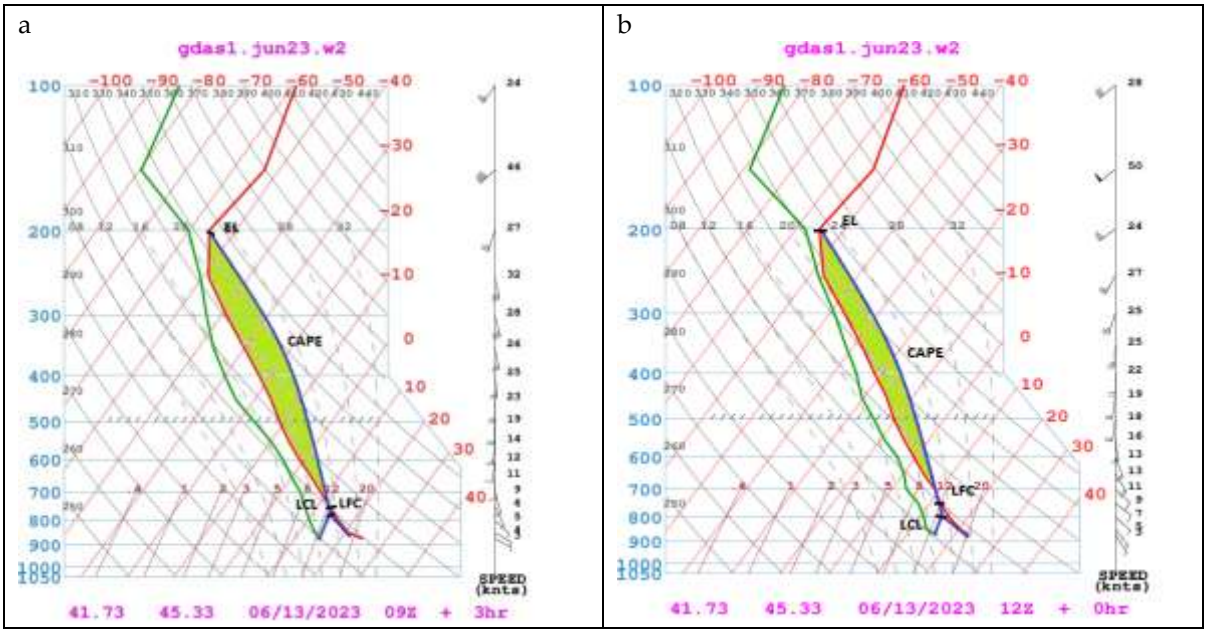


Fig. 3: *Aerological diagrams of Gurjaani.* ***a*** *- June 13, 2023, at 09 UTC;* ***b*** *- June 13, 2023, at 12 UTC.*

However, it should be noted that the numerical value of instability energy at 09 UTC (CAPE = 2020 J/kg) was greater than at 12 UTC (CAPE = 1500 J/kg, when heavy rain occurred). The right side of Fig. 3, a, and b shows the vertical distribution of wind in the territory of the Gurjaani municipality, it can be seen that at 09 UTC (Fig. 3, a), when CAPE is maximum, the wind speed at the level of 250 mb is 32 knots, and at 12 UTC (Fig. 3, b) when CAPE is comparatively lower, the wind speed is 27 knots. Thus, the study of the vertical distribution of wind speed is of great importance when assessing the energy of instability in the hail protection of the operational service.

On June 15, 2023, at 18:39, a cold atmospheric front entered Eastern Georgia and the cloud system locally intensified in most regions of Kakheti (Akhmeta, Sagarejo, Gurjaani, Telavi, Kvareli, Lagodekhi, and Sighnaghi). Half an hour later, due to torrential rain and heavy hail (accompanied by strong winds), the streets of Gurjaani were flooded so much that the water almost flooded the cars and flooded the offices on the ground floor (Fig. 4).

The results of the WRFv.4.5.1 model calculations performed with different schemes showed that although the background synoptic situation occurring in Georgia was modeled quite well, the local convective processes that occurred on June 15, 2023, over Kakheti were not modeled well enough.



Figure 4: *Disaster in the Gurjaani municipality of Kakheti, June 15, 2023. Streets of Gurjaani, **a**-June 15, 2023, 16:00, b- June 15, 2023, 17:00.*

Fig. 5, a - shows radar data of cloud intensity in Eastern Georgia on June 15, 2023, at 17:04, where the legend indicates the reflectivity of the clouds, and in the right and upper part of the image the cloud height in km is indicated. As can be seen from Fig. 5, a, in the vicinity of Gurjaani (in Fig. 5, a - the locations of Tbilisi, Sagarejo, and Gurjaani are indicated) there is a massive cloud system and the main part of the clouds is spreading from the northeast to the southwest, across the territory of the Gurjaani and partly Kvareli districts, on June 15 at 17:04. According to Fig. 5, a, a cloud with a reflectivity of 55-60 dB, which corresponds to the dark red color in the image, was recorded by 17:04 mainly in the territory of the municipalities of Gurjaani and Kvareli and the upper boundary of the cloud is 12 km (Fig. 5, a - the upper boundary of the cloud is clearly visible from the vertical section of the cloud corresponding to the upper and right parts of the image).

Fig. 5, b - presents the aerological diagram of June 15, 2023, obtained by ARL READY at 12 UTC for the Gurjaani region, when strong convective clouds formed. On all the presented aerological diagrams, we have constructed the curve of the state of the particle (blue), the location of which determines the value of the instability energy and, accordingly, the strength of local convection processes.

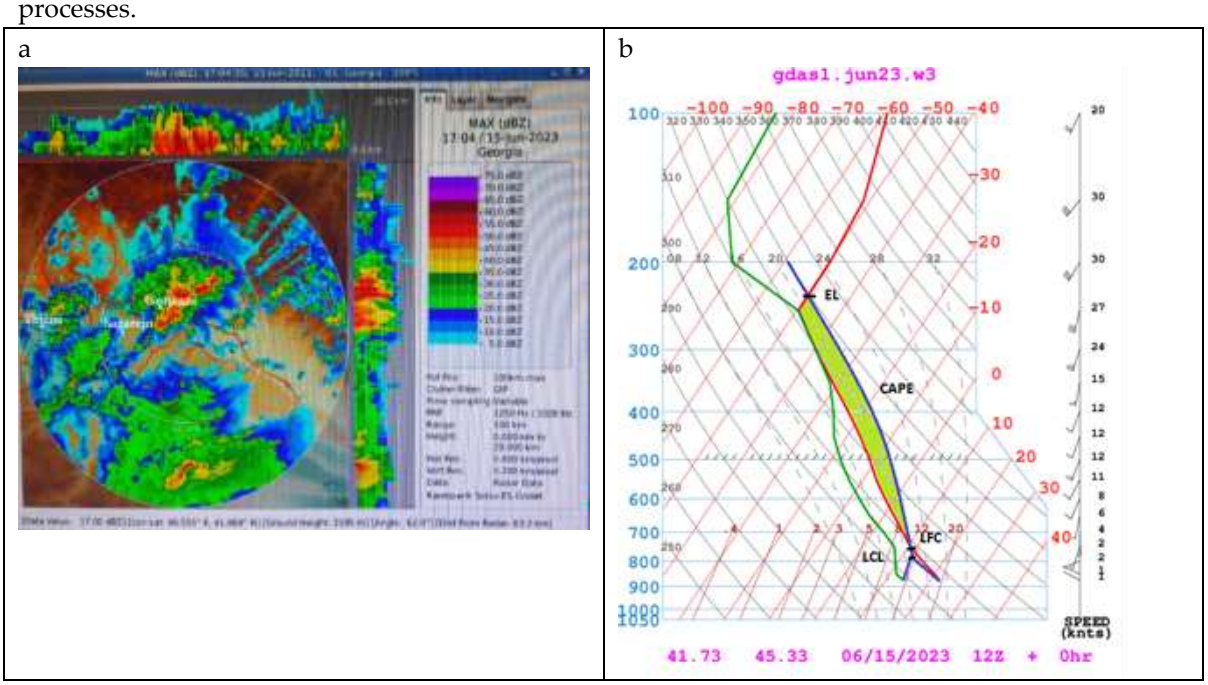


Figure 5: ***a*** *- Cloud intensity in Kakheti according to meteorological radar data. (June 15, 2023);* ***b*** *- Aerological diagram of Gurjaani on June 15, 2023 (12 UTC).*

The area of the green figure (between the LFC and EL levels) is the value of the instability energy. For the day under study, the maximum values of instability energy (CAPE=1450 J/kg) were recorded at 12 hours UTC, and the wind value in the vertical direction was maximum up to the level of 200 mb and amounted to 30 knots.

According to the Kakheti weather radar, on August 2 and 3, 2023, a cold atmospheric front entered Eastern Georgia from the southwest, which spread to almost the entire territory of Kakheti (Sagarejo, Telavi, Akhmeta, Kvareli, Gurjaani, Sighnaghi, and Lagodekhi), but the cloud was especially enhanced by local convection in the Kvareli region.

Indeed, Fig. 6 shows that the strongest cloudiness (with a reflectivity of 60 dB) was recorded in the territories of the municipalities of Gurjaani and Kvareli, the upper boundary of the cloud reached 18 km, and the maximum size of hailstones in the cloud reached 47 mm. Numerical calculations performed using the WRF model were able to approximately correctly predict the maximum hailstone size, but the location of the hailstone was not accurately predicted.

From Fig. 7, presented aerological diagrams constructed for the Kvareli district (geographic coordinates 41.57'N, 45.49'E), it is clear that for the presented days the maximum values of instability energy (CAPE=1400, 1200 J/kg) are fixed at 15 UTC.

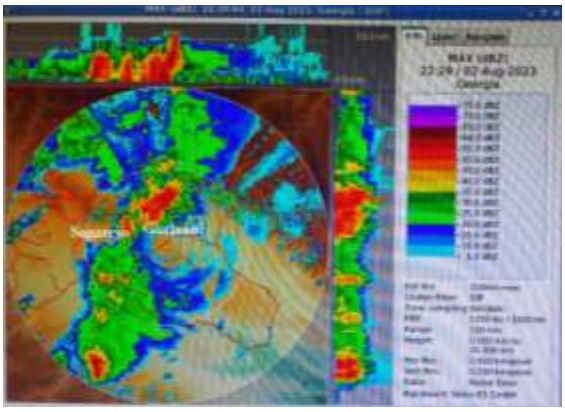


Figure 6: *Cloud intensity in Kakheti according to meteorological radar data at 22:29 August 2, 2023.*

On the right side of the diagrams, where the vertical wind distribution is presented, the maximum wind speed is presented at 200 mb and is 82 knots in Fig. 7, a), and in Fig. 7, b - maximum wind speed at the same level 68 knots. Despite the different values of instability energy, the magnitude of the wind in the cloud plays a very important role in assessing the ascending convective flows, and the aerological diagrams constructed for the Kvareli region well reproduce the real situation that took place on August 2 and 3. 2023.

An additional search was also carried out for days when heavy precipitation (hail, rain) came to the territory of Eastern Georgia in the summer of 2021 and 2022. For the 25 days tested, 14 days were chosen when the energy of heavy precipitation (hail) was unstable and exceeded 1000 J/kg (CAPE>1000 J/kg.

For simplicity, Table 1 presents the numerical values of the instability energy (CAPE > 1000 J/kg) and the corresponding updraft velocities at the EL level during hazardous meteorological processes that developed in 2022 in some regions of Eastern Georgia. As can be seen from Table 1, during dangerous meteorological processes that developed in 2022, the numerical values of instability energy increased and reached their maximum in the time interval 09 UTC-15 UTC, this is about 13-19 hours local time, which is when the soil temperature and vertical velocities are high and, among other favorable reasons, a favorable time comes for the formation of local convective clouds [6,7,9,12]. It should be noted that the calculations showed that in all cases we had different levels of instability and the difference was noticeable. Indeed, sometimes storms with high CAPE conditions produce less hail because the horizontal wind speed in the updraft becomes too high

[13] and, conversely, some calculations have shown that storms with low CAPE conditions produce heavy rain and hail, but in any case, energy instability reached its maximum in the time interval 09 UTC-15 UTC. That is why, when forecasting local convective processes in regions with complex orography, together with regional forecasting models (WRF), it is necessary to study the thermodynamic state of the atmosphere in the time interval 09:00-12:00 UTC (based on CAPE and the aerological diagrams of the ARL READY system), and if unstable energy with a significant lift index appears, then there is a high probability of causing an adverse atmospheric event.

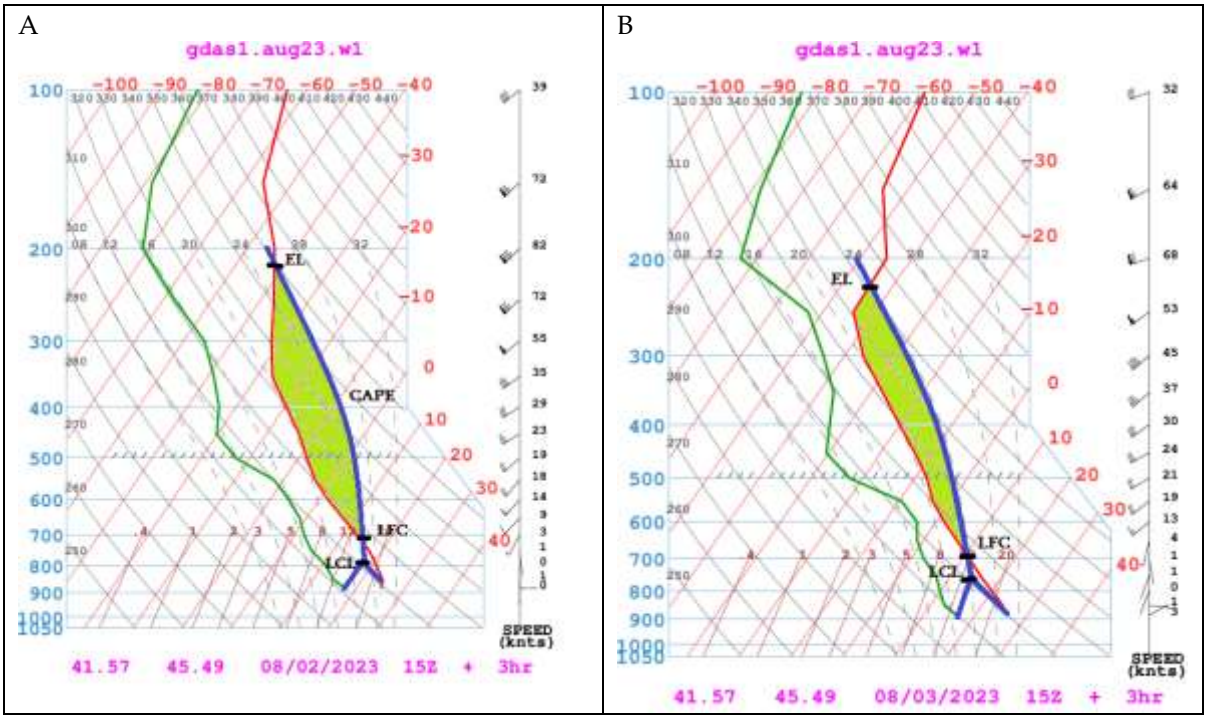


Figure 7: *Aerological diagrams of Kvareli.* ***a*** *- on August 2, 2023, at 15 UTC;* ***b*** *- on August 3, 2023, at 15 UTC.*

Table 1: *Numerical values of instability energy (CAPE > 1000 J/Kg) and vertical velocity of upward airflow (Wzm) during dangerous meteorological processes developed in some regions of Eastern Georgia in 2022.*

Day	06/06	13/06	28/06	29/06	31/06	02/07
CAPE 00UTC	174	0	3	70	30	288
CAPE 06UTC	200	600	730	730	437	873
CAPE 09UTC	1300	1100	1120	1170	1100	1040
CAPE 12UTC	1050	1150	1200	1180	900	1225
CAPE 15UTC	1740	710	1390	1260	800	950
CAPE 18UTC	800	77	323	464	104	580
W_{zm} m/s	**59**	**46**	**53**	**50**	**46**	**49**

V. Conclusion

This article presents a comparative study of the results of numerical calculations performed by the WRF v.4.5.1 model and the READY system in comparison with weather radar data. The study was conducted against the background of three exceptional local short-term heavy rainfall events (with hail) that occurred in eastern Georgia in the summer of 2023. The instability energy (based on CAPE and upper-air diagrams of the ARL READY system) of all exceptional local short-term heavy precipitation (with hail) that occurred in Eastern Georgia in the summer of 2021 and 2022 was also studied. Analysis of the calculation results showed that almost none of the combinations of the MP and CPS schemes in the WRF v.4.5.1 model could accurately predict real deep moist convective atmospheric phenomena in Kakheti (the famous wine-growing region). The aerological diagrams (ARL READY system) constructed for the cases discussed accurately showed the instability of the atmosphere over the study area. Although we had different levels of instability in all cases, the difference was exactly the same as the actual meteorological conditions of the day in question (as measured by the weather station and weather radar). To test our findings for the above three cases, all hazardous heavy precipitation events in 2021–2022 were examined. In particular, one of the main thermodynamic characteristics of atmospheric instability CAPE was studied (at times: 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 UCT) on the specified days. Analysis of the calculation results showed that the numerical values of CAPE were completely different, but for all 25 events, the maximum CAPE values were observed in the time interval 09:00-15:00 UTC. It should be noted that maximum CAPE values were recorded 15 times at 12:00 UTC and 5 times at 09:00 and 15:00 UTC, respectively. Thus, for forecasting local convective atmospheric processes, the CAPE value obtained in the time interval 09:00-15:00 UTC (11:00-19:00 local time, when the values of unstable energy show their maximum) is one of the best indicators to assess atmospheric instability and expected adverse atmospheric events. Indeed, along with all other favorable conditions, the temperature of the Earth's surface during this period reaches its maximum and the most favorable conditions are created for the development of local convective processes. Thus, when forecasting local convective processes together with regional forecasting models (WRF), it is desirable to study the thermodynamic state of the atmosphere in the time interval 09:00-12:00 UTC (based on CAPE and the aerological diagrams of the ARL READY system), and if unstable energy appears, then there is a high probability of an unfavorable atmospheric event.

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DISRUPTION OF BUSINESS MODELS IN THE CONTEXT OF DIGITALIZATION

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Abstract

The article examines the main trends in the modern transformation of economic systems in relation to digitalization and identifies the factors of economic growth in the context of restructuring business models. In particular, it considers changes to the business models of trading and digital companies, which have led to new approaches to conducting activities across all areas. The article describes how trading and digital companies operate in these new conditions and how they use various kinds of resources, including those arising in the digital space. It is noted that the adoption of new business models significantly alters the approaches to defining the value proposition and operating model, leading to disruption throughout the entire chain of interrelated elements (resources, costs and revenues). Particular attention is paid to the risks of corruption for enterprises that are unable to adapt to new conditions. However, the opportunities that digitalization offers if there is a timely transition to new ways of doing business are also highlighted.

Keywords: business model, disruption, innovation, technology, transformation, digital economy

I. Introduction

Modern processes of business model disruption occur under the influence of digitalization of all spheres of life, affecting the activities of companies in all countries of the world. Digital transformation is fundamentally changing the key trends, technology drivers, industry cases and challenges that organizations face at the current stage of development. Special attention for the purposes of further research should be paid to the ongoing changes in industry, retail, the financial sector and service companies, as well as issues of integrating new IT solutions and developing ecosystems arising due to the digitalization of personnel and infrastructure barriers.

Digitalization has become a key driver of transformation and disruption of business models in recent years. With the rapid technological development, the growth of cloud services, artificial intelligence and the Internet of Things, companies are forced to rethink traditional approaches to creating and delivering value. According to expert estimates, digital transformation is becoming a matter of survival for businesses and one of the main national priorities until 2030.

II. Methods

Regarding the theoretical aspects of the key foundations of the ongoing disruption of business models, it should be noted, firstly, what it represents.

Business model disruption is the process of radical change or replacement of traditional business models under the influence of new technologies and market conditions [14]. In recent years, the development of the Internet, IoT, big data and learning systems has led to the emergence of new models such as subscription, sharing economy, platform and ecosystem solutions.

Digital transformation involves not only the implementation of individual IT solutions, but also a fundamental restructuring of operational processes, interactions with clients, partners and employees, as well as the creation of new sources of income.

To understand the overall integrity of the changes taking place, a comprehensive and system approach to research is necessary, which requires the use of such methods as general scientific methods of cognition, description, characteristics and generalizations, methods of statistical observations and time series. Based on a number of studies already conducted and practical experience, albeit small at this stage, it can be concluded that incorrect interpretation and understanding of the ongoing changes can cause significant damage to the activities of companies, loss of their financial stability due to problems in making incorrect management decisions. Of great importance, in this case, is the correctness of organizational and management approaches to new types of business, and in existing ones, timely reconfiguration to the use of modern technologies (in their entire spectrum) is necessary to strengthen their positions in sales markets and maintain the stability of key indicators.

The aim of this article is to examine the key features of the construction and functioning of business models, and to identify the main drivers of their sustainability and growth.

The working hypothesis consists of studying the entire depth and scale of the innovative component of modern companies, which is manifested not only and not so much in their technical and technological re-equipment, but in the development of new ideas for growth and expansion of supply, creating value for manufactured products or services.

An innovative business model is a model that aims to change the dominant industry logic in such a way that the customer receives more value and the company receives a competitive advantage and greater profits [15]. In this case, the disruptive business model will have a unique innovativeness that creates a competitive advantage in the value creation for the customer from competing companies in this area.

Currently, “traditional” business model formats are not effective, so it is necessary to revise the conceptual approach to the formation of business models from the position of rethinking the impact of the “digital revolution”.

III. Results

Given that disruption itself implies natural selection, strengthening in the market of goods and services will be achieved by those companies that can promptly respond to changes in a timely manner, using an appropriate innovative model of their functioning, offering the market something exclusive. In this way, companies acquire a certain set of characteristics that enable them to evolve among mass producers.

One of the most important features of modern companies using digital technologies is the frequency of formation of growth and development strategies, which in traditional conditions are carried out two or even three times less often [8]. According to research conducted by IBM and BCG (Boston Consulting Group), the vast majority of innovative companies (over 70%) [8]

regularly review their business model, since current changes require adequate adjustment to market demands.

In this regard, modern companies using disruptive business models focus not so much on creating a high-quality product that is needed by the market, but on creating its value for the market. It is the value of the product that creates a competitive advantage for the company compared to other manufacturers in this field. The creation of value for a modern product serves as a kind of basic asset, using which a company can strengthen its market share, while increasing its profits.

Digitalization, innovation and new technologies are launching new logistics chains when traditional channels and methods of production, supply and sales cease to be effective. New levels of competition are created, based not on the scale and volume of production, but on the achievement of set goals and results obtained.

The vertically/horizontally integrated systems of value creation used by companies in the traditional economy assumed step-by-step management of commodity, information and cash flows, which was a strategically correct construction of business models at that stage of development, but led to at least two negative consequences: the growth of transaction costs and the increase in the scale of production as fundamental components of the creation and growth of surplus value [13].

With the growth of the scale of traditional business models that underlie the functioning of most large companies, the conditions of competition have become more toughen, in which incorrect and unfair methods of competing for sales markets have begun to be used at an increasing rate. As a result, prices for goods and services rise regardless of the consumer value produced. An increase in the scale of production, that is not supported by a corresponding increase in effective demand, leads to a decline in sales, which is unacceptable in the new conditions, when goods quickly become obsolete and will not be in demand by the market, even under the condition of an adequate and moderately low price.

Modern companies can avoid or minimize these negative trends by using innovative business models. The most well-known model today is the so-called Freemium model, which is based on expanding the customer base by offering some goods/services for free (basic ones, without a heavy cost base), while the premium level (promoted by the company) requires payment (which usually covers the cost of the free offer).

It is obvious that such a model cannot be used in all areas of business activity (it is mainly used by such companies as Spotify, Linkedin, Canva.com, MailChimp), but its elements can be widely distributed [15].

There is also a subscription model, the essence of which is to promote a product over time. A service or product can be purchased on a subscription basis, where the customer pays not once, but periodically for the duration of the contract. This makes it possible to attract more customers and expand the boundaries of receiving and paying for services/goods, while simultaneously expanding the range of offers, service quality, etc. (marketplaces, Internet platforms, Internet providers, etc.).

Other business models based on methods such as on-demand models, the model of sharing economy, a trading platform, etc. are also being actively implemented. Each of the models has its own set of tools, with the help of which the goal of a unique offer is achieved through a different configuration of its elements: free services; service support; duration of interaction with the client, supported by the expansion of options for the sold product/service, etc. The use of innovative business models not only helps to reduce costs, but also to gain competitiveness among the many producers of goods and services.

Today, it is already possible to identify the key drivers of digital disruption.

1. Cloud technologies

Cloud services allow companies to quickly scale their IT infrastructure, reduce costs, and

accelerate the launch of new products. In 2024, cloud technologies were named one of the most popular technologies, and the cloud solutions market in Russia is growing by 40% annually.

2. Artificial Intelligence and Big Data

AI and data analytics are at the core of process automation, personalized offerings, and supply chain optimization. Companies use AI to forecast demand, manage inventory, provide customer service, and even create new digital products.

3. Internet of Things (IoT)

IoT allows one to collect and analyze data from physical objects, increasing the transparency and manageability of business processes. In industry, IoT is used for equipment monitoring, predictive maintenance, and production optimization.

4. Platform and ecosystem solutions

Platform-based business models connect producers, consumers, and partners into a single digital ecosystem. This allows companies to expand their range of services, increase their customer base, and create new sources of income.

The evolution of companies using new business models occurs under the influence of the following factors:

1. Digitization of organizational culture – with the ever-changing digital technology environment, hiring, training and encouraging learning ability among employees.

2. Using modern technology solutions such as cloud and mobile technologies rather than the mainframes of the past.

3. Developing or restructuring an existing R&D (research and development) unit – seeking new business opportunities that use digital technologies at the periphery or perhaps in adjacent areas of current offerings, even if they may consume existing businesses [5].

4. Reflections on how digital capabilities can transform core business.

The primary focus should be on improving customer service quality through digital channels, as customers expect a simpler, more intuitive, and compelling digital experience as they become more complex.

5. While the pace of change today is rapid and means that many current organizational architectures need to change, it is important to map out a path for making changes in stages. These changes should be evolutionary rather than revolutionary, but it is important to set a course, measure progress or lack thereof, and adjust course as companies learn to find new innovative solutions [6].

The above-mentioned factors for a company's transition from the physical world to the digital world with the sale of both physical goods and digital goods and services can very likely indicate that depending on the product and customer convenience, the model will change to achieve maximum efficiency.

Digitization is reimagining the process of maximized production in very disruptive ways. In fact, of all the steps and business models described in this article, this one has the most disruptive effect, as it can destroy entire industries. The rethinking of the fact that several customers can simultaneously use digital goods that can be replicated at zero marginal cost reduces prices to zero. For example, large-scale open online courses provide education at near-zero marginal cost.

Understanding the innovative development of modern business models should not be based on a narrow perception of technical and technological innovations, but on the level of building relationships with customers – from loyalty to expanding opportunities.

IV. Discussions

Thus, not only companies using new business models are being transformed, but also industries. For example, in 2023, the volume of the Russian market for digitalization of industrial

business processes reached 300 billion rubles, showing a 20% increase compared to the previous year. Large enterprises are actively implementing IoT, automation, digital twins and cloud solutions to improve production efficiency and reliability [12]. Particular attention is paid to the integration of new IT systems with existing ERP and CRM, as well as ensuring information security.

The financial sector is also developing dynamically, where the introduction of digital platforms and AI allows banks and fintech companies to offer clients new services – from instant payments to personalized financial products. Not only digital banks are developing, but also decentralized financial services (DeFi), which leads to a decrease in the role of traditional banks and the emergence of new monetization models [11].

Retail actively uses cloud technologies, AI and analytics to optimize supply chains, manage product ranges and personalize customer experience [14]. In 2024, the growth of phygital models (integration of online and offline channels) is observed, as well as the development of social and subscription services.

Small businesses are increasingly integrating digital solutions through partnerships with IT companies and startups. Flexibility, speed of innovation, and the ability to build win-win partnerships are becoming key success factors.

At the same time, digitalization creates significant barriers and threats for companies and the economic system as a whole. Among them, the most pressing issues today are personnel shortages, cybersecurity, data management, and for certain countries – import substitution and integration due to the breakdown of established international economic ties.

Personnel shortages.

The shortage of specialists in digital technologies and AI, as well as insufficient digital literacy of staff, remains an acute problem.

Import substitution and integration.

In conditions of limited access to foreign software, companies are forced to switch to domestic solutions and ensure compatibility between new and old systems, which requires significant investment and expertise.

Cybersecurity.

The growth of digitalization leads to an increase in the risks of cyber-attacks and data leak, which requires the implementation of modern security tools and compliance with regulatory requirements.

Data management.

The significant growth in data volume requires the development of storage infrastructure, integration of disparate sources and the implementation of a single digital loop for end-to-end analytics.

Trends and prospects for 2025.

- Accelerated cloud-based expansion: many companies are switching to cloud services to increase flexibility and resilience.
- AI Integration and automation: AI is becoming an integral part of business processes, from customer service to production management.
- Transition to ecosystems: companies are building partner networks and digital platforms, combining various services and products.
- Focus on information security: a significant share of investments is directed towards protecting data and critical infrastructure.
- Import substitution and development of domestic IT solutions: Russian companies are actively introducing local digital products and services.

In general, the digital economy presents new opportunities and is undoubtedly a positive factor in the socio-economic life of society. Intangible (digital) assets play a significant role in the capitalization of companies and in modern conditions, they are taking priority positions.

Digital data is a key resource of the digital economy. Economic growth is ensured on the basis of digital data and digital technologies. The digital economy is characterized by an increase in the share of knowledge, innovation, and growth in the share of the service sector that dominates over the production sphere. At the same time, the implementation of digital technologies in a company depends on its organizational [8] knowledge of Internet technologies, mobile communications, electronic payment technologies, logistics, and technologies for creating and using robotics.

The disruption of business models in the context of digitalization is becoming an integral part of modern business. The success of companies is determined by the ability to quickly adapt to technological changes, integrate innovative solutions and build effective ecosystems. Key challenges remain personnel shortages, cybersecurity issues and the need for comprehensive integration of IT systems. In the coming years, we can expect further acceleration of digital transformation, development of domestic solutions and increased competition in the digital ecosystem market.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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RISK- BASED DESIGN OF SOLAR AND WIND ENERGY SYSTEMS

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Abstract

This study addresses the challenges and risks associated with implementing autonomous solar and wind energy systems in remote communities, focusing on a risk-based design approach. These systems, while crucial for decarbonization and energy independence, face complexities due to meteorological variability, technical limitations, and socio-economic constraints. This research employs an interdisciplinary methodology, integrating system analysis, risk assessment, and geoinformation analysis, to identify and classify key risks, including climatic, technological, and social factors. By developing failure scenarios and implementing mitigation strategies such as hybrid energy systems, intelligent control, and robust maintenance plans, the study aims to enhance the reliability and sustainability of these systems. The findings emphasize the importance of comprehensive risk management, advanced forecasting, and local capacity building to ensure the long-term effectiveness and economic viability of renewable energy solutions in remote settings. This approach not only reduces operational and capital risks but also ensures resilience against extreme conditions, fostering a sustainable energy future for underserved communities.

Keywords: renewable energy systems, remote community, climate variability, hybrid energy systems, solutions

I. Introduction

In recent decades, renewable energy sources (RES) have become central to sustainable development, serving as an integral tool for decarbonisation and increasing energy independence, particularly in the context of energy supply to remote rural communities [1,2]. Projections from the International Energy Agency indicate a substantial increase in the global use of renewable energy sources (RES), rising from 35.3% of energy consumption in 2025 to more than 40% in 2028. This upward trend is anticipated to continue (Fig. 1). Unlike the traditional centralised energy system, which is characterised by a high dependence on fossil fuels and significant losses during energy transmission, decentralised solar and wind installations provide autonomous energy supply, help reduce greenhouse gas emissions, and contribute to a more adaptive and sustainable energy infrastructure [3,4].

Despite the clear environmental and economic benefits, the operation of renewable energy systems in remote communities faces numerous risks and uncertainties [5]. Among the key factors limiting the effectiveness of these systems are [6]:

- the instability of generated power due to varying meteorological conditions,
- maintenance challenges,
- equipment degradation,
- socio-economic barriers affecting operational sustainability.

These factors necessitate an integrated approach to the design of autonomous power systems, aimed at considering potential threats and developing strategies to mitigate them [7,8].

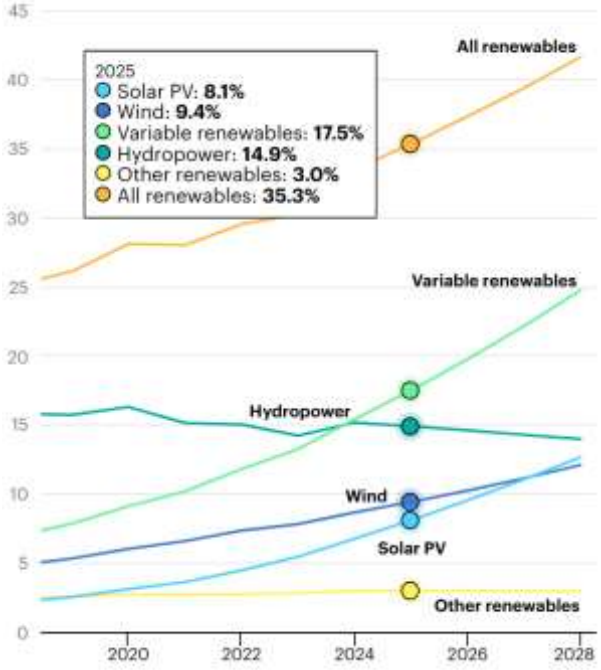


Fig. 1: *Renewable Energy Systems generation by 2020-2028, https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028*

In this context, risk-oriented design is of particular importance, involving a comprehensive analysis of uncertainties, systemic management of operational risks, and optimization of the architecture of energy systems from the standpoint of long-term sustainability [9,10]. This methodological approach allows for accounting for the impact of climatic and seasonal variations, developing fault-tolerant operating scenarios, and integrating intelligent energy supply management systems that provide predictive control and adaptation to changing conditions [11].

Risk-based design is a methodological approach to the development of engineering systems that places a key emphasis on the analysis and management of risks at all stages of the life cycle—from conceptual design to operation and disposal. In the context of solar and wind energy systems intended for remote villages, this approach involves the early identification and assessment of potential threats, such as climate variability, technological failures, economic constraints, and social factors [12].

Scenarios of failures and instability of energy supply are developed to account for the uncertainty and variability of external conditions. Design solutions focus on ensuring the sustainability of systems, including safety margins to withstand extreme weather conditions such as hurricanes, snowfalls, and droughts, as well as addressing seasonal and daily fluctuations in energy generation [13,14]. To minimize risks, hybrid energy systems combining solar and wind generation with energy storage are widely used, along with intelligent control systems that optimize the distribution of energy resources and predict consumption. An essential element of the sustainability of such systems is the development of backup mechanisms, including the ability to connect to the grid or use additional generators [15].

Power system operation is based on adaptive strategies, including algorithms for forecasting energy production based on meteorological data, remote monitoring and diagnostic systems for equipment, and optimized maintenance and component replacement plans to minimize the likelihood of failures. This is especially important for remote villages, where the lack of backup energy sources makes power supply critically vulnerable [16].

This article focuses on risk-based design, which not only reduces operational and capital risks but also improves the economic efficiency of investments in renewable energy sources [17]. In the context of climate change, this approach ensures the creation of autonomous power systems that are resistant to extreme conditions, making them a reliable and long-term solution for providing energy supply in remote communities [18].

This study examines key risks affecting the performance of solar and wind power plants in remote communities and identifies innovative mitigation strategies aimed at improving the reliability and efficiency of autonomous power systems.

II. Methods

This study is based on an interdisciplinary approach, incorporating methods of system analysis, quantitative and qualitative risk assessment, and expert forecasting. The comprehensive nature of the methodology allows for the consideration of a wide range of factors affecting the efficiency and reliability of autonomous solar-wind energy systems in remote communities. In combination with theoretical and empirical methods, a thorough analysis of risk-forming parameters and the development of strategies to mitigate them are provided.

The first stage of the study involves a system analysis aimed at identifying and classifying key risks affecting the design and operation of renewable energy systems. Within this stage, four main risk groups are identified:

- climatic and meteorological (variability of solar radiation, wind speed, and extreme weather events).
- technical and technological (failure of equipment, instability of energy storage devices, and energy conversion losses).
- social and infrastructural (limited availability of technical services and insufficient training of local specialists).

This classification allows for the systematization of potential threats and the determination of priority areas for risk management.

Geoinformation analysis is used for spatial risk assessment and the optimal placement of energy facilities, including the processing of data on solar radiation, wind speed, and direction, as well as their seasonal and daily fluctuations. Within this stage, geoinformation technologies (GIS) are employed to integrate satellite and ground meteorological data. This enables the identification of the most favorable areas for the installation of solar panels and wind generators, considering both climatic and infrastructural conditions.

Thus, the applied research methods facilitate a comprehensive identification of risk-forming factors, their quantitative and qualitative assessment, and the development of optimal risk management strategies. This contributes to enhancing the reliability, sustainability, and economic efficiency of autonomous solar-wind energy systems designed for operation in remote settlements.

III. Results and discussion

Designing solar and wind energy systems for remote communities is a complex engineering task that requires the consideration of numerous technological, operational, and infrastructure factors. The effective implementation of such systems demands a detailed analysis of potential risks that could affect their reliability, sustainability, and efficiency in the long term (Fig. 2).

A key factor determining the efficiency of renewable energy sources is their resource base. Due to the high dependence of solar and wind installations on variable meteorological conditions, the instability of incoming energy can significantly limit their productivity. To reduce this uncertainty, a thorough assessment of climate parameters in a particular region is required, taking into account seasonal and daily variations [19,20]. Additionally, advanced forecasting methods should be applied, utilizing machine learning algorithms and statistical modeling to minimize

errors in assessing the availability of solar and wind energy.

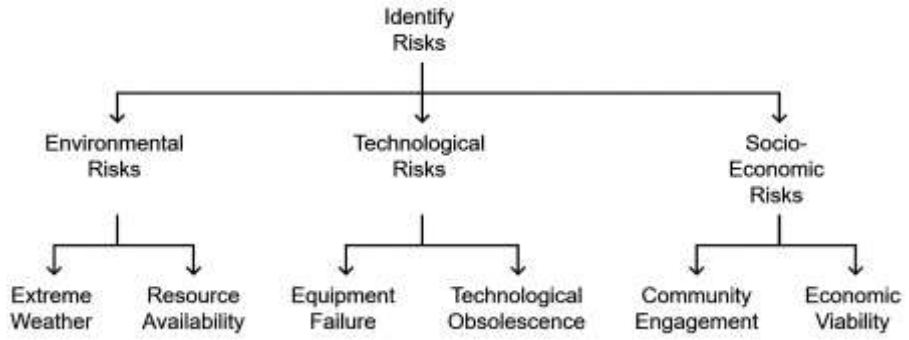


Fig. 2: *Identifying risks in renewable energy systems*

The technical equipment used has a significant impact on system stability. The operation of power plants in remote areas places increased demands on their reliability and resistance to extreme climatic conditions [21,22]. Therefore, it is critical to use equipment that has undergone rigorous testing and certification, as well as to implement regulated maintenance procedures. In particular, the complexity of integrating individual system components (generators, battery units, converters, and controllers) requires special attention. For example, batteries, despite their key role in energy storage, remain the most vulnerable element, subject to degradation due to temperature fluctuations. Accordingly, it is necessary to carefully calculate their capacity, develop thermal protection strategies, and optimize operating modes.

Equipment degradation, the complexity of maintenance, and the high cost of component replacement are significant limitations that should be considered when designing autonomous power systems. The introduction of modern remote monitoring systems, fault diagnostics, and preventive maintenance strategies helps extend equipment service life and optimize operating costs.

Another critical aspect affecting system efficiency is the installation process and subsequent operation. Limited availability of qualified specialists and underdeveloped infrastructure can make it challenging to install equipment in remote areas. This requires detailed planning of logistics and construction work, the involvement of professionals, and the use of modular solutions that simplify the assembly and adjustment process. Further maintenance may also be difficult due to the remoteness of service centers, making it necessary to train local personnel in basic operational skills and troubleshooting.

Additionally, it is important to consider environmental factors. For example, noise pollution from wind turbines and sunlight reflection from solar panels can impact both the environment and local communities, requiring appropriate mitigation measures.

One of the most significant challenges is the integration of renewable energy sources into existing energy infrastructure. Compatibility with local power grids requires the implementation of additional converters, load control devices, and voltage stabilizers. Without these measures, voltage fluctuations may occur, potentially leading to unstable operation for connected consumers. Therefore, system design should include the development of mechanisms for managing energy flows and regulating network parameters to ensure uninterrupted power supply.

To effectively mitigate these risks, a comprehensive approach is required, including (Fig. 3):

- a detailed assessment of resource potential,
- selection of reliable equipment,
- utilization of advanced forecasting and design techniques,
- development of maintenance strategies.

Socio- economic and infrastructural barriers also significantly impact the sustainability of autonomous power systems. The limited availability of qualified technical personnel, insufficient awareness among the local population about equipment operation, and logistical difficulties

necessitate an integrated approach to training and service support. Developing specialized training programs for professionals and localizing the production of key components can enhance the autonomy of power systems and reduce operational costs. An essential element of sustainable system operation is training local residents in basic maintenance and troubleshooting, which will increase system autonomy and lower service costs.

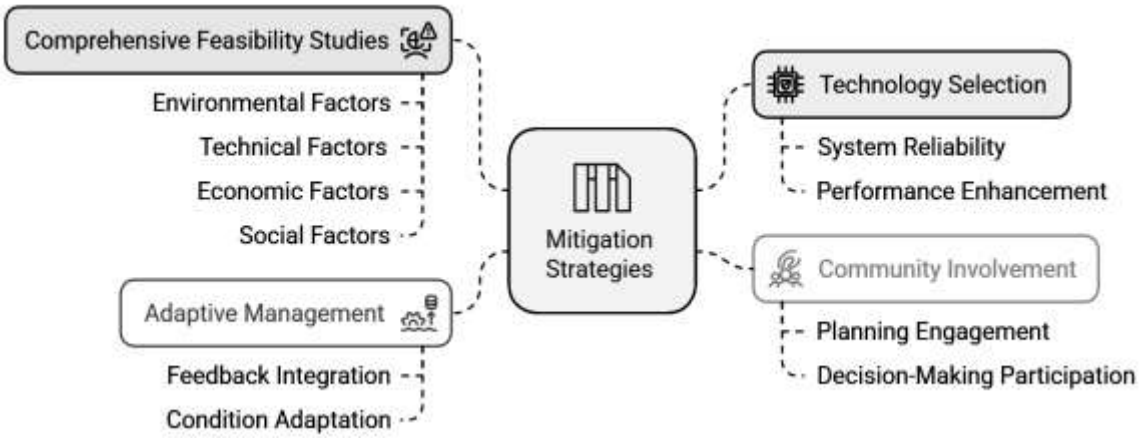


Fig. 3: *Risk mitigation strategies*

Finally, providing backup energy sources, such as hybrid systems or battery storage, will help minimize the impact of unforeseen factors and improve energy supply reliability.

Thus, with proper design and risk management, solar and wind energy systems can be successfully implemented in remote villages. This will ensure a stable and environmentally friendly electricity supply, contributing to improved living standards and infrastructure development in regions with limited access to traditional energy resources.

V. Conclusion

This study demonstrates the critical importance of a risk-based approach to the design and operation of off-grid solar-wind energy systems for remote communities. Despite the significant environmental and economic benefits of renewable energy sources, their implementation is associated with several technical, operational, and infrastructural challenges that require comprehensive analysis and the development of risk management strategies.

One of the key factors affecting the reliability of autonomous power systems is the high variability of climatic conditions, which creates the need for advanced forecasting methods and adaptive solutions in power supply architecture. The integration of hybrid systems combining solar panels, wind generators, and energy storage devices, along with intelligent control algorithms, enhances power supply stability and reduces dependence on weather fluctuations.

Overall, the study shows that the successful integration of renewable energy sources into remote communities is possible through comprehensive risk analysis and the implementation of adaptive management strategies. An integrated approach—including a detailed assessment of resource potential, the use of reliable equipment, the implementation of intelligent forecasting and monitoring systems, and the development of effective service strategies—creates the foundation for ensuring the long-term sustainability and economic efficiency of autonomous solar-wind energy systems.

Thus, competent design and effective risk management enable the successful implementation of renewable energy sources, which, in turn, helps improve the quality of life in remote communities, reduce dependence on centralized energy systems, and create a more sustainable and environmentally friendly energy infrastructure.

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ALGORITHM FOR IMPROVING THE DETERMINATION OF TERRIGENOUS ROCK PERMEABILITY

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Abstract

This paper analyses the current methods used to determine the permeability of rocks, as well as the challenges involved in this process. An improved methodology was developed for determining the permeability of terrigenous rocks using petrophysical, well geophysical and direct methods. The paper provides an overview of how the methodology is implemented and applied. This methodology can be summarized as follows: - The coefficients of variation of permeability obtained by well geophysical survey methods, hydrodynamic logging and rock sampling are compared. - A graphical dependence is created between oil-water phase permeability and water saturation, as well as between oil-water phase permeability and effective permeability. - A graph is created to compare the coefficient of specific productivity with the coefficient of average effective permeability. The oil or water saturation of the formations is analyzed according to the situation of the points characterizing the wells. Significant differences in permeability values are observed based on data from hydrodynamic logging, rock sampling, and well geophysical survey methods. The low permeability value is due to relative permeability in productive and water-bearing layers. Effective permeability does not permit the formation of a layer filtration model. Therefore, it is advisable to conduct research using hydrodynamic logging in 20 cm steps. In this case, the margin of error in the determined effective permeability decreases. There is also a close correlation between the coefficient of specific productivity and effective permeability. To increase the accuracy of the results, all three studies must be conducted together. This methodology can be applied to any oil or gas field.

Keywords: permeability, phase permeability, hydrodynamic logging, well geophysical survey, rock sample, packing

I. Introduction

Rocks consist of a mineral skeleton, or solid phase, and a pore space usually filled with liquid and gas components.

Permeability is the property of rocks to transmit liquids, gases and their mixtures in the presence of a pressure gradient. Permeability is a parameter characterizing the ability of reservoir rocks to transmit fluid.

Absolute permeability is the permeability of a rock in the case of filtration through it of a homogeneous liquid or gas inert with respect to the surface of the solid phase. Phase permeability is the ability of rocks saturated with a mixture of oil, gas and water or any other inhomogeneous fluid to permeate its individual phases.

Relative permeability of a porous medium is the ratio of phase permeability of this medium for a given phase to absolute permeability. To estimate the permeability of rocks, the linear Darcy filtration law is usually used. According to the values of permeability coefficient, rocks are divided into permeable (gravels, sands, weakly cemented sandy-clay sediments, cavernous carbonate sediments), semi-permeable (clayey sands, finely fractured chalky limestones and dolomites) and

practically impermeable (clays, argillites, shales, marls, densely cemented sandstones and siltstones, dense chalk and limestone).

The permeability of the rocks is based on the difference in the pressures created in the reservoirs' pores, and the rock's ability to release the fluids filling the pores is assumed. The studied quantity is characteristically a dynamic quantity, characterizing the fluid's displacement in the rock's pores. Permeability is considered the most dynamic quantity in reservoir rocks. Therefore, the limit of change of permeability does not correspond to the value of the rock's porosity in most cases. It is difficult to explain logically [1,7,10,11]. Predicting the correlation of its relationship with other static quantities (clayness, sandiness, etc.) often does not allow the estimation of permeability [8,9,14]. This complicates the interpretation of geophysical data and the study of rock samples in the laboratory. The relationships obtained do not sufficiently reflect the properties of reservoir rocks, which are observed in all wells located in the Bahar field. As a result, the error that can be omitted in the operative interpretation obtained based on the data of well geophysical survey (WGS) methods increases [2,3,13]. To increase the accuracy of the results obtained, it is necessary to use the data of hydrodynamic logging (HDL - direct method), WGS, and rock samples jointly.

II. Exploration target

The sections of oil and gas wells located in Azerbaijan are mainly represented by terrigenous rocks. The Bahar oil and gas condensate field is located in the Caspian Sea, 40 km south-east of Baku and 20 km south of Qum Island (Fig.1).

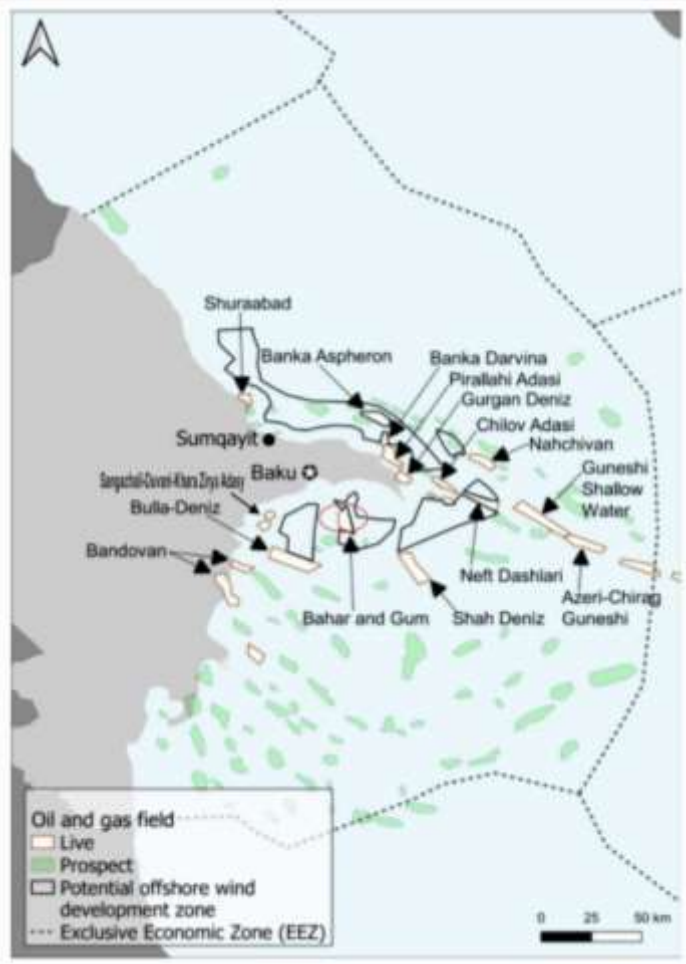


Figure 1: *Schematic map of oil and gas fields in Azerbaijan.*

The upper Miocene–Quaternary sedimentary complex is present in the part of the Bahar field section that has been drilled. The geological section includes deposits from the Miocene, Productive Series, Akchagyl stage and Quaternary period.The Productive Series consists of lower and upper parts and is subdivided into suites and horizons: Sub-Kirmaky (SK), Kirmaky, Upper Kirmaky Sandy (UKS), Upper Kirmaky Caleyey (UKC), Fasila, as well as the Balakhany (horizons V, VI, VII, VIII, IX, X), Sabunchi (horizons I, III, IV, IVa, IVb) and Surakhany (horizon I) reservoir suites. The Fasila Suite the upper part of the Productive Series has the highest sand content — 73%, of which 10% is sandstone.

The structure is complicated by regional and local tectonic disturbances and divided into eight tectonic blocks. The Bahar structure extends in a north-south direction. However, near the southern periclinal, this extension turns to the south-east. The northern periclinal of the structure is elongated, while the southern one is shorter. The saddle of the structure is located in its southern part, near a mud volcano that complicates the southern slope. Among the eight tectonic blocks of the deposit, blocks I, II and III are considered to be the main ones in terms of hydrocarbon content.

In Blocks II and III, the Fasila Suite forms oil and gas condensate fields, with hydrocarbon flows generally being mixed in nature. In these reservoir layers, oil (with a gas cap) was first discovered on the western wing of the anticline in Block III, and on the eastern wing with the presence of gas condensate also being detected. Gas inflows were obtained in Block III, and the presence of oil is considered likely [5].

III. Methodology

Research with HDL in the well is carried out in the following stages: packaging in the research area; creating hydrodynamic excitation of the layer; closing the packer.

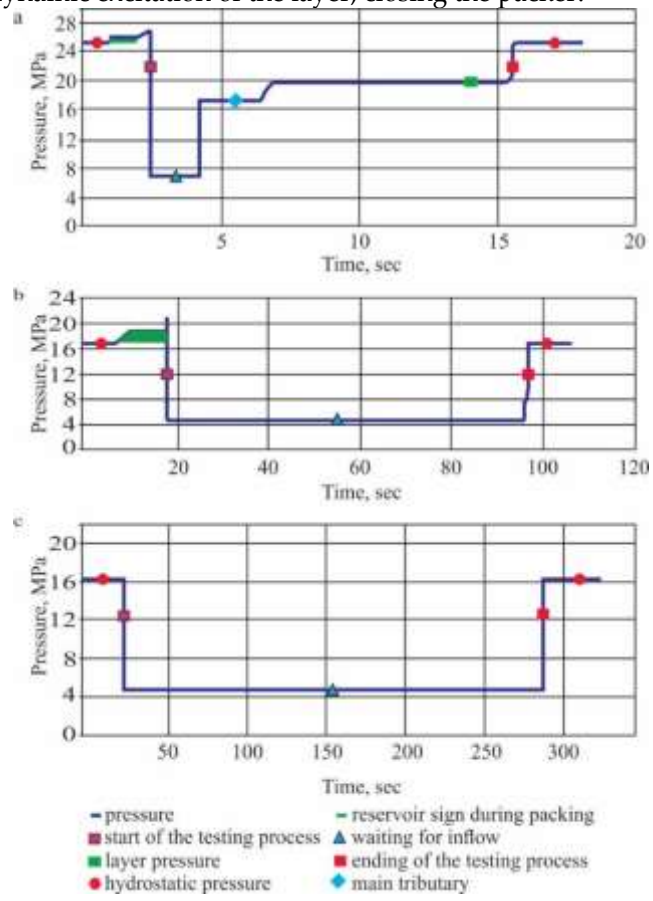


Figure 2: *An example of a hydrodynamic logging pressure diagram*

Hydrodynamic logging refers to direct methods of investigation. With this method the formation pressure is recorded in graphical form (Fig. 2 a, b, c). The graph, as a rule, is divided into three parts:

1) At the first stage, the logging device is installed with the packer and put into operation (differential pressure is created); high pressure is recorded for a certain time (left part of the graphs);
2) After the fluid withdrawal process begins, the graph shows a rapid decrease in pressure.
3) When fluid begins to move out of the reservoir, the pressure curve stabilizes, reflecting the actual reservoir pressure.

During the survey, fluid flows from the reservoir into a special section on the logging tool and the water or oil content is determined from the sample.

When applying hydrodynamic logging in a well, the primary measured quantity is layer pressure (fig. 2).

A sharp increase in the graph during packing indicates the presence of mud cake, and this feature belongs to reservoir layers (Fig. 2a). After a sharp rise, the pressure decreases sharply, which indicates the awakening of the layer. In the other two cases, no growth is noted in the graph during packing.

In the first case (Fig. 2b) 20-100 seconds, and in the second case (Fig. 2c) 20-300 seconds, the flow through the layer is not recorded, during this period, there is no change in the graph of pressure. This shows that the permeability is different for the thickness of the layers.

Filtrate movement in the reservoir depends directly proportional to the effective porosity of rocks and inversely proportional to its viscosity. Therefore, the mobility of the filtrate in front of each depressed layer is calculated by the following formula [4,6,12]:

$$\frac{k_{ef}}{\mu} = \frac{V_i}{A\Delta t_i \Delta P_i} \quad (1)$$

where A is the coefficient that considers the geometry (flowability) of the fluid entering the well from the rock; V_i is the volume of the filtrate causing the depression; Δt_i is the time the filtrate percolates through the layer; ΔP_i is the pressure difference during the depression; an average value of effective permeability coefficient k_{ef}, μ is the viscosity of the filtrate.

The research is carried out in the following order:

- rock sampling: - determination of oil saturation (S_{oil}), porosity coefficient (k_p), an average value of effective permeability coefficient (k_{ef}), and coefficient of variation of permeability (W_k) in small-grained and low-clay rocks;
- study of WGS data: layer thickness (h), porosity coefficient (k_p), probable permeability (k_{per}), coefficient of variation of permeability (W_k);
- investigation of hydrodynamic logging data: the thickness (h_{HDL}), the average value of the effective permeability coefficient (k_{ef}) and coefficient of variation of permeability (W_k) of the studied interval.

After determining these data, the coefficients of permeability variation obtained by WGS, HDL, and rock sampling are compared.

The graph is based on geophysical logging data between the permeability of the oil-water phase (considering the absolute gas permeability (k_{oil}+k_w)/k_g) and the water saturation (Sw) is the percentage value of water).

The graph is analyzed: the reference value of k_{ef} in the washout zone is taken, and the permeability prediction under current oil saturation conditions is given. For this purpose, a relative value characterizing the relationship between water-oil saturation and effective porosity is determined using the following relationship:

$$\frac{(k_{oil}+k_w)/k_g}{k_{ef}/k_g} = \frac{k_{oil}+k_w}{k_{ef}} = a; \;\; k_{oil} + k_w = ak_{ef} \quad (2)$$

where,

k_{oil} is the permeability of the oil phase;

k_w is the permeability of the water phase; a is the value characterizing the ratio of water-oil saturation and effective porosity coefficient;
k_g is the absolute gas permeability coefficient.

A comparison graph between the specific productivity coefficient (k_{core}/k_{HDL}) and the average effective permeability coefficient (k_{ef}) is constructed and analyzed.

Application. As indicated in the methodology, the WGS – Neutron methods, rock sample – 56 and HDL data of 4 intervals on the rocks that comprise the studied formation (Fasila Suite) for Bahar field were collected and analyzed for the 4 wells. For the application of the methodology, information was collected on conventional wells A, B, C, and D, and a graph was made between the permeability of the water-oil phase [(k_{oil}+k_w)/k_g] and the water saturation (S_w) (Fig. 3).

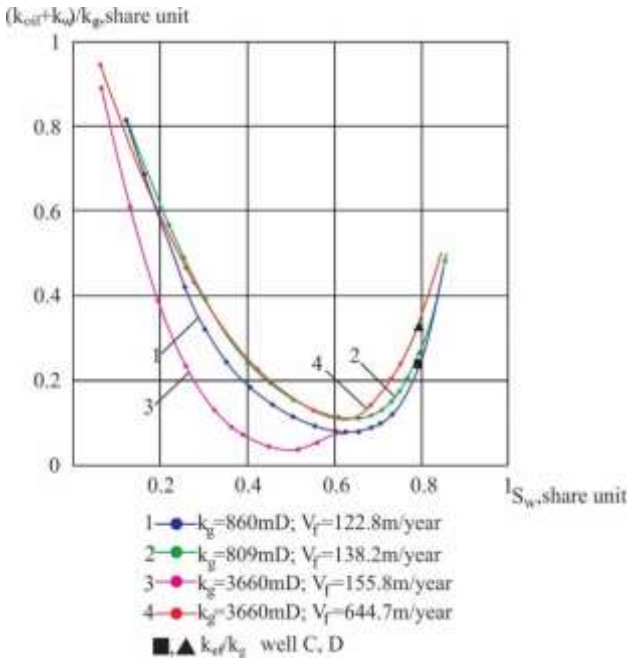


Figure 3: *Graph of the relationship between water-oil phase permeability and water saturation. (1) k_g=860 mD, V_f=12.8 m/year (annual change in water saturation according to field operation data); (2) k_g =809 mD, V_f=238.2 m/year; (3) k_g =3660 mD, V_f=155.8 m/year; (4) k_g =3660 mD, V_f=644.7 m/year.*

k_g is the absolute gas permeability coefficient; V_f is the filtrate rate; k_{ef} is the effective permeability.

As can be seen in the figure, in wells C and D, the relationship between (k_{oil}+k_w)/k_g and S_w coincides up to S_w = 0.65. After this point, the dependencies begin to diverge. In order to evaluate this section, a computational processing was carried out.

An estimate of the k_{ef}/k_g ratio for well D based on data from well C is presented in the following Table 1, where we replace $\frac{(k_{oil}+k_w)/k_g}{k_{ef}/k_g}$ with W for well D:

Table 1: *Estimation of k_{ef}/k_g for Well D Using W Parameter*

For well C					For well D
Water saturation, %	Oil saturation, %	(k_{oil}+k_w)/k_g	k_{ef}/k_g	W	k_{oil}+k_w=k_{ef}·W
20	80	0,62	0,242	2,256	0,59
50	50	1,12-0,16	0,242	0,58	0,13
40-30	60-70	0,32-0,38	0,242	1,037	0,24

Under these conditions, the report's results for well D will be the same as the results of borehole C. This is because the lithological composition and conditions of the studied interval are the same. So, since the comparison is used in our methodology, rocks of the same composition and age belonging to the same layer suite in different wells are taken as the research object.

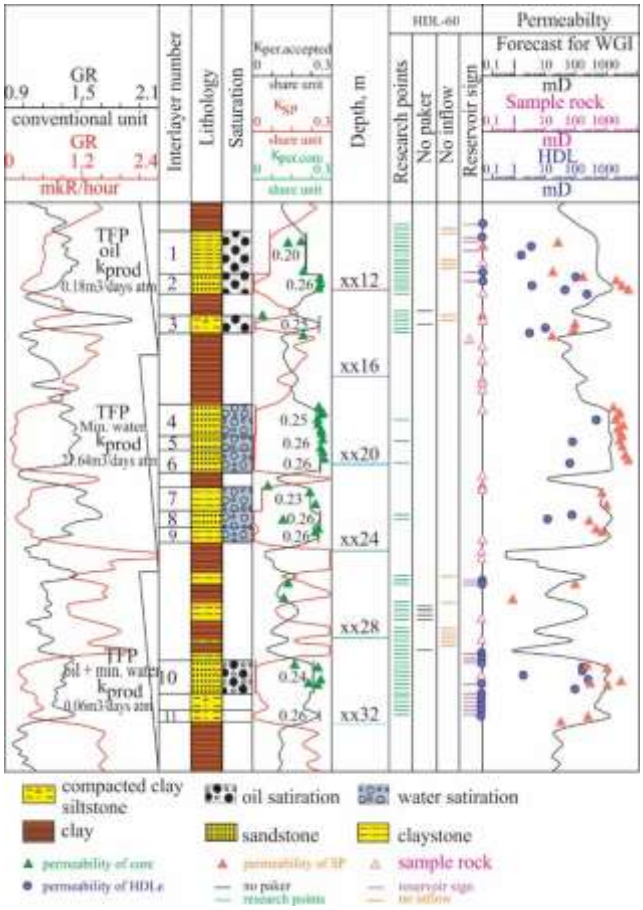


Figure 4: *Logging curves and results obtained in the well B*

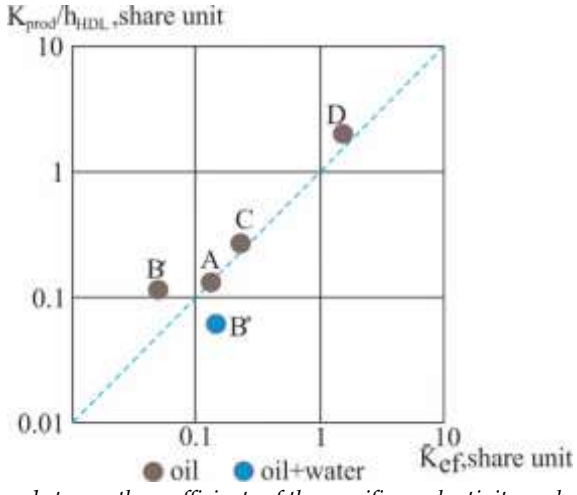


Figure 5: *Comparison between the coefficients of the specific productivity and effective permeability*

This calculation for 4 wells shows that when S_{oil}=80%, the permeability of the oil-water phase (k_{oil}+k_w) is 2-3 times larger (0.62>0.23), and when S_{oil}=40-50% it is 1.7 times smaller (0.14<0.23). When S_{oil}=60-70%, the permeability of the oil-water phase corresponds to k_{ef} (0.23851=0.24), it is

approximately equal (These results are derived from the comparative analysis carried out in the corresponding report). The results obtained in wells A and B are slightly different, and the reason for this is given below (Fig.5). Logging curves in borehole B are provided as an example (Fig. 4).

Analyzing the build graph, it appears that three features are obtained. The position of the points characterizing the wells is different compared to the trend line:

- lies in a straight trend line (A, C, D) – the resulting product is a mixture of water and oil;
- below the trend line ($B^{//}$) – dominated by water;
- above the trend line ($B^{/}$) - dominated by oil.

Point $B^{/}$ is associated with high filtration recorded in formations №1, 2 and 3. At the same time, according to the results of HDL, point $B^{//}$ is explained by watering of formations №10 and 11. Thus, based on the adjusted graph, the saturation of the studied formations in the wells is determined unambiguously.

A comparison graph was build for 4 wells of selected filed between the coefficient of specific productivity (k_{prod}/h_{HDL}) and the effective permeability (k_{ef}) (Fig. 5).

IV. Conclusion

- The obtained results show a sharp difference in the values of permeability obtained based on HDL, rock sample, and WGS data (depends on geologic conditions);
- The permeability values determined by hydrodynamic logging (HDL) are underestimated compared to other methods in oil-saturated and watered reservoirs;
- It is impossible to build a full-fledged reservoir filtration model based on effective permeability based on HDL data alone;
- It is reasonable to perform hydrodynamic logging with a uniform step of 20 cm for the studied wells. In this case, the magnitude of the error in certain effective permeability tends to decrease, which is due to the lithologic composition of rocks in the section of this well;
- We see that there is a close correlation between the specific productivity coefficient and the effective permeability (however, this relationship decreases as the clay content of the rocks increases);
- Conducting all three studies together increases the accuracy of the obtained results (in the absence of at least one of them, the degree of reliability is significantly reduced).

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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WIND CONDITIONS AT THE HEYDAR ALIYEV BAKU AND SHOTA RUSTAVELI TBILISI INTERNATIONAL AIRPORTS IN 2015–2024

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Abstract

Meteorological conditions, including surface wind speed and direction, have a significant impact on aviation. They play an important role in both aviation accidents and ensuring the safe operation of aircraft. Consequently, there is a focus on the continuous monitoring of weather conditions at airports, as well as the scientific analysis of this monitoring data, worldwide, including in Azerbaijan and Georgia. This study examines wind conditions at Heydar Aliyev Baku and Shota Rustaveli Tbilisi international airports between 2015 and 2024. Data on mean wind speed (F) and gusty wind speed (G) for different wind directions were obtained from [https://rp5.ru]. Period of record: 2015–2024; observation interval: 30 min. Wind direction sectors: 22.5° each (total: 18 sectors). Statistical analysis was performed on the following amount of data: Baku: F: 166,825 measurements and G: 12,245 measurements; Tbilisi: F: 166,704 measurements and G: 7,533 measurements. The following results were obtained in particular. The mean gusty wind speed at Baku airport is 0.4 m/s higher than at Tbilisi airport (5.3 and 4.9 m/s, respectively). The mean gusty wind speed in Baku is 2.0 m/s lower than in Tbilisi (17.2 and 19.2 m/s, respectively). The maximum values of F and G in Baku are lower than in Tbilisi (23 and 31 m/s and 26 and 33 m/s, respectively). The number of gusts in Baku is significantly higher than in Tbilisi (1,225 and 753 cases per year, respectively). The repeatability of the mean and gusty wind speeds at the two airports is similar: unimodal for F and bimodal for G. The correlation between F and G values is very high for both airports (R = 0.97). The maximum repeatability of mean wind speed is in the north-northwest direction in Baku (20.2%) and in the north-west direction in Tbilisi (28.3%). As in the previous case, the maximum repeatability of wind gust speed in Baku and Tbilisi occurs in the same direction: 56.1% in Baku and 72.4% in Tbilisi. The maximum number of cases per year with wind speeds of ≥15 m/s (count ≥15 m/s) in Baku is 95 in the North-Northwest direction and 290 in the North-West direction in Tbilisi. The maximum number of counts of wind speeds of at least 15 m/s in Baku for G is 661, and for Tbilisi it is 529 (the same directions as in the previous case for both airports). The indicated values of the number of cases per year with wind speeds of ≥15 m/s at both airports coincide well with the direction of aircraft take-off and landing. In Baku, there are 10 cases per year of crosswinds and winds close to it with a speed of ≥15 m/s, whereas in Tbilisi there are none.

Keywords: aviation meteorology, wind speed, wind direction, risk estimation, statistical analysis

I. Introduction

It is known that meteorological conditions have a significant impact on aviation and play an important role in aviation accidents and also ensuring the safe operation of aircraft. Wind, visibility, precipitation intensity and amount, weather phenomena, etc. are the most important meteorological parameters that affect the working of aerodromes [1]. Therefore, continuous monitoring of weather conditions at airports, as well as scientific analysis of this monitoring data, are given special attention worldwide [2-6], including in Azerbaijan and Georgia [7-11]. These studies are also important for assessing the role of climate change on the expected variability of meteorological conditions at airports.

In particular, the article [2] presents a systematic review of the growing but somewhat dispersed academic literature on climate change impacts and adaptation in the aviation sector. Information was synthesised from 131 studies (published between January 2000 and November 2022) on eleven climate change effects and the associated impacts and potential adaptation measures. Six areas for action to address knowledge, awareness and implementation gaps were identified: (i) to broaden geographical coverage, particularly to address the current lack of studies addressing climate risks and responses in Central and South America, Africa and the Middle East; (ii) to extend knowledge of physical impacts; (iii) to address known-unknowns such as the risks associated with unprecedented or compound extreme events; (iv) to extend knowledge of adaptation including cost–benefit analysis and consideration of integrated mitigation and adaptation; (v) to identify and apply other relevant research; and (vi) for sector bodies to support and facilitate collaboration between researchers and practitioners to co-develop accessible user-oriented climate adaptation services.

The paper [3] presents a detailed analysis of ten years of data (2011-2020) on wind speed and direction at Minangkabau international airport. It was found that, the condition of the overall average wind direction and speed at this airport was in the safe category for the takeoff and landing process. In the work [4] it is noted that weather is considered a causal factor in about 30% of all US aviation accidents. The author reports that fatal aviation accidents data related to ceiling, fog, and wind are estimated at 20%, 14%, and 10%, correspondingly. It is indicated that knowing weather conditions can help to improve operational planning, including fuel consumption and people safety. In the article [5] deals with the occurrence of storms and their associated dangerous phenomena at Slovakia's international airports which are located in different orographic conditions of the country in 2018-2023. This paper provides a valuable insight into the safety of airport operations, the safety of the flight itself.

In the work [6] authors provide a comprehensive spatiotemporal analysis of fatal weather-related general aviation accidents from 1982 through 2013 using data culled from the United States National Transportation Safety Board (NTSB). Weather was a cause or contributing factor in 35% of fatal general aviation accidents, of which 60% occurred while instrument meteorological conditions were present. Fatal weather-related general aviation accidents occur most frequently between October and April, on weekends, in early morning and evening periods, and along the West Coast, Colorado Rockies, Appalachian Mountains, and the Northeast. There has been a long-term reduction in weather-related general aviation accidents and fatalities since the 1980s; nonetheless, these accidents are still responsible for nearly 100 fatalities/year in the United States. This study provides pilots, academics, the Federal Aviation Administration, the NTSB, and other aviation organizations with information to advance mitigation efforts aimed at reducing future aviation-related accidents in the United States.

The paper [7] presents the results of studies of changes in the surface air temperature regime and its possible impact on the conditions of takeoff and landing of aircraft in the Ganja-Gazakh region (Azerbaijan). In paper [8] regularity of distribution of precipitation at the airdromes of Azerbaijan was studied.

In papers [9,10] the results of study of characteristics of fogs in the airport of Tbilisi city are presented.

Detailed data on meteorological elements (visibility, wind speed and direction, air temperature, dew point and humidity, absolute and mean atmospheric pressure, weather phenomena, rainfall) at Georgian aerodromes (Tbilisi, Kutaisi, Batumi) in [11] are presented. Period of record: 2010-2016, observation interval: 30 min. Wind direction sectors - 30° each (12 sectors).

This work is a continuation and addition to the previously conducted studies. It presents some results of the studies of wind conditions at the Heydar Aliyev Baku and Shota Rustaveli Tbilisi international airports in 2015–2024.

II. Study area, material and methods

Study area: Heydar Aliyev Baku international airport (Baku airport, or Baku) and Shota Rustaveli Tbilisi international airport (Tbilisi airport, or Tbilisi). In Fig 1,2 images of these airports against the background of a wind rose contour (Table 1) are presented.



Figure 1: *Image of Baku airport against the background of a wind rose contour.*



Figure 2: *Image of Tbilisi airport against the background of a wind rose contour.*

Table 1: *Wind direction list.*

Wind blowing from	Abr.	Degree	Wind blowing from	Abr.	Degree
North	N	0	South	S	180
North-Northeast	NNE	22.5	South-Southwest	SSW	202.5
North-East	NE	45	South-West	SW	225
East-Northeast	ENE	67.5	West-Southwest	WSW	247.5
East	E	90	West	W	270
East-Southeast	ESE	112.5	West-Northwest	WNW	292.5
South-East	SE	135	North-West	NW	315
South-Southeast	SSE	157.5	North-Northwest	NNW	337.5
Variable wind direction	VD		Calm, no wind	Calm	

Baku Airport (METAR UBBB) has two almost parallel runways about 4 km and 3.2 km long. Tbilisi Airport (METAR UGTB) has one operational runway 3 km long. Both airports accept all types of passenger and cargo aircraft, including the world's largest Airbus A380 and An-225 (Mriya) [https://www.biletik.aero/handbook/pomoshch/perelet/chem-opasen-silnyy-veter-pri-posadke-samolyeta/]

In the work data of [https://rp5.ru/Weather_archive_in_Baku,_Heydar_Aliyev_(airport) and https://rp5.ru/Weather_archive_in_Tbilisi_(airport),_METAR] on mean wind speed (F, m/sec), and gusty wind speed (G, m/sec), for different wind directions are used. Period of record: 2015-2024, observation interval: 30 min. Wind direction sectors – 22.5° each (18 sectors, Table 1).

In fact, take-off and landing are the only times during a flight when high winds can result in flight delays—almost every flight deals with high winds at some point during its climb or descent. With this in mind, horizontal winds (also known as "crosswinds") in excess of 15 m/sec are generally prohibitive of takeoff and landing most types of aircraft [https://www.skyscanner.com/tips-and-inspiration/what-windspeed-delays-flights].

In the proposed work the analysis of data is carried out with the use of the standard statistical analysis methods [12].

The following designations except those specified above will be used below: Mean – average values; Min - minimal values; Max - maximal values; Range – Max - Min; St Dev - standard deviation; C_v – coefficient of variations (C_v = 100· St Dev/ Mean, %); Count - number of measuring; Count, ≥15 m/sec - number of cases in year with wind speed ≥15 m/sec; R^2 – coefficient of determination; R – coefficient of linear correlation; difference between mean values was produced with the use of Student's criterion with the level of significance α not worse than 0.01. The degree of correlation was determined in accordance with [12]: very high correlation ($0.9 \le R \le 1.0$); high correlation ($0.7 \le R < 0.9$); moderate correlation ($0.5 \le R < 0.7$); low correlation ($0.3 \le R < 0.5$); negligible correlation ($0 \le R < 0.3$).

III. Results and discussion

Results in Tables 2,3 and Fig. 3 – 8 are presented.

Table 2 presents statistical characteristics of mean and gusty wind speed at Baku and Tbilisi airports for all observation data from 2015 to 2024.

Table 2: *Statistical characteristics of mean and gusty wind speed at Baku and Tbilisi airports.*

Location	Baku		Tbilisi	
Parameter	F	G	F	G
Mean	5.3	17.2	4.9	19.2
Min	0	8	0	7
Max	23	31	26	33
Range	23	23	26	26
St Dev	3.2	2.6	3.8	3.5
C_v (%)	60.1	15.1	78.4	18.3
Count	166825	12245	166704	7533

As follows from this Table mean value of F in Baku airport is on 0.4 m/sec higher than in Tbilisi airport (5.3 and 4.9 m/sec respectively). At the same time mean value of gusty wind speed in Baku is on 2.0 m/sec lower than in Tbilisi (17.2 and 19.2 m/sec respectively). Max values of F and G in Baku are lower than in Tbilisi (23 and 31 m/sec and 26 and 33 m/sec respectively). It is important to note that number of gusty wind in Baku is significantly more than in Tbilisi (1225 cases at 30 min intervals per year and 753 cases respectively).

Repeatability of mean and gusty wind speed at Baku and Tbilisi airports have the same appearance: for F - unimodal, for G – bimodal (Fig. 3). The max repeatability of mean wind speed

in Baku falls on 3 m/sec (13.9 %), and in Tbilisi - on 2 m/sec (19.9%).

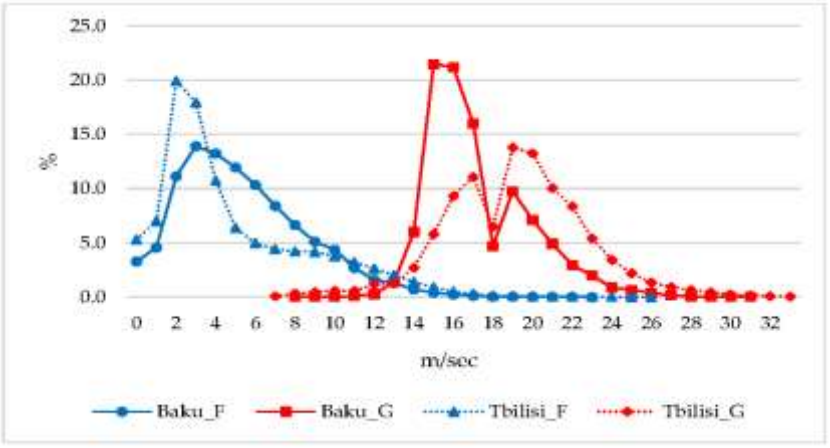


Figure 3: *Repeatability of mean and gusty wind speed at Baku and Tbilisi airports.*

The first extreme of wind gust repeatability in Baku falls on 15 m/sec (21.5%), and in Tbilisi - on 17 m/sec (11.1%). The second extremes of these repeatabilities at both airports falls on the same wind speed - 19 m/sec (Baku - 9.75%, Tbilisi - 13.8%).

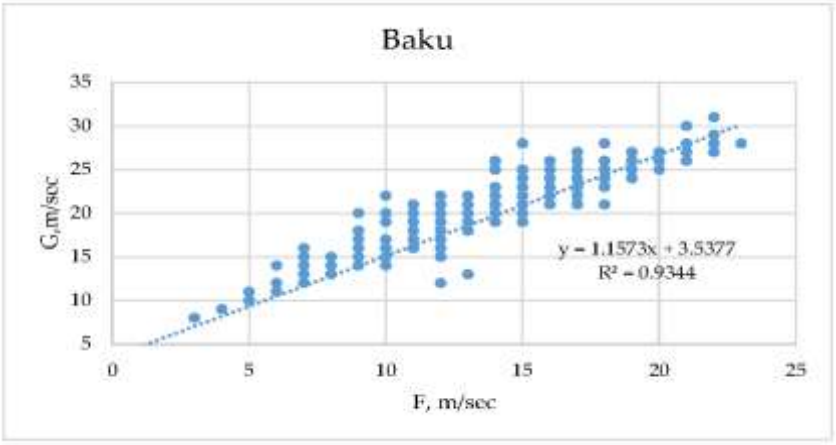


Figure 4: *Linear correlation and regression between of mean and gusty wind speed at Baku airport.*

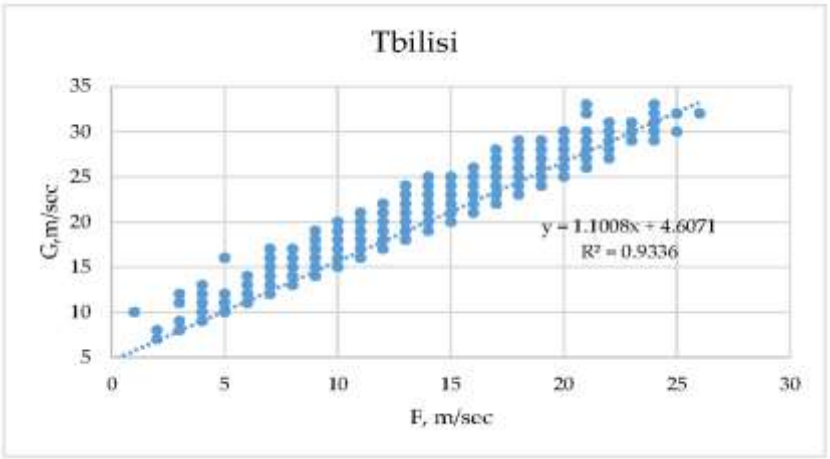


Figure 5: *Linear correlation and regression between of mean and gusty wind speed at Tbilisi airport.*

Fig. 4 and 5 show graphs of linear correlation and regression between mean and gusty wind speeds at Baku and Tbilisi airports. For both airports, the correlation between F and G values is very high (R = 0.97).

Fig. 6 and 7 presents data about repeatability of mean and gusty wind speed at Baku and Tbilisi airports for different wind directions.

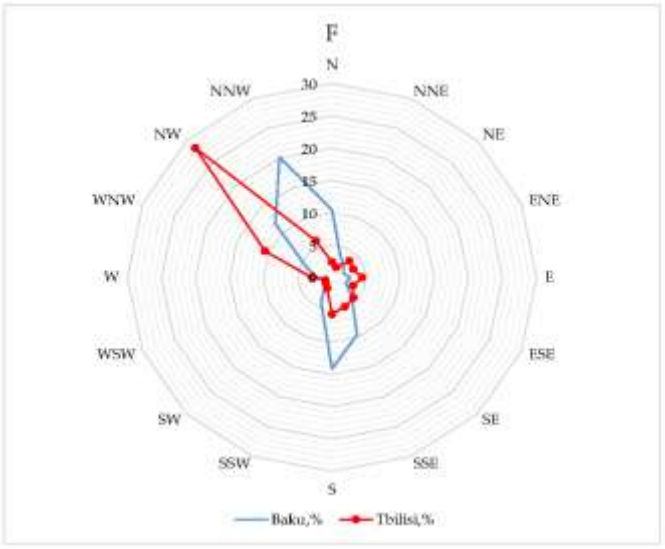


Figure 6: *Repeatability of mean wind speed at Baku and Tbilisi airports for different wind directions.*

As follows from Fig. 6, the max repeatability of the mean wind speed in Baku is in the NNW direction (20.2%), and in Tbilisi – in the NW (28.3%). Note that in Baku the repeatability of variable wind direction is 1.72%, and in Tbilisi – 8.65%. The repeatability of cases with calm in Baku is 3.28%, and in Tbilisi – 5.3%.

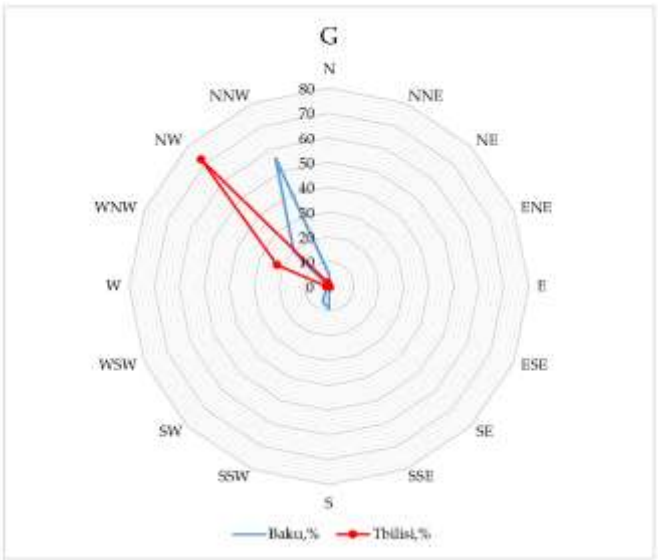


Figure 7: *Repeatability of gusty wind speed at Baku and Tbilisi airports for different wind directions.*

It follows from Fig. 7 that, as in the previous case, the max repeatability of wind gust speed in Baku and Tbilisi falls on the same direction (NNW and NW, respectively). In Baku, this repeatability is 56.1%, and in Tbilisi – 72.4%. In the studied period of time, cases with VD for G were observed only in Tbilisi – 0.4% of all measurement cases.

In Table 3 statistical characteristics of mean and gusty wind speed at Baku and Tbilisi airports for different wind directions are presented. The same Table presents the data about number of

cases in year with wind speed ≥15 m/sec for both airports at different wind directions.

Table 3: *Statistical characteristics of mean and gusty wind speed at Baku and Tbilisi airports for different wind directions.*

Parameter	Direct.	Baku		Tbilisi		Direct.	Baku		Tbilisi	
		F	G	F	G		F	G	F	G
Mean	N	6.1	17.0	2.9	11.5	S	5.8	15.7	2.9	11.0
Min		1	9	1	7		1	10	1	8
Max		20	25	14	14		16	23	9	14
Count, ≥15 m/sec		5.5	55.5	0	0		1.3	91.8	0	0
Mean	NNE	4.8	14.8	2.7	16.6	SSW	6.1	15.9	2.6	12.0
Min		1	9	1	14		1	11	1	11
Max		13	19	13	19		20	26	8	13
Count, ≥15 m/sec		0	0.8	0	0.4		3.2	64.7	0	0
Mean	NE	4.4	12.5	2.9	13.4	SW	4.5	15.7	2.5	12.2
Min		1	10	1	10		1	12	1	9
Max		11	17	13	20		21	26	11	14
Count, ≥15 m/sec		0	0.2	0	0.2		0.8	14.4	0	0
Mean	ENE	3.9	8.5	2.9	12.8	WSW	3.2	16.2	2.6	14.9
Min		1	8	1	10		1	12	1	10
Max		10	9	12	19		21	26	13	21
Count, ≥15 m/sec		0	0	0	0.1		0.3	4.6	0	0.3
Mean	E	3.7	13.0	3.3	12.1	W	2.6	16.3	3.3	15.1
Min		1	11	1	1		1	12	1	8
Max		10	14	10	10		15	21	14	23
Count, ≥15 m/sec		0	0	0	0.2		0.1	1.8	0	4.8
Mean	ESE	3.6	13.0	3.3	12.1	WNW	3.0	16.2	6.8	18.3
Min		1	13	1	9		1	12	1	9
Max		11	13	11	15		17	28	23	31
Count, ≥15 m/sec		0	0	0	0.3		0.2	2.9	38.9	154
Mean	SE	4.3	14.3	3.2	10.5	NW	5.7	17.4	8.7	19.7
Min		1	11	1	8		1	9	1	10
Max		13	16	11	14		23	31	26	33
Count, ≥15 m/sec		0	0.4	0	0		33.8	227.7	289.5	529.3
Mean	SSE	4.7	15.7	3.1	10.0	NNW	7.6	17.6	5.5	18.2
Min		1	13	1	7		1	12	1	9
Max		14	19	8	14		22	30	21	27
Count, ≥15 m/sec		0	3.3	0	0		95.3	661	8.7	10.5
Mean	VD	1.0	0			VD			1.6	8.6
Min		1	0						1	7
Max		2	0						7	12
Count, ≥15 m/sec		0	0						0	0

In particular, as follows from Table 3, for different wind direction mean values of F in Baku varied from 2.6 m/sec (W wind) to 7.6 m/sec (NNW wind) and in Tbilisi varied from 2.5 m/sec (SW wind) to 8.7 m/sec (NW wind). Mean values of G in Baku varied from 8.5 m/sec (ENE wind) to 17.6 m/sec (NNW wind) and in Tbilisi - from 10.0 m/sec (SSE wind) to 19.7 m/sec (NW wind). For different wind direction max values of F in Baku varied from 10 m/sec (ENE and E wind) to 23 m/sec (NW wind) and in Tbilisi varied from 8 m/sec (SSE wind) to 26 m/sec (NW wind). Max values of G in Baku varied from 9 m/sec (ENE wind) to 31 m/sec (NW wind) and in Tbilisi - from 10 m/sec (E wind) to 33 m/sec (NW wind).

In Baku mean values of F for variable wind direction is 1.0 m/sec, and of G – 0. For VD in Tbilisi mean values of F is 1.6 m/sec, and of G – 8.6 m/sec; max values of F is 7 m/sec, and of G – 12 m/sec (Table 3).

Max number of cases in year with wind speed ≥15 m/sec in Baku for F is 95 (NNW wind) and for Tbilisi - 290 (NW wind). Max number of cases in year with wind speed ≥15 m/sec in Baku for G is 661 (NNW wind) and for Tbilisi - 529 (NW wind). Note that the indicated values of count, ≥15 m/sec in the direction at both airports coincide well with the direction of takeoff and landing of aircraft.

The number of cases per year with crosswinds and winds close to it with a speed of ≥15 m/sec in Baku is 10 cases, and in Tbilisi it is absent.

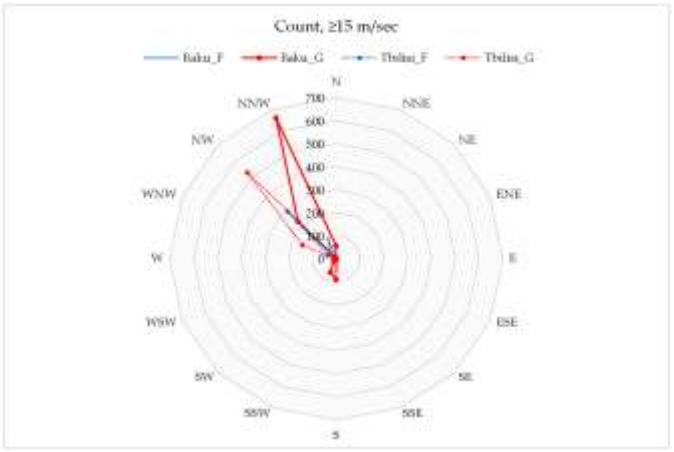


Fig. 8: *Number of cases in year with wind speed ≥15 m/sec at Baku and Tbilisi airports for different wind directions.*

Finally, for clarity, Fig. 8 shows a diagram of the dependence of the number of cases per year with a wind speed of ≥15 m/sec at the airports of Baku and Tbilisi on different wind directions.

V. Conclusion

A study of wind conditions at the Heydar Aliyev Baku and Shota Rustaveli Tbilisi international airports in 2015–2024 was conducted. Data on mean wind speed (F), gusts (G) and directions at both airports were compared.

The statistical characteristics of the specified parameters were studied. In particular, comparison made repeatability of mean and gusty wind speed at Baku and Tbilisi airports; linear correlation and regression relationships between F and G values were established for both airports; repeatability of mean and gusty wind speed at Baku and Tbilisi airports for different wind directions were installed; statistical characteristics of mean and gusty wind speed at both airports for different wind directions are studied; data about number of cases in year with wind speed ≥15 m/sec for both airports at different wind directions are presented.

In the near future, we plan to conduct similar studies for individual months of the year. In addition, it is planned to study other meteorological characteristics related to the safe operation of airports (visibility, atmospheric phenomena, thermal conditions, etc.). It is also planned to conduct the above studies for other airports in Azerbaijan and Georgia.

Such studies can be useful from both a scientific and practical point of view (improving knowledge in terms of regional climate study, using research results to climate change modeling, using the information obtained in training flight crews and maintenance personnel, as well as improving their qualifications, etc.).

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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FINANCING INNOVATIVE PROJECTS TO ENSURE SAFE DEVELOPMENT OF REGIONAL INFRASTRUCTURE

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Abstract

This article examines the current issues surrounding the financing of innovative projects for regional infrastructure development. The study aims to analyze modern financing mechanisms for such projects, including assessing their effectiveness and suitability for Russian conditions. The study employs systemic and institutional approaches. Methods of statistical data analysis, economic and mathematical modelling, expert assessment and comparative analysis were employed. The article systematizes key approaches to defining innovative infrastructure and studies sources of financing, such as budget loans, public–private partnerships and venture funds. It also develops a model for assessing the economic efficiency of projects. The main results include the classification of innovation infrastructure components, the identification of regional financing features, and recommendations for optimizing resource allocation. The study found that combining public and private instruments increases project sustainability, and that industry clustering contributes to an economic multiplier effect. The results of the study can be used to formulate regional development strategies.

Keywords: innovative projects, financing, regional infrastructure, clustering, public-private partnership, institutional approach

I. Introduction

The development of the regional innovative infrastructure remains one of the key tasks of the modern economy, but there is still a shortage of comprehensive studies devoted to the mechanisms of its financing in the scientific literature.

In a number of works [5], the authors focus primarily on methods for assessing the efficiency of projects, but do not take their regional specifics into account. Other studies [1; 7] systematized

the components of infrastructure (technological, financial, personnel), but do not propose clear algorithms for attracting investment.

A critical analysis of the works [10] by Grekov E.I. and Roshchina L.N. [8] revealed gaps in the study of the role of budget loans and public-private partnerships (PPP). For example, in the article "Budget credit as a mechanism of financial support..." [4] an algorithm for obtaining infrastructure loans is described, however, there is no assessment of their impact on the long-term development of regions. The research of E.A. Rybkina [9] shows, that foreign experience, demonstrates successful cases of mixed financing, but their adaptation to Russian conditions requires considering institutional limitations, such as a high share of state participation and weak development of the venture market [3].

The relevance of the study is due to the need to develop a methodology that combines theoretical approaches to structuring infrastructure with practical financing instruments. This will allow regions to overcome the imbalance between the need for innovation and limited resources.

II. Methods

The study used the following approaches:

1. A systemic approach is used to analyze innovation infrastructure as an entire system of interconnected elements (organizations, legal institutions, resources).

2. Institutional approach studies the role of state and social institutions in creating favorable conditions for investment.

The following methods were used:

- Statistical data analysis of Rosstat Statistical analysis and regional reports to assess the dynamics of patent activity and investment volume.

- Economic and mathematical modeling – calculation of project efficiency using formulas of net present value (NPV) and internal rate of return (IRR).

- Expert assessments – materials from interviews with representatives of the Ministry of Construction of the Russian Federation and regional administrations on the implementation of regional financing programs.

- Comparative analysis – comparison of cluster financing mechanisms in Russia

III. Results

The regional innovative infrastructure is defined as a system that includes four components [1]:

- technological and organizational (technological parks, business incubators);
- financial (venture funds, budget loans);
- personnel (educational organizations);
- innovation and legal (patent law, databases).

The successful functioning of the regional innovative infrastructure implies the effective interaction of all its components. Technological parks and business incubators provide a platform for the development of new technologies and start-ups, ensuring access to resources and expertise. Financial instruments such as venture funds and budget loans make it possible to provide financing for innovative projects at various stages of development.

Educational organizations that train qualified personnel for research and production companies play a key role in the formation of innovation potential. The innovation and legal component, which includes patent law and databases, ensures the protection of intellectual property and facilitates access to the necessary information for innovation activities.

The comprehensive development of all four components and their integration into a single system allows creating a favorable environment for the generation, commercialization and implementation of innovations, promoting economic growth and increasing the competitiveness of the region.

Financing of innovative projects aimed at developing regional infrastructure can be implemented through various models, adapted to the specific needs of participants and the capabilities of the regional market. The following financing models are most common in Russian regions.

Self-financing, in which each infrastructure participant finances the project using his own funds in accordance with a single, agreed business plan.

The model of collective self-financing is also used quite often. The essence of this model is that the participants of the infrastructure system create a special fund on a parity basis, accumulating funds to finance projects.

The model for attracting investment loans means that infrastructure participants attract borrowed funds in accordance with an agreed business plan.

A special role in the innovative projects` financing aimed at the development of regional infrastructure is given to the model involving state subsidies. Within the framework of this model, individual participants or a specially designated project participant, or a fund created by it, can receive state support within the framework of procedures established by the legislation of the Russian Federation.

The venture financing model is aimed at attracting investments from venture funds, both at the level of individual participants and through the fund created by them, in compliance with the rules adopted in this area.

It is also worth noting the model of financing infrastructure projects based on leasing operations. It consists in the fact that infrastructure participants or a fund created by them can acquire the necessary equipment on lease.

An alternative way to raise funds is to issue bonds by infrastructure entities or a specially created legal entity. Bond loans allow for the accumulation of significant capital required for the implementation of large infrastructure projects, while ensuring the diversification of funding sources. The attractiveness of bonds for investors increases with the presence of government guarantees or sureties.

Concession agreements are very important financing instruments. Under a concession, a private investor receives the right to construct and operate an infrastructure facility for a certain period, receiving income from its use. The state, in turn, receives a finished infrastructure facility built using private funds.

Among the new approaches, it is worth to highlight crowdfunding, which allows attracting small amounts from many investors through online platforms. This method is especially relevant for projects that have social significance and enjoy the support of the local population.

It is also possible to implement a mixed financing model that combines the various approaches listed above.

According to the study, investing in projects aimed at developing regional infrastructure brings benefits of varying significance to its participants. The value of these benefits largely depends on the level of significance of the participant, which is determined by its position in the hierarchical structure of the infrastructure entity – for example, belonging to the core or peripheral layers.

Direct financial benefits include:

- cost saving due to specialization, concentration and centralization of production and business processes;

- cost reduction through the use of transfer prices for products and services of joint ventures

and organizations

- profit markup due to monopolization of certain market segments and production of higher quality and more expensive products.

Strategic (indirect and long-term) benefits include:

- stabilization of operational processes and increase in order volumes;
- joint financing of investments, including external sources, which promotes collective development;
- expansion of the product range while maintaining a high level of unification and standardization.

A uniform approach to pricing is applied to participants in infrastructure entity. However, in fact, different profitability rates may be set for representatives of different status levels. This stimulates their desire to improve their status, increasing their importance for infrastructure entity. The influence of infrastructure projects on the position of participants is manifested in the redistribution of resources and competencies. Companies occupying central positions gain access to advanced technologies and expanded information, while peripheral organizations often focus on standardized tasks, contributing to the improvement of the overall efficiency of the system.

Stimulating status raising through the rate of return creates a healthy competitive environment. Companies strive to innovate and improve efficiency to gain a better position in the hierarchy and access to more resources and opportunities. This process continuously pushes the infrastructural entity to develop. At the same time, it is important to consider the possible risks associated with the concentration of power in the hands of the core of the infrastructural entity. A mechanism of controls and balances is needed to ensure a fair distribution of resources and opportunities among all participants, preventing imbalance and stagnation in development.

A study of various materials (statistical, reporting, etc.) for the period 2022–2025 showed a variety of sources of financing for regional innovation infrastructure. The structure of financing for regional innovation infrastructure, determined from a sample of data based on the author's calculations, is presented in Table 1.

Table 1: *Structure of financing for regional innovation infrastructure*

Source	Share in total volume (%)
Budget loans	42
PPP (private-public partnership)	28
Venture funds	10
Own funds	16
Foreign investment	4

As can be seen, the data analysis revealed the dominance of government instruments, which account for 42 percent of the total volume of finance.

A significant method of financing innovation infrastructure facilities is self-financing. It allows supporting certain role functions (production, maintenance) of infrastructure systems and individual enterprises, carried out outside the infrastructure entity and empowering them to independently determine the directions of activity. Self-financing implies the availability of stable and sufficient sources of income generated by the innovation infrastructure facility itself, including income from commercialization of developments, provision of services, rental of premises or participation in other similar projects. Effective management of these incomes and their reinvestment allows for the maintenance and development of infrastructure without constant

dependence on any external sources of financing.

In the context of ensuring the operation of innovative infrastructure, self-financing is especially relevant for stimulating entrepreneurial activity and increasing competitiveness. It enables small innovative enterprises and start-ups located in the infrastructure formation, to independently determine the vector of development, develop and implement their innovative ideas. It is also important that self-financing helps to form a culture of responsibility and efficiency in the use of resources among participants in the innovation infrastructure. Innovative infrastructure facilities that depend on their own income are significantly more inclined to optimize costs and search for new opportunities for earnings. This potentially makes them more sustainable and attractive to investors and partners.

As a rule, the settlement of accounts between participants in the innovation infrastructure and external partners for the rendered services are carried out according to generally accepted rules established for legal entities.

It was found that combining financing instruments (budget loans, PPP, venture, own funds) increases the sustainability of innovative projects by 20–30%, while at the same time the risks of their underfunding are reducing.

The efficiency of regional innovation infrastructure projects varies significantly. Calculation of the NPV for projects showed that with a discount rate of 12%, payback is achieved in 5–7 years.

In the regions of Russia, the creation of clusters as infrastructure entities based on mixed financing (60% - budget, 40% - private investment) is widely practiced, which leads to an average growth of the gross regional product (GRP) by 3-8%; the creation of 1.2 thousand jobs; an increase in patent applications by 15%.

Clustering of regional innovation infrastructure provides a multiplier effect: 1 ruble of investment generates 2.3 rubles of GRP.

A comparison of data across regions of the country revealed a correlation between the level of infrastructure development and innovation activity.

The study showed that regional socio-economic differences, as well as the specifics of the regions' innovative infrastructure, require appropriate adaptation of financing models. They should consider, for example, the specifics of the formation of transport infrastructure for the regions of Siberia, or tourism clusters for the South of Russia.

IV. Discussions

The results confirm the hypothesis about the key role of state financing under weak development of the private sector. At the same time, it was revealed that exceeding the share of budget loans over 50% reduces the flexibility and efficiency of innovative projects.

In Russia, the share of venture investments is 3 times lower than in the EU, which requires the stimulation of tax incentives.

Successful experience in clustering infrastructures in a number of regions of the country does not solve long-standing problems with insufficient diversification of the economy, the output of products with a low share of added value, the aging and shortage of engineering and labor personnel.

To improve the financing of regional innovation infrastructure, further institutional reform measures are needed, including tax incentives, simplification of administrative procedures, and private capital raising.

V. Conclusions

The conducted study allowed us to identify key aspects of financing innovative projects for the development of regional infrastructure, as well as to offer recommendations for increasing their effectiveness. It was established that innovative infrastructure is a complex system, including technological, financial, personnel and legal components, which require an integrated approach to financing. Data analysis showed that in Russia state financing instruments such as budget loans and public-private partnerships (PPP) dominate, which is due to the underdevelopment of the private sector and venture capital market. However, exceeding the share of state financing above 50% reduces the flexibility and efficiency of projects, which emphasizes the need for a balanced approach.

The results of the study confirmed that combining various sources of financing (budget loans, PPP, venture funds, own funds) increases the sustainability of innovative projects by 20-30% and reduces the risks of their underfunding. Particular attention is paid to clustering as an effective mechanism for the development of regional infrastructure. Clusters based on mixed financing (60% budget, 40% private investment) demonstrate a multiplier effect: 1 ruble of investment generates 2.3 rubles of gross regional product (GRP), which contributes to economic growth, job creation and increased innovation activity.

Nevertheless, problems related to the insufficient economy diversification, low share of added value of production and shortage of qualified personnel have been identified. To solve them, further institutional reforms are needed, including tax incentives, simplification of administrative procedures and stimulation of private investment. The results of the study can be used to develop regional development strategies adapted to the specifics of each region, which will help overcome the imbalance between the need for innovation and limited resources.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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CONCEPTUAL FEATURES AND OBSTACLES TO THE IMPLEMENTATION OF A CIRCULAR ECONOMY MODEL

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Abstract

The article concludes that, at this stage of human development, the economy has become a significant factor in the direct influence on the natural environment. This influence has arisen from economic development aimed at meeting human needs while disregarding the need to ensure the environmental neutrality of production and consumption. The article presents the results of a study that identifies promising areas for the development of the circular economy. It considers the circular economy to be a certain stage of economic evolution and an integral component of real anthropogenic and natural resource cycles. Using this approach alongside the conceptual provisions of the circular economy enabled the development of a system for defining economic types, a cyclical-resource model of the anthropogenic environment and a set of theoretical and methodological support for substantiating the development of the circular economy.

Keywords: circular economy, economic development, technology, environment, anthropogenic impact

I. Introduction

At the present stage of human development, the economy is acquiring the significance of a factor of direct impact on the natural environment. This is confirmed by the facts of landscape changes, depletion of mineral deposits, environmental pollution, etc. The most significant climate changes on Earth in the current era of geological history are determined by periods of global warming, but modern global warming is occurring at a somewhat faster pace than in previous periods. A significant part of the expert community claims that the cause of this phenomenon is the negative anthropogenic impact on the environment, caused by the growth of the population and its needs, and, consequently, the scale of the economy.

The solution to this problem today is seen in the construction of a system of production relations that, along with satisfying human needs, would ensure the growth of rational use of natural resources and the reduction of anthropogenic load on the environment. The solution to this problem requires supplementing the industrial model of the economy, objectively formed over centuries of economic evolution, with requirements for rational use of natural resources.

The results of the search for ways to solve this problem are seen today in the implementation of the concepts of sustainable development, circular economy, and “green” economy.

Many works by domestic and foreign scientists are devoted to the consideration of various elements of the circular economy, in particular, it is worth highlighting: T.V. Uskova [1], E.D. Kopytova [1], R.N. Botavina [2], I.A. Yakovlev [3], L.S. Kabir [3], S.N. Bobylev [4], S.V. Solovieva [4]. At the same time, the problems of the circular economy are becoming relevant right now, since it is capable of transforming the production model, promoting economic growth, reducing the volume of waste and providing consumers with innovative products.

II. Methods

The purpose of this study is to substantiate the directions of structural and technological transformations in the national economy aimed at the formation of systemic features in it that meet the conceptual requirements of the circular economy.

The following methods were used in the research: comparative analysis (assessment of public policy measures); abstract logical (problem statement, justification of conclusions); monographic (analysis of scientific works).

Given the objective of the study, the initial position of this article is to systematize the defining features of various types of economies inherent in past stages of economic evolution and the conceptual requirements of the circular economy [1-5], namely, types of natural resource sources, types of economic resource cycles and degrees of anthropogenic impact on the environment, the characteristics of which are summarized in Table 1. The defining features in the aggregate are inherent in the circular economy, as well as those that are present in the models of other economies, are hereinafter referred to as "circular".

Table 1: *Defining features of historical types of economic development*

Type (model) of economy	**Defining features**		
	types of resource sources	**type of economic resource cycle**	**degree of anthropogenic impact**
pre-industrial economy	mostly inexhaustible and renewable	open	unimportant
industrial economy	inexhaustible and renewable, non-renewable	open with closed elements	essential
Circular Economy (perspective concept)	inexhaustible and renewable, non-renewable	closed	unimportant

The data presented in Table 1 indicate the dependence of anthropogenic impact on the natural environment on the specifics of various economic models.

In the pre-industrial economy, the degree of anthropogenic impact on the environment was insignificant due to the use of renewable resources, despite the openness of the resource cycle and the lack of regular waste disposal and land recreation practices.

In the conditions of industrial economy, anthropogenic impact on the environment has reached a level capable of causing undesirable significant changes in the natural environment of the planet. The reason for this is the use of an open resource cycle with a significant increase in the share of non-renewable resources compared to the pre-industrial economy and the insufficiency of targeted measures to prevent and neutralize the negative consequences of this phenomenon.

III. Results

The introduction of the circular economy model is often considered today as a promising path to sustainable development. Ideally, the concept of a circular economy involves the involvement of natural resources in the economic resource cycle in a volume sufficient to ensure growth in the scale and environmental neutrality of economic activity by increasing the rationality of resource use, creating closed resource cycles in the areas of production and consumption, and creating a waste disposal industry.

The totality of planetary resource cycles in the aspect of the formation of anthropogenic impact can be presented in the form of a closed hierarchical system, the structural elements of which are resource cycles of specific environments of certain spheres of human activity.

Taking into account the structural identity of the hierarchical system of resource cycles of all types of economies, it can be argued that qualitatively different consequences of anthropogenic impact on the natural environment are determined by the parametric consistency of resource cycles in certain areas of anthropogenic activity. The formation of the global resource cycle under the influence of anthropogenic activity occurs in sequence according to the principle "from the particular to the general", which allows us to methodically correctly consider the results of any type of anthropogenic activity as factors in the formation of parameters of the natural environment.

Thus, the creation of an ecologically neutral economy model requires structural changes in certain resource cycles, increasing the rationality and efficiency of resource use, which will also lead to a change in the defining features of the economic model.

In terms of the formation of an ecologically neutral economy, it is important that different types of economic activity have different impacts on the environment. In this regard, the problem of determining the types of economic activity, the provision of targeted development of which will determine the most significant results in achieving the signs of ecological neutrality of the economy, arises.

On a global scale, the greatest negative impact on the environment is exerted by types of economic activity that have acquired high rates of development in the conditions of an industrial economy, namely energy, metallurgy, transport, etc., which are currently the main sources of anthropogenic emissions of carbon dioxide, that is, greenhouse gas, the increase in the content of which in the atmosphere is one of the significant factors in the acceleration of the rate of global warming.

It should be separately determined that the difference in the economic development of world regions, and consequently, of certain countries, also determines differences in the volumes of social production and consumption, rationality and efficiency of resource use, anthropogenic impact, which should be taken into account when determining the directions of development of the circular economy in a particular country.

The rapid growth of the scale of economic efficiency occurred in the industrial era and was determined during the first industrial revolution as a result of the growth in the use of mineral fuels due to the development of industrial methods for converting them into energy. This resulted in the creation of industrial-type energy as a separate type of economic activity. At the same time, this phenomenon not only does not reduce the importance of the fuel and energy, metallurgy, transport and logistics sectors in the modern economy, but also contributes to the development of these types of economic activity. However, these same industries are also the main sources of anthropogenic greenhouse gas emissions, since most of the primary energy consumed by these sectors consists of various types of organic fuel, the by-product of the combustion of which is carbon dioxide.

The magnitude of anthropogenic impact on the environment is closely related to the level of consumption of primary fuel and energy resources (primary energy), but the relationship of the trends of these characteristics with the scale of the economy does not demonstrate a clearly expressed general pattern of change in trends in certain regions of the world, as evidenced by the

results of studies [6]. The data indicate a weakening of the correlation between the trends in the growth rates of the global economy and the use of primary energy and the anthropogenic impact on the environment. The outpacing growth rates of global GDP over the growth rates of primary energy use and anthropogenic impact on the environment determines the trend of increasing energy efficiency of the economy against the background of an increase in the absolute value of primary energy use.

The energy efficiency of the economy and the degree of its impact on the environment largely depend not only on the total volume of primary energy use, but also on its specific structure. The results of studies [6] show significant differences in the structure of primary energy use in the world and determine the need to consider the specifics of each region separately.

IV. Discussion

The main sources of anthropogenic carbon dioxide emissions are the processes of energy conversion of organic fuels used in almost all types of economic activity. The share of organic fuel in the global volume of used primary energy in 2020 was 82.2%, of which 26.8% was solid (carbon) fuel, and 55.4% was hydrocarbon. Analysis of the chemical composition of the feedstock and energy conversion products shows that combustible substances are chemical elements - carbon (C), hydrogen (H), as well as hydrogen (H2) and incompletely oxidized compounds - carbon monoxide (CO) in the composition of the products of primary conversion of solid fuels (artificial gases). The different chemical composition of certain types of organic fuel during their combustion also determines the composition of greenhouse gas emissions. Thus, when coal is burned, mainly carbon dioxide is formed, and when hydrocarbons are burned, carbon dioxide and less physically stable water vapor are formed, and this determines the possibility of reducing anthropogenic emissions of carbon dioxide through the use of organic fuels with a high hydrogen content, that is, hydrocarbons and artificial gases.

Considering the wide raw material and technological variability of the modern sphere of energy conversion of organic fuels, it can be argued that the targeted development of a circular economy should ensure structural technological changes in the most energy-intensive types of economic activity.

In accordance with the conceptual provisions and taking into account the conditions and limitations defined above, the development of a circular economy should occur in conditions of satisfying the growing needs of society, a relative reduction in the volume of use of economic resources and an absolute reduction in the anthropogenic load on the environment.

Modern national economies of the world can be considered as a set of types of economic activity that were mastered as a certain country developed economically. In this regard, different types of economic activity in terms of composition and degree of manifestation of defining features have different levels of compliance with the conceptual features of the circular economy.

A large number of studies have been devoted to identifying the factors hindering the development of a circular economy [1-3; 7, etc.], the systematization of which allows us to identify the main groups of such obstacles: socio-cultural; legislative; poor awareness of consumers and producers about the principles and best practices of implementing a circular economy; economic; technological.

Taking into account the above, the following should be identified as promising areas for the development of the circular economy:

– preservation of circular characteristics by types of economic activity with a high degree of compliance with the requirements of the circular economy;

– formation of circular characteristics by types of economic activity with a high degree of non-compliance with the requirements of the circular economy.

In the sphere of energy use, the compliance of the value of circular characteristics of types of economic activity with conceptual requirements can be assessed on the basis of the following criteria: significance in the total volume of use of mineral organic fuel; efficiency of use of mineral organic fuel; degree of anthropogenic impact on the environment.

It is advisable to carry out a weighted assessment of the circular characteristics of certain types of economic activity on the basis of a system of indicators reflecting the criterion dependencies of these characteristics, namely, indices of economic efficiency of resource use and anthropogenic impact:

– level 1 – includes types of economic activity with a high index of economic efficiency of resource use and a low index of environmental impact. An increase in the share of these types of economic activity in the structure of the national economy causes an acceleration of the growth of circular features in it, which indicates a significant potential for accelerating the development of the circular economy according to this factor.

– level 2 – includes types of economic activity with low indices of economic efficiency of resource use and impact on the environment.

– level 3 – types of economic activity with low indices of economic efficiency of resource use and high indices of environmental impact. These types of activity have the least manifestation of circular characteristics, which determines their high potential for accelerating the development of the circular economy.

– level 4 – includes one type of economic activity with high indices of economic efficiency of resource use and environmental impact – processing industry. Reducing the negative anthropogenic impact of this type of economic activity has significant potential to accelerate the development of manifestation of circular features in the circular economy.

Taking into account the above, the promising areas for the development of the circular economy can be defined as:

– advanced economic development of types of economic activity included in the first level, namely: agriculture, forestry and fisheries; wholesale and retail trade, repair of motor vehicles;

– reduction of the negative anthropogenic impact on the environment and increase in the economic efficiency of resources for types of economic activity included in the third level, namely: supply of electricity, gas, steam and air conditioning; metallurgical production;

– reduction of the negative anthropogenic impact on the environment by types of economic activity included in the fourth level, namely the processing industry;

– economic development by types of economic activity included in the second level, namely: extractive industry and quarrying; transport, warehousing, postal and courier activities; construction; catering; water supply, sewerage, waste management.

Thus, it can be stated that the domestic economy has significant potential for circular development, which can be realized through the formation of trends: accelerated growth of production, falling on types of economic activity with a high level of circular characteristics; reduction of the negative anthropogenic impact on the environment by types of economic activity, which are characterized by a high level; sustainable growth of the efficiency of resource use by accelerating their circulation and reducing standard costs in production.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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LEADING SUSTAINABILITY: THE PATH FROM RESPONSIBLE CONSUMPTION TO A GREEN ECONOMY

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Abstract

This study examines the complex relationship between responsible consumption and the economic transformation required for the development of a global green economy. The authors emphasize the significant impact of responsible consumption at all stages of social reproduction. The systemic implementation of the green economy concept at a global level is not only based on the UN Sustainable Development Goals declared in 2015. It is also based on variant scenarios of world economic development, which can be clearly outlined in accordance with long-term historical trends. Firstly, when the human community reaches the ultimate limits of its economic activity and the global economy exerts a determining influence on all groups of stakeholders, it is crucial that the world utilizes all opportunities to reduce the consumption of non-renewable resources and mitigate the anthropogenic impact on the environment. The absence of effective, exemplary macroeconomic models recognized worldwide causes significant diversity in approaches to and national models of green economy development. In such circumstances, a country's capacity to 'green' its national economy is a key indicator of its macroeconomic growth, the development of green technologies, and the adoption of sustainable business practices, which are essential for evaluating its contribution to global sustainable development. The key determinants of the transformation of the green economy are the dominance of neoliberal policies, large-scale economic liberalization, increased social mobility, and the socialization of economic activity. The article emphasizes that achieving a sustainable green economy requires the adoption of environmentally friendly and responsible consumption practices. To this end, it is necessary to encourage consumers to adopt a more careful attitude towards nature and resources, conserve the environment, minimize waste, and reject products that harm the ecosystem. Modern society plays a crucial role in promoting these values by favouring products and companies that are consistent with environmental sustainability. The authors explore various forms of responsible consumption, such as the sharing economy, switching to eco-friendly products and packaging, avoiding disposable goods and encouraging product repair and extension of their lifespan. They emphasize that the main goal is to make consumption more environmentally friendly, which would unify national consumption patterns and create a global culture of responsible, sustainable consumption.

Keywords: assessment sustainable economy, climate change, circular economy, global production chains, green finance, green economy

I. Introduction

As the final stage of the universal process of reproduction of the social product and one of the key forms of economic and social activity, the sphere of consumption in its concentrated form not only reflects a diverse "palette" of social relations formed at all previous stages of the reproduction process (production, distribution and exchange), but also has a powerful influence on the behavior of economic actors at all its stages. And if the industrial era of world economic development was

based on the example of production with the unconditional dominance of commodity fetishism and alienation of labor as the institutional and ideological basis of the capitalist market system, then in the conditions of post-industrialization of global economic development, modern society is witnessing an unprecedented increase in the scale of consumption, its dynamic diversification and structurization, the complication of consumer objects and items, the expansion of forms of realization of consumer goods and services, as well as the expansion of consumer goods and services [1-5].

The main drivers of these transformational changes in the system of consumer relations are the powerful influence of a number of global determinants. Among them, the key role is played by: the dominance of neoliberal economic policy in most Western countries in the post-war period with relatively low inflation rates and a continuous in-crease in consumer lending; systemic liberalization of cross-border movement of goods, services and factors of production; expansion of export-oriented sectors of national economies of different states; increasing levels of social mobility of their populations; deepening processes of socialization and humanization of economic activity; and the development of a new economy [6-8].

Between 2013 and 2023 alone, as Figure 1 shows, the number of high net worth individuals increased from 3.3 million to nearly 7 million in North America; from 3.3 million to 7 million in Asia and the Pacific; from 3.1 million to 5.4 million in Europe; from 0.4 million to 0.8 million in the Middle East; from 0.5 million to 0.6 million in Latin America; and from 0.1 million to 0.2 million in Africa [9-11].

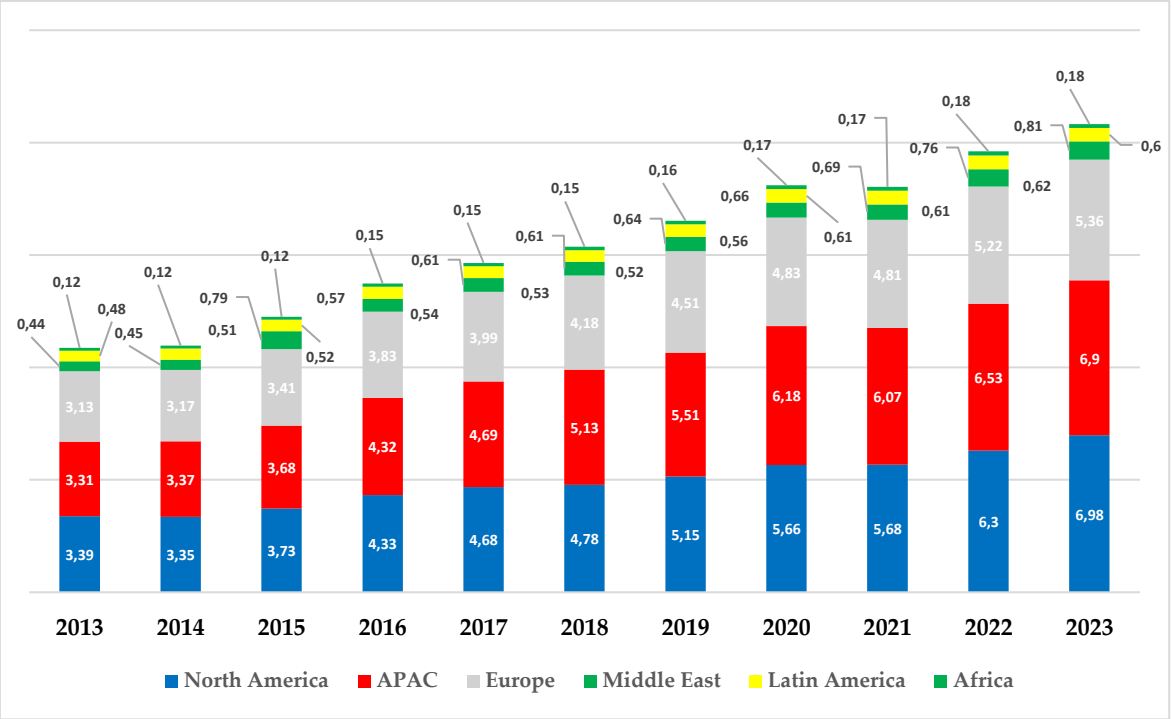


Figure 1: *Number of rich citizens by individual regions in 2013-2023, mln people.*

In regional terms, the increase in household wealth had the following distribution: in North America, from 36.7 trillion to 158.9 trillion between 1999 and 2021 (with a projection of 202.3 trillion in 2026); Western Europe, from 22.3 to 105.9 trillion (129.1 trillion); Latin America, from 0.6 to 12.9 trillion (18.6 trillion); Middle East, from 1 to 11.4 trillion (15.1 trillion); and Oceania, from 1 to 12.5 trillion (16.8 trillion, respectively). It is quite natural that such a rapid increase in the value of household wealth in all regions of the world without exception objectively leads to both a steady increase in the scale of global consumption of goods and services and diversification of its product

structure. Suffice it to say that in the period 1970-2020 the global volume of household final consumption expenditures increased from $2.2 to almost $62 trillion. As of 2020, it amounted to $ 41.1 trillion for the group of high-income countries; $20.2 trillion for middle-income countries; $20.6 trillion for low- and middle-income countries; and $407.9 billion for low-income countries [12-14] (Table 1).

Table 1: *Household final consumption expenditures by individual regions and country groups in 2020, billion USD*

Country Team	Expenses	Region	Expenses
High-income countries	41068.3	North America	18442.8
Middle-income countries	20213.2	OECD	40581.7
Upper middle-income countries	14601.1	Central Europe and the Baltic region	1242.4
Lower middle-income countries	5612.3	Latin America and the Caribbean	3817.1
Low- and middle-income countries	20595.3	Middle East and North Africa	2267.9
	407.9	Asia-Pacific countries	16923.9
Low-income countries		Europe and Central Asia	16528.8
		EU	11344.0
		World	**61884.4**

Source: authors.

A significant fundamental trend of increasing consumption is evident in the United States, where aggregate household final consumption expenditure increased more than 22-fold between 1970 and 2019, from $646.7 billion to $14.5 trillion, and per person from $14.4 to $38,600 (Fig. 2).

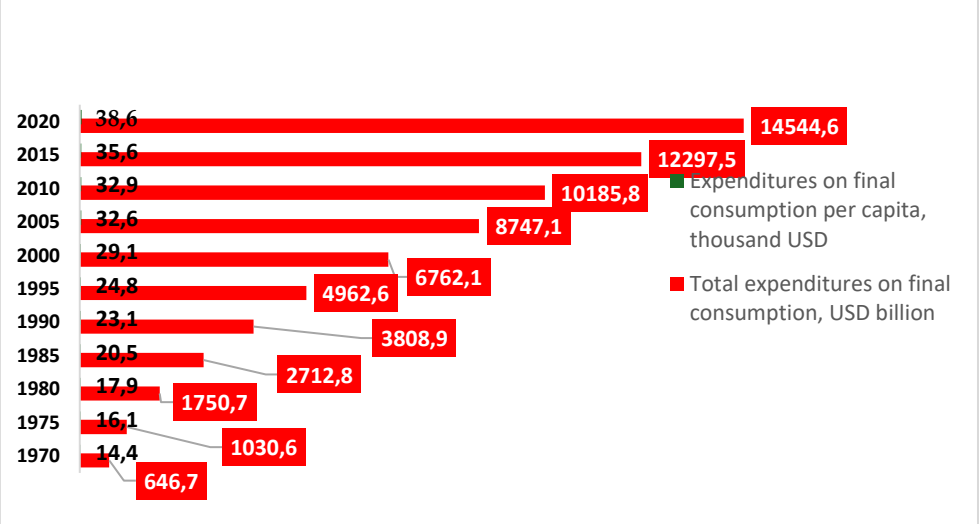


Figure 2: *Final consumption expenditures of US households (total and per capita) in 1970-2019.*

This means the development of a hypertrophied global consumer society, which is based on the spread of consumer models of consumerism [15]. It is the consumer trend of consumerism that determines the artificial formation of more and more economic needs and demands of consumers by the market, thus multiplying the scale of the resource base involved in production and increasing the anthropogenic load on the environment [16]. Another eloquent confirmation of the dynamic spread of the consumerism trend and the closely related wasteful consumption of resources in the global system of consumer relations is the data on the world's accumulated food waste.

Annual food losses and wastage globally amount to 1.3 billion tons of food, approximately one-third of the world's production. In terms of monetary value, these losses amount to US$ 680 billion and US$ 310 billion for developed and developing countries,

respectively [17].

An analysis of food waste in various food categories revealed the following trends:

- Cereals: 30% of world production;
- Root crops, fruits and vegetables: 40-50% of world production;
- Oilseeds, meat and dairy products: 20% of world production;
- Fish and seafood: 30% of world production.

Equally impressive is the extent to which products are wasted at the retail chain level due to failure to meet strict quality standards in terms of appearance. For example, in the UK alone, inadequate appearance of 30% of vegetable crops is the reason why they cannot be sold by retail channels; and households in the UK throw away about 6.7 million tons of food each year, accounting for one-third of the 21.7 million tons of food purchased. This means that around 32% of the food purchased in a year by British households is not consumed at all, the majority of which (almost 6 million tons, or 88%) is actively collected by local authorities today [18-20].

Integrating food losses with data on government subsidies in agriculture reveals an even larger scale of financial losses. Global efforts to reduce food losses and optimize public subsidies in agriculture are critical for food security and sustainability (Table 2).

Table 2: Government subsidies in agriculture (in billions of US dollars)

Country/Region	2021	2023 (assessment)
USA	212	220
EU	188	195
China	149	155
Japan	62	65
South Korea	57	60
India	55	58
Canada	32	34
Australia	29	31
Brazil	27	29
Mexico	26	28
Africa	25	27
Total (OECD)	**797**	**830**

Source: authors.

Note: Data for 2023 are estimates based on current trends and are subject to change.

In the conditions of colossal food losses and in the parameters of global green ecosystem development, this means not only the wasteful involvement in production processes of a huge amount of natural capital and resources (water, land, energy, labor, financing, etc.), but also the generation of ever-increasing masses of "idle" greenhouse gas emissions, which are the cause of rapid climate change, global warming and a significant increase in the anthropogenic load on the environment [21, 22].

As of 2023, 115 countries reported that they had implemented about 900 different policies related to sustainable consumption, in line with the Paris Agreement's goals of limiting global warming to below 2°C and ideally below 1.5°C. These policies cover a wide range of areas, including energy, transportation, food and waste. Countries are increasingly recognizing the important role of sustainable consumption in combating climate change. Sustainable consumption involves using resources and products in ways that minimize negative environmental impacts without compromising the needs of future generations (Table 3).

Thus, it is in the sphere of consumption, as in no other sphere, that we can observe the global influence of mechanisms of social structurization of society, which with all obviousness "expose" all the economic contradictions, deformations, asymmetries and the nature of socio-economic relations accumulated here.

Table 3: *Country policies on sustainable consumption, data for 2023*

Area	Number of policies
Energy	350
Transportation	220
Food	150
Waste	100
Other	80
Total	**900**

Source: authors.

A powerful impetus for limiting individual consumption and its ecologization was the Covid-19 pandemic, which significantly limited the physical ability of consumers to make purchases in quarantine mode [23]. As a result, many of them fully realized the fallacy and ecological threat of the dominant model of consumer behavior in the "pre-Covid" period. Against the background of simultaneous introduction of restrictions on the use of public transportation and significant expansion of the use of digital technologies, the ecological type of consumption has finally established itself in the minds of global consumers [24-26].

Thus, a significant reduction in consumer demand for industrial goods has led to a corresponding reduction in their production supply and the scale of freight transportation, which together have had a powerful positive impact on the natural self-purification of natural ecosystems [27-30].

II. Methodological Approach

First of all, it should be noted the increasing orientation of the aggregate world consumer towards joint (collective) consumption of goods. This phenomenon, qualified in Western scientific literature as "sharing economy" (or its synonyms "participatory economy", "on-demand economy", "access economy", "collaborative economy", etc.), is based on the institution of trust between participants in exchange processes and represents a highly efficient and digitally based economy), is based on the institution of trust between the participants of exchange processes and represents a highly effective and digital technology-based communication platform of interaction between economic actors on the free provision of resources for use or joint consumption of various types of material goods on the basis of their exchange or lease. This is the basis for the realization of rather specific property rights in the shearing economy, based on interpersonal behavioral relations regarding the possession of rare economic goods and aimed at maximizing the overall consumer utility by providing access to them to other economic actors. It should be noted that 28% of companies in the media and entertainment sector, 20% in the accommodation and hospitality industry, 19% in the transport sector, 19% in the retail and consumer goods sector, 14% in the service sector, 11% in the financial sector and 10% in the equipment rental sector already operate in the organizational mode of the sharing economy.

Therefore, thanks to the Sharing Economy, one of the key goals of sustainable development is achieved - a significant reduction of the ecological footprint as a result of limiting human participation in consumer relations, transition of economic actors to rational consumption patterns, lengthening the life cycle of consumer goods, reducing emissions and waste, as well as transferring the consumption process to the principles of circular economy.

In other words, the formation of the model of responsible consumption in the format of the shearing economy occurs not by reducing its volume and specification of property rights, but due to consumer mobility, maximizing the utility of goods and services, their consumption as the need arises, expanding the access of external consumers to unused assets, as well as optimizing the scale

of consumption. In this way, consumers lose their orientation to the constant purchase of more and more new goods, and thus - do not accumulate unnecessary surplus of commodity mass by providing access to them to all interested subjects. It is quite natural that the determining role in this process is played by the system of deep collaborative and social interactions of all participants of the shearing economy, through which their efforts are consolidated to realize the strategic goals of global sustainable development, to combat global poverty and impoverishment of the population, as well as to overcome the deep asymmetries of global socio-economic development. On this basis, we qualify the shearing economy as an important institutional platform for the development of the responsible consumption model in global coordinates, which changes the consumer paradigm itself, destroys the dominant business models and production processes in different sectors of the economy and generates a huge social, financial and consumer-cultural value for the global society.

The high dynamics of development of the shearing economy and the growing popularity of consumer goods and services sold through its channels are confirmed by the fact that by 2025 its total capitalization will grow to USD 335 billion, while in 2014 it did not exceed USD 15 billion. The enterprises of the shearing segment will grow, according to experts' estimates, by 2133% in twelve years (from 2015 to 2025) (Fig. 3), which will equal the sharing economy in terms of company revenues with the traditional economy of the corresponding sectors. As of today, 72% of Americans already plan to utilize the services of the sharing economy within the next two years. At the same time, the National Statistical Office of Great Britain, based on the generalization of a whole system of indicators - from the total value of online purchases made to the amount of payment for marketing services provided - found that in 2015, 275 European platforms for cooperation in the format of the sharing economy were operating on the territory of this country, which generated a total income of 4 billion pounds sterling and ensured the realization of transactions worth 28 billion pounds.

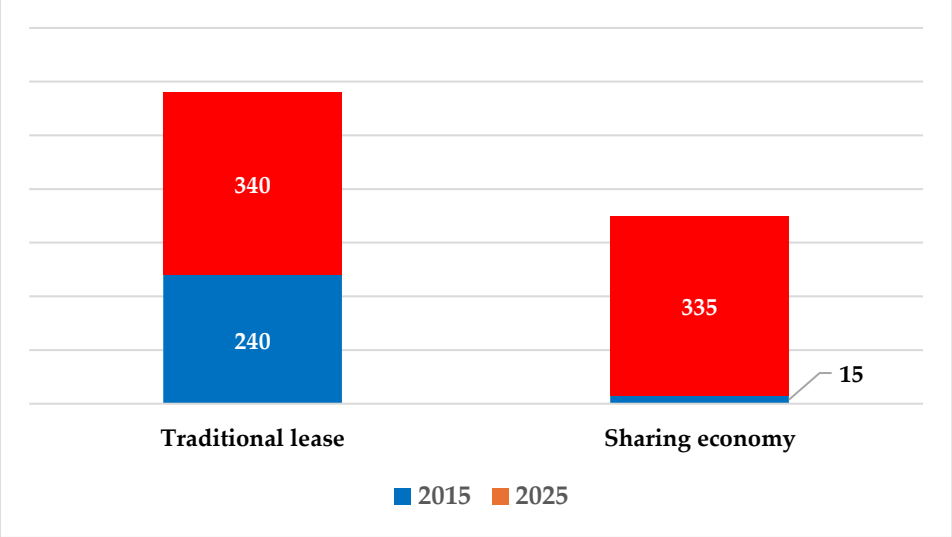


Figure 3: Projected revenues of the traditional rental and sharing economy in 2015 and 2025, billion USD

The aggregate income of the operators of the shearing economy due to the active development of its global infrastructure will increase from USD 18.6 billion in 2017 to USD 40.2 billion in 2022. It should also be noted that these figures do not cover all economic transactions in the sharing economy, but reflect only the profits of companies in such leading sectors as lending, home rentals, ridesharing, music and video streaming, and telecommuting. And although there are still a very small number of publicly traded companies in the sharing economy sector in the global economy as of now, however, there has been a significant increase in their public offering activity in recent years. This offers them a rather encouraging prospect of increased access to low-cost investment capital to finance their current operations and strategic development.

The most common forms of responsible consumption in the format of the sharing economy,

which have the greatest prospects for further growth, are: crowdfunding, online recruitment, carsharing, as well as equipment and car rentals.

Thus, during 2019-2023 alone, the total annual revenue of carsharing companies increased from $8.4 billion to $11.2 billion, with a forecast of growth to $16.5 billion by 2026. At the end of the period, the total number of users of carsharing services will amount to 60.7 million people with an average level of income generated by one user at the level of USD 255.2. Rapid dynamics is also characteristic of the total distance traveled by cars integrated into the carsharing industry: if in 2015 it was about 4% of the distance traveled by all cars in the world, in 2030, according to Morgan Stanley experts, it will reach 26%.

A comprehensive analysis of the activities of companies in the shearing sector gives grounds to identify a number of "bottlenecks" in their functioning, which are already causing serious complaints from companies and firms of traditional business.

First of all, it is a rather clear orientation of the business models of shearing companies to consolidate their monopolistic and oligopolistic positions in the global market, which to a certain extent deforms competitive relations in a number of sectors of the world economy and leads to a decrease in revenues of traditional companies. Special attention should also be paid to the tax component of the activities of online platforms of shearing firms, the mechanism of which gives them ample opportunities to avoid paying taxes, license and insurance fees, as well as to save significant funds on organizational and management costs. This leads to the spread of unfair competition practices with companies in traditional sectors of the economy and opens up opportunities for shearing firms to ignore many issues related, in particular, to working conditions and wages, fulfillment of requirements of social protection of workers and unemployment insurance. However, even the above-mentioned drawbacks of shearing companies' work are not able to offset all their significant competitive advantages associated with the establishment of the responsible consumption model in the world coordinates, and, consequently, the development of the global green ecosystem.

III. Results and Discussion

In the comprehensive characterization of strategic directions of development of the global model of responsible consumption, special attention should also be paid to the practices of consumers in the system of consumer relations in developed countries of the world to minimize solid domestic waste and their transition to sorting garbage and separate method of its disposal. In this context, let us emphasize that the key to high environmental friendliness of waste management systems operating in these countries is their sorting at the initial stages of disposal (i.e. near residential buildings), which allows to simplify and reduce the cost of this technologically complex process. For example, in Sweden, households separately collect paper, plastic, food products, electrical appliances, light bulbs, batteries, metal products and glass. The collected garbage is further recycled, melted down, reused, or used for the production of materials, fertilizers and biogas. At the same time, hazardous waste, electronics and chemicals are collected by special transport, while bulk waste is taken by Swedes themselves to special recycling centers on the outskirts of cities.

In turn, in Germany, the separate method of household waste disposal was introduced back in 1991 as part of the implementation of a national program called "Duales System Deutschland GmbH". The result of the thirty-year period of its implementation is that now up to 90% of all German households carry out separate waste collection, while no sanctions in case of non-compliance with its rules are provided by the current legislation. Every year, every German resident receives a special letter with detailed information on solid waste disposal sites and collection days for each type of waste. The circular nature of solid waste management in Germany is also manifested in the transfer of steam generated from the incineration of garbage to power plants, which brought

the share of energy produced in this way in Berlin alone to 12% of the total needs of German households. Another global leader in the implementation of responsible consumption models through the utilization and recycling of garbage is Switzerland, where very sophisticated recycling systems have been created as a result of the more than doubling of household waste over the last fifty years. By doing away with landfills back in the early 2000s, Switzerland has ensured that now more than 50% of all garbage is recycled and the rest is incinerated, with the resulting thermal energy transferred to heat homes and generate electricity. The country now leads the world in recycling of paper into new paper products (60%) and in recycling of glass containers (90%), plastic bottles (82%), and tin and aluminum bottles. At the same time, separate recycling of PET bottles, old electrical appliances, household appliances, daylight bulbs, cans, residual vegetable and machine oil, construction and other waste allows to ensure high environmental friendliness of the household waste utilization process.

In the period from 1995 to 2020, the European Union countries for 15 years have shown a significant increase in waste management by recycling (from 23 to 67 million tons, or from 11.6 to 29.8% of total recycling) and composting (from 14 to 40 million tons and from 7.1 to 17.8%) against a twofold drop in landfill disposal (from 121 to 52 million tons and from 61.1 to 23.1%, respectively).

Such a trend testifies not only to a significant increase in the level of "greening" of the waste management system in the states of this integration grouping, but also to a huge economic and social effect of the implemented measures. This is confirmed, in particular, by the calculations of the Waste to Wealth program of the American non-profit organization Institute for Local Self-Reliance, according to which sorting and recycling of garbage per one ton provides ten times more jobs with a high level of remuneration com-pared to landfills or waste incineration. For example, the paper recycling and plastics sector provides 60 times more jobs per ton of output compared to landfills. In the development of a green ecosystem based on responsible consumption, it is difficult to overestimate the importance of such a tool as the increasing orientation of economic actors towards the consumption of environmentally friendly goods and healthy food. Thus, it is thanks to the promotion of healthy lifestyles that in recent decades global consumers have been actively developing a culture of buying this group of products. Let's turn to the figures: according to a study by the Stern Center for Sustainable Business at New York University in the period 2013-2018, the number of products sold as eco-friendly grew 5.6 times faster compared to the non-eco-friendly product group [65]. The capitalization of the global market for low-carbon environmental goods and services is now estimated at $4.2 trillion, and the market for eco-friendly furniture - $35.2 billion in 2019 with a projected growth to more than 50 billion in 2027. According to a recent report by the Economist Intelligence Unit commissioned by the World Wildlife Fund, the popularity of online searches for eco-friendly products has grown by 71% in the last five years alone, not falling even during the COVID-19 pandemic.

As consumer behavior shifts towards increased consumption of environmentally friendly products and foods, the next, higher level of responsible consumption becomes a preference for purchasing those goods and services produced by environmentally oriented companies. Thus, in the context of a huge surplus of goods on the global market and their deep differentiation, both price and non-price factors influence consumers' choice of a particular brand. Among the latter, the business reputation of manufacturing companies and their declared values play a key role, which has already prompted a number of global brands to intensify their actions to position themselves as environmentally oriented companies. For example, back in 2009, Xerox reported savings of around $400 million and Zara reported savings of €500 million through ecodesign of its products, which minimized environmental impact over the life cycle of manufactured goods. For its part, Puma Corporation said that 94% of the environmental impact of its manufactured products occurs along all links in its supply chains. As for global consumers, according to a recent study by EU experts, which assessed the impact of the COVID-19 pandemic on the global consumer system, at least 50%

of consumers around the world will increasingly pay attention to the impact of their products on society in the coming years. According to a survey, 95% of Americans between the ages of 25 and 40 are currently focusing their investments on business activities that can improve the ecological state of the environment. At the same time, one more important circumstance should not be overlooked: the growing demands of global consumers to the environmental characteristics of products offered on the market from year to year actualize for all participants of international trade operations the issues related to the greening of production, sales, investment, credit, financial and marketing activities. This requires, first of all, a radical restructuring of the existing systems of interaction with suppliers of semi-finished products, raw materials and material resources for their compliance with the established environmental standards, etc., causing, at the same time, a certain increase in consumer prices for environmentally friendly products. At the same time, global manufacturers in their economic activities should move to the introduction of business models of circular economy tested in the world practice, which have been confirming their high ecological efficiency for years and stimulate the processes of ecologization of the system of consumer relations. They are represented, in particular, by the construction of circular (cyclical) value chains, which involve the complete replacement of limited resources with renewable ones; the recovery and recycling of natural resources through the use of technological innovations; the extension of the life cycle of manufactured consumer goods through repair and restoration work, as well as the implementation of remarketing activities; the provision of joint access to consumer goods or assets with a low utilization rate; and the use of renewable resources. As we can see, all these measures fully fit into the fundamental principles of circular economy, which are based on the paradigm of "3R" - Reduce, Reuse, Recycle, namely: ecological optimization of the production process itself; joint and reuse of produced goods and materials while preserving their intrinsic value for subsequent consumers in the supply chain. Thus, according to the estimates of reputable international experts, the implementation of measures for the reuse of materials in production processes and waste prevention for companies in the European Union alone can provide savings in transaction costs of about 600 billion euros per year and reduce greenhouse gas emissions by 2.4%. The deep industrial symbiosis of industrial asset sharing among economic actors as an integral component of the circular economy, as well as digital technologies and information data for optimizing production processes and supply chains through the use of renewable energy sources and virtualization tools, also deserve special attention.

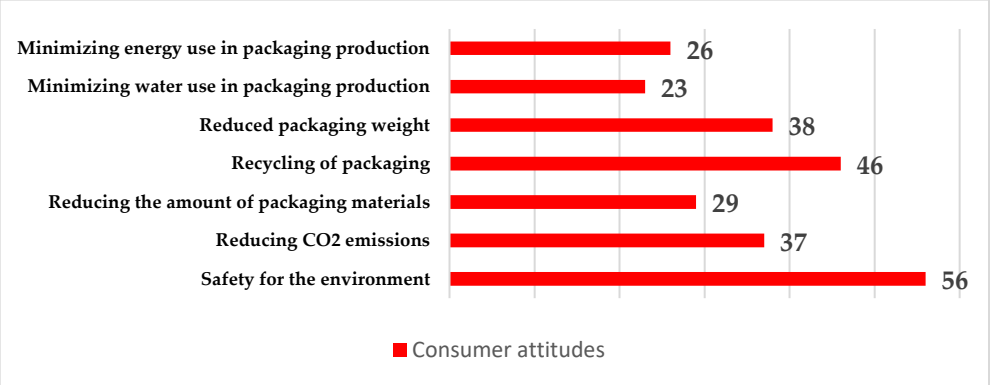


Figure 4: *Consumer attitudes towards different sustainability factors of packaging materials of packaging materials, %*

In the comprehensive characterization of the tools for building a model of responsible consumption in global coordinates, special attention should be paid to such a direction as consumers' refusal from disposable packaging of purchased goods in favor of its economical variants, as well as reusable and environmentally friendly packaging. This is primarily a refusal to buy prepackaged

products and reuse paper and plastic bags and cans, which not only encourages consumers to switch to more economical consumption, but also encourages manufacturers to produce products that are as durable and long-lasting as possible and can last for more cycles. According to the Grocer Vision White Paper and PwC's research, about 33% of consumers are already prepared to radically change their loyalty to a brand if the packaging of its products does not comply with the principles of sustainable development.

At the same time, consumers, being informed about the threat of single-use plastic packaging to the environment, are increasingly demanding environmentally friendly packaging materials from manufacturers, reducing greenhouse gas emissions, reducing the quantity and weight of packaging, as well as providing opportunities for recycling and minimizing the use of water and energy in the production of packaging materials (Fig. 4).

This has already led, in particular, to the dynamic development of the global organic food packaging market, which was capitalized at $196.3 billion in 2021 and will reach $280.1 billion by 2026 at an annual growth rate of 7.3%. The exceptional importance of responsible consumer attitude to the issue of packaging of purchased goods is evidenced, in particular, by the fact that today its share in the total volume of generated solid waste in Europe is 36%, and the world economy annually loses from 80 to 120 billion dollars on packaging materials suitable for reuse or recycling.

Currently, no more than 21% of plastic waste is recycled or utilized, while the remaining 79% accumulates in landfills and in the environment. At the same time, about 3% of the plastic produced annually in the world (which is 8-12 million tons) gets into the world's oceans, and only in 2020 its plastic pollution has increased by another 4-6 thousand tons. Every year plastic kills about 100 thousand marine mammals and turtles and more than 1 million sea birds, the scale of destruction of fish, invertebrates and other animals cannot be counted. Thus, reducing waste in the packaging of purchased goods prevents excessive resource extraction and littering, and significantly reduces energy consumption, waste generation and greenhouse gas emissions. As for reusable packaging, current economic practice shows that it avoids greenhouse gas emissions associated with the production of new types of disposable packaging.

V. Conclusion

Foreign trade activities of economic entities of different nationality materialize the core of global exchange processes, embodying the whole "palette" of cross-border movement of the results of the work of national production complexes, their sale and consumption at the international level on the basis of free competition, freedom of commodity and monetary exchange. Despite all the positive consequences of international trade relations for the national economic interests of states, the steady increase in their scale and dynamic structural diversification against the background of the elimination of cross-border barriers to the movement of investment, credit and financial capital have a natural consequence of a rapid increase in many types of environmental pollution and a large-scale increase in global environmental losses. In international trade practice, the greatest efficiency is demonstrated today by the instruments of international trade in greenhouse gas emission quotas (UN-certified carbon credits, operations of regulated and voluntary carbon markets, carbon offsets, carbon auctions, spot and futures contracts for carbon, tokenized emission quotas), environmental standardization, certification, labeling and licensing. However, a huge number of problems that have accumulated in recent decades in the greening of world trade and international competition of environmentally "clean" and "dirty" products, due to the economic, ideological and political inability of many states and regions of the world to implement large-scale and allencompassing measures to "green" their own industrial complexes.

The key inherent features of the development of the global model of responsible consumption are supranational standardization of the prevailing models of environmentallyoriented personal

and production consumption, formation of international green consumption funds; customization of consumption as a tool for the development of social initiatives; dynamic diversification of consumer green needs of tangible and intangible nature; growth of the share of green consumption in the national incomes of different countries; and the increase in the share of green consumption in the national income of different countries. The steadily growing segment of responsible consumers has a sig-nificant impact on the transformation of consumer relations, thus forming qualitatively new sources of competitive development of business structures and stimulating the processes of forming a global culture of consumption based on responsibility and reasonable sufficiency.

Business practices of corporate environmental responsibility play a significant role in the development of the global green ecosystem to achieve sustainable economic development. One of the components of the implementation of corporate environmental responsibility mechanisms by business structures is their compliance with environmental standards, which, on the one hand, are developed by governments and international organizations, and on the other hand, are initiated by companies themselves as part of the implementation of corporate environmental management strategies. All standards, despite their great diversity and uniqueness, are based on systematic approaches to development and implementation in real business practice, as well as high requirements to the quality and relevance of the information provided by corporations.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE ROLE OF SOCIAL WORK IN THE FORMATION OF HUMAN CAPITAL AND THE PROMOTION OF SUSTAINABLE ECONOMIC GROWTH IN REGIONS

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Abstract

In an era marked by pressing challenges such as climate change, environmental degradation, and social inequality, the influence of the human factor on the economic growth of regions and countries has become increasingly significant. Human capital, which includes not only education and skills but also health, creativity, and social cohesion, plays a pivotal role in determining the trajectory of economic development. This paper examines the multifaceted relationship between the human factor and economic growth within the context of sustainable development, emphasizing the necessity for a holistic approach that integrates economic, social, and environmental dimensions. Human capital is a critical driver of innovation and productivity, influencing the competitiveness of economies at both regional and national levels. Regions that invest in education, vocational training, and health care are better positioned to foster skilled workforces capable of adapting to the demands of a rapidly changing global economy. Furthermore, social factors such as trust, community engagement, and cultural values significantly affect the effectiveness of economic policies and initiatives aimed at sustainable development. This study analyzes various case studies from diverse regions, illustrating how the human factor has led to differing economic outcomes in the context of sustainable development. For example, regions that prioritize inclusive education and promote gender equality tend to experience higher levels of innovation and economic resilience. In contrast, areas with limited access to education and healthcare often struggle with persistent poverty and underdevelopment. The paper also addresses the challenges and barriers that hinder the effective utilization of human capital, such as socioeconomic disparities, inadequate infrastructure, and a lack of supportive policies. It highlights the importance of creating environments that empower individuals and communities to contribute to sustainable economic growth.

Keywords: regional development, social aspects, ecological sustainability, policy recommendations, education, healthcare, community engagement, gender equality, socioeconomic disparities, inclusive development.

I. Introduction

The relationship between the human factor and economic growth has garnered increasing attention, particularly in the context of sustainable development. Human capital—encompassing education, skills, health, and social capital—plays a pivotal role in determining a region's or country's ability to achieve economic growth while maintaining ecological balance and social equity.

In an era where environmental concerns and social inequalities are at the forefront of global discourse, understanding how human factors contribute to sustainable development is essential.

Regions and countries that prioritize the development of human capital tend to experience more robust economic growth. A skilled and educated workforce not only drives innovation and productivity but also fosters adaptability in response to environmental changes and economic fluctuations. Moreover, the integration of sustainable practices into economic activities hinges on the willingness and ability of individuals and communities to embrace and implement these practices.

The influence of the human factor on economic growth manifests through various channels. First, education equips individuals with the necessary skills to engage in higher-value economic activities, leading to increased productivity. Second, health and well-being contribute to a more capable workforce, reducing absenteeism and enhancing performance. Third, social capital—characterized by networks, trust, and norms—facilitates collaboration and the sharing of knowledge, further driving innovation and growth.

However, the interplay between the human factor and sustainable development is not without challenges. Issues such as inequality in access to education and healthcare, migration, and demographic changes can hinder the potential benefits of human capital. Therefore, policies aimed at fostering human capital must also consider social inclusivity and environmental sustainability to create a holistic approach to economic growth.

In summary, recognizing and leveraging the human factor is critical for achieving sustainable economic growth. By investing in education, health, and social cohesion, regions and countries can enhance their resilience and adaptability, paving the way for a more sustainable future. This paper will explore the various dimensions of the human factor, its impact on economic growth, and the implications for sustainable development, providing a comprehensive understanding of this crucial relationship.

II. Methods

The study of the influence of the human factor on the economic growth of regions and countries in the context of sustainable development requires a comprehensive and interdisciplinary approach. The main methods used to study this problem are presented below.

1. Econometric modeling

One of the most common methods is econometric modeling, which allows you to assess the impact of various factors on economic growth. In the context of the human factor, models can be used that include the following variables:

Education level.

Life expectancy.

Workforce skill level.

Human Development Index (HDI).

Fertility and mortality rates.

Econometric methods such as regressions, time series, and panel data help identify the relationship between human capital and economic growth.

2. Qualitative methods (interviews, focus groups)

Qualitative methods can be used to obtain in-depth data on the impact of the human factor on economic development. Interviews with experts in the field of economics, education, employment, or sustainable development provide information on practical aspects and barriers. Focus groups help to identify the opinions and expectations of different social groups.

3. Analysis of human capital indicators

Using human capital indicators such as:

Human Development Index (HDI).

Education index.

Gender equality index.

Income distribution.

Comparison of these indices with indicators of economic growth of a region or country allows for a detailed analysis of the relationship between human capital development and economic efficiency.

III. Results

The state may possess natural, technological, and financial resources, but all of this is insignificant without a highly qualified workforce and a high level of human development. In today's rapidly changing world, the importance of human capital is continually increasing. "In the era of digitalization and transformation of production processes, human capital is becoming the foundation for the development of the economy of any country" [12].

In a broad sense, human capital encompasses the abilities, knowledge, skills, intellect, and health of individuals utilized in production processes and to generate income for families and the nation as a whole.

The following types of human capital are identified in the economy:

1. **National human capital** refers to a portion of national wealth that includes intellectual, physical, and labor capabilities that aid in the economic development of the country.
2. **Organizational human capital** consists of the knowledge, skills, intellectual and professional abilities, as well as the physical and psychological well-being of personnel, utilized to achieve high performance in a specific organization.
3. **Individual human capital** comprises the knowledge, skills, health, and abilities of an individual that affect their standard of living and income.

The human capital of each country can be measured. Since 2018, the World Bank (WB) has been compiling the Human Capital Index (HCI) rankings by country. The HCI can help countries analyze problem areas in their socio-economic policies and assess their readiness to transition to a sustainable development model based on the growth of human capital.

The HCI is calculated based on three components:

- Survival;
- School life expectancy adjusted for learning outcomes;
- Health status.

The United Nations (UN) employs a different indicator to assess human development—the Human Development Index (HDI), which is a composite measure reflecting an individual's ability to lead a long and healthy life, gain knowledge, and achieve a decent standard of living.

The following factors are considered when calculating the index: health and longevity, access to education, and a decent standard of living.

The index categorizes countries into four groups based on their level of human development:

- Very high value—an index of at least 0.800;
- High value—an index of 0.700-0.799;
- Medium value—an index of 0.550-0.699;
- Low value—an index below 0.550.

In 2020, the HCI included data on health and education from 174 countries, representing 98% of the global population. According to the World Bank, Russia ranks 41st in the world HCI rankings, with an index of 0.68, or 68%. This indicates that a child born in Russia today can achieve 68% of the productivity of an adult with complete education and good health in the future. For instance, Russia's education indicators surpass those of many higher-income countries, but its health indicators fall short of the global average. The top-ranked countries in the index are Singapore (88%), Hong Kong (81%), and Japan (80%).

Furthermore, as demonstrated in other research, there is a strong positive correlation between

subjective well-being (SWB) and the Environmental Protection Indicator (which covers a wide range of issues such as biodiversity, ecosystems, climate, energy, air and water pollution, agriculture, and sanitation). These findings suggest that well-being is linked to the long-term outcomes of environmental policies, even if it is not necessarily positively correlated with the short-term efforts required by these policies.

The challenge for policymakers is to overcome short-term trade-offs by decoupling improvements in human well-being from the consumption of natural resources and greenhouse gas emissions. A recent OECD report addresses this challenge by proposing climate change mitigation through a well-being perspective, placing people at the center of climate action. The countries identified in our analysis, that perform well on SDG 12 and SDG 13 while also achieving high levels of well-being suggest there may be pathways to enhancing well-being without compromising environmental sustainability. These countries include a mix of large and small nations. For instance, Germany has heavily invested in renewable energy infrastructure, creating 'green jobs' while simultaneously reducing emissions. The combination of carbon taxes, incentives for renewable energy, and ambitious social policies has enabled Nordic countries to transition away from fossil fuels without burdening low-income households with higher energy costs. Similarly, Costa Rica ranks among the top nations for investment in renewable energy relative to GDP and has committed to achieving carbon neutrality starting in 2021. It offers an alternative model for developing nations to avoid the carbon-intensive development path of the West.

According to the World Bank, human capital constitutes 64% of the world's wealth, estimated at $1,152 trillion. This highlights that human intelligence, health, and the development of professional and creative abilities—along with education—are becoming crucial resources, comparable to oil, gas, innovative technologies, and other assets of the national economy. A robust level of human capital fosters increased income, well-being, and quality of life not only for individuals but for the entire country. Therefore, "national programs should primarily focus on enhancing the education system, healthcare, and the social sector".

The contemporary world demands modern solutions. Innovations are now integral to every sector of economic activity. Currently, the advancement of high-tech industries represents a key competitive advantage for nations. According to Rosstat, there has been an increase in the contribution of these sectors to total GDP over the past decade. Consequently, producing high-tech products necessitates highly qualified professionals. As technological innovations expand within the country, the demand for human capital is set to rise accordingly.

Human development as a factor in ensuring the economic security of the EAEU countries. The Eurasian Economic Union (EAEU) is a growing integration association in the post-Soviet region, aimed at implementing a unified economic policy and facilitating the free movement of goods, services, capital, and labor resources [8]. One of its founding goals is the comprehensive development of modernization, cooperation, and enhancing the competitiveness of the member countries' economies within the global context. In today's environment, human potential has become a critical factor in ensuring the economic security of the EAEU.

An examination of population data from the EAEU countries over the last fifteen years indicates a notable rise in this metric. From the analysis of the data, several conclusions emerge. At the start of the study period (2005), Russia had the largest population, followed by Kazakhstan, Kyrgyzstan, and Belarus. Throughout this time, the population trends of these countries diverged. For instance, Russia exhibited relative stability, remaining close to its initial population level by 2020. In contrast, Kazakhstan showed positive growth, significantly increasing its population by 2020. Kyrgyzstan, however, maintained relative stability, with its population level staying near the initial figure.

Overall, the EAEU countries have experienced population growth over the past fifteen years, reaching notable increases by 2020. These developments underscore the significance of demographic factors in analyzing the region's socio-economic landscape and highlight the necessity of considering population trends when crafting development strategies.

Regarding age demographics, Russia, Belarus, and Armenia are characterized by a relatively low percentage of minors and a considerable elderly population, indicating that these nations are facing the challenges of population aging. This trend may diminish their economic and military influence, necessitating primary focus on ensuring the effectiveness of pension and healthcare systems, as the overall demographic burden on the working-age population is projected to nearly double by mid-century.

Thus, human potential plays a crucial role in all aspects of economic security, including production, food, foreign economic, and socio-demographic security, among others. Key destabilizing factors affecting human potential and economic security in the EAEU countries include significant disparities in human development and socio-demographic progress; gender inequality; increasing income disparities; and declining quality of life and well-being. Furthermore, Russia, Belarus, and Armenia continue to face issues of depopulation and aging, which directly result in a loss of labor resources.

Given the considerable challenges surrounding the levels and synchronicity of human potential development across EAEU nations, it is essential to reevaluate approaches to intra-integration interactions concerning the formation, development, implementation, and preservation of human potential. Strengthening cooperation should be prioritized, focusing on the following key areas:

1. Rapid advancement of digital transformation across all areas of human activity and society as a whole.
2. Enhancing collaboration in healthcare.
3. Emphasizing environmental sustainability in the creation of new joint projects aimed at achieving sustainable human development.
4. Boosting cooperation in education, science, and innovation.

Addressing these priorities and implementing them will enable the development of human potential, thereby ensuring a sufficient level of economic security for both individual EAEU countries and the entire Union.

Furthermore, Russia's national goals and strategic objectives for development until 2024 are supported by the national projects established in various sectors, including demography, healthcare, education, housing and urban development, ecology, safe and high-quality roads, labor productivity and employment, science, digital economy, culture, entrepreneurship, and more. These projects align with the principles outlined in the human potential development concept.

The Strategy of Economic Security of the Russian Federation identifies the development of human potential and the challenge of enhancing its quality as critical areas and significant threats to economic security in the social sphere.

The Russian government places particular emphasis on several key areas to promote the development of human potential:

1. **Education**: The Government of the Russian Federation is investing in the education system, focusing on improving the quality of primary and secondary education as well as vocational training. Additionally, there is increased funding for higher education and a push for greater international collaboration. Federal Law No. 273 establishes fundamental principles and regulations governing education in Russia, covering primary, secondary, and higher education, alongside provisions for preschool, vocational, and adult education.

2. **Healthcare**: The Government of the Russian Federation allocates funds to enhance the healthcare system, concentrating on improving medical care quality, increasing access to services, and encouraging healthy lifestyles among citizens. The government has also implemented measures to combat infectious diseases. Federal Law No. 323 outlines the fundamental principles and regulations for the healthcare system in Russia, including the organization of medical care, funding for services, and patient rights protection.

3. **Science and Technology**: The government invests in advancing science and technology, particularly focusing on fostering innovation, technology transfer, and the growth of high-tech

industries. Funding for research and development is being increased, along with efforts to enhance international cooperation in this field. Federal Law No. 127 lays down the basic principles and regulations for science and innovation development in Russia, covering research funding, intellectual property protection, and the commercialization of scientific findings.

4. **Social Services**: The Russian government is committed to enhancing social services, prioritizing affordable housing, social security benefits, and assistance for those in need. Additionally, the government promotes cultural development and the preservation of Russia's cultural heritage. Federal Law No. 442 defines the key principles and regulations for social service provision in Russia, focusing on support for vulnerable groups, including the disabled and elderly, as well as affordable housing and social security.

5. **Regional Development**: The Russian government implements policies aimed at stimulating economic growth across its regions, particularly in job creation, support for small and medium-sized enterprises, and fostering regional cooperation.

In 2023, state initiatives for developing human potential in Russia will concentrate on these critical areas while also encouraging broader international cooperation.

IV. Discussion

I. Subsection One

Russia has established a comprehensive framework for its development until 2024, centered around national projects in key sectors such as demography, healthcare, education, and more. This multi-faceted approach reflects the government’s recognition of the interconnection between human potential and economic security, highlighting the importance of investing in various areas to foster sustainable growth and resilience.

Human Potential Development

The emphasis on human potential development is particularly relevant in today’s rapidly changing global landscape. By prioritizing education, healthcare, science and technology, social services, and regional development, Russia aims to enhance its human capital, which is essential for economic advancement and social stability. The government's commitment to these areas not only seeks to improve individual quality of life but also to bolster national competitiveness in an increasingly interconnected world.

Key Areas of Focus

1. Education: Investments in education are crucial for equipping the workforce with the necessary skills to meet the demands of the modern economy. By improving the quality of primary, secondary, and vocational education, the government is laying the foundation for a skilled labor force that can adapt to technological advancements. The focus on higher education and international collaboration also suggests a strategic vision to foster innovation and attract global talent.

2. Healthcare: The enhancement of the healthcare system is vital for ensuring a healthy population capable of contributing to the economy. By improving access to medical services and promoting healthy lifestyles, the government addresses both immediate health concerns and long-term demographic challenges, such as population aging. Effective healthcare policies can significantly impact productivity and overall economic performance.

3. Science and Technology: Investing in science and technology is essential for driving innovation and economic diversification. By promoting research and development and protecting intellectual property, the government aims to create an environment conducive to technological advancements. This focus not only strengthens domestic industries but also positions Russia as a competitive player in the global market.

4. Social Services: Providing robust social services is integral to promoting social cohesion and stability. By ensuring affordable housing and support for vulnerable populations, the government addresses critical social needs that can otherwise hinder economic development. The emphasis on cultural preservation also reflects an understanding of the importance of social identity in fostering national pride and unity.

5. Regional Development: Stimulating economic growth in various regions is crucial for balanced national development. By supporting small and medium-sized enterprises and fostering regional cooperation, the government seeks to reduce disparities between urban and rural areas. This approach not only enhances local economies but also contributes to overall national resilience.

Challenges and Considerations

While the strategic objectives set forth by the Russian government are ambitious, several challenges may impede their successful implementation:

- Resource Allocation: Ensuring adequate funding and resources for these initiatives may pose difficulties, especially in times of economic uncertainty or budget constraints. Prioritizing investments will be crucial for achieving desired outcomes.
- Social Inequalities: Addressing social inequalities and ensuring that all populations benefit from development efforts will be essential. Failing to do so could lead to social unrest and undermine national unity.
- International Collaboration: Strengthening international cooperation can bring about opportunities for knowledge exchange and technological advancements. However, geopolitical tensions may hinder collaborative efforts, particularly in science and technology.
- Demographic Trends: Russia faces demographic challenges, including an aging population and declining birth rates. Addressing these trends will require comprehensive policies that encompass family support, immigration, and workforce development.

The development of human potential is a vital component of Russia's strategic vision for the future. By focusing on education, healthcare, science and technology, social services, and regional development, the government aims to create a resilient and dynamic society capable of navigating the complexities of the modern world. However, addressing the inherent challenges and ensuring inclusive growth will be key to realizing these ambitious goals. As Russia moves forward, a holistic approach that considers the interplay of various factors will be essential in fostering sustainable human potential development and economic security.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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FINANCING SUSTAINABLE DEVELOPMENT: RISKS AND GROWTH POTENTIAL

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Abstract

The green economy, focused on sustainable development and reducing environmental impacts, has become an increasingly attractive area for investment. This paper provides an in-depth analysis of the opportunities and risks associated with investing in the green economy. Key sectors examined include renewable energy (solar, wind, and bioenergy), sustainable agriculture, electric vehicles, energy efficiency technologies, waste management, and carbon capture solutions. The analysis explores how these sectors are benefiting from global trends such as climate change mitigation policies, corporate commitments to carbon neutrality, technological innovations, and growing consumer demand for sustainable products and services.On the opportunity side, investors stand to gain from significant market growth, government incentives, and regulatory frameworks such as carbon pricing and renewable energy targets. For example, renewable energy is becoming more cost-competitive with fossil fuels, and electric vehicle sales are projected to rise as countries phase out internal combustion engines. Green bonds and environmental, social, and governance (ESG) criteria have also opened new financing channels for green projects, providing investors with diversified portfolios that align financial performance with positive environmental impact.

Keywords: green technologies, sustainable agriculture, electric vehicles, carbon capture, regulatory risks, green bonds, sustainability, technological innovation, investment risks, capital intensity, policy uncertainty, resource scarcity

I. Introduction

The transition to a "green" economy and its models, global divestments in the world (redistribution of investments from non-ecological and high-carbon sectors to low-carbon sectors), support for new technologies, "green" financing, etc. can significantly increase financial support for the greening of the economy. A significant reserve for investments in the "green" economy can be the elimination of various types of subsidies and grants for nature-exploiting sectors. For example, the "brown" economy relies to a significant extent on traditional types of fuel. The total amount of subsidies for the production and consumption of fossil fuels in the world has exceeded 400 billion US dollars per year, which hinders the improvement of energy efficiency and the wider use of renewable energy sources (see Section V). There are many obstacles to the formation of a "green" economy, including those associated with widespread stereotypes. Thus, perhaps the most widespread is the myth of the existence of an inevitable contradiction between environmental sustainability and economic progress. There is now ample evidence that greening the economy does

not hinder the creation of wealth or jobs, and that investment in many green sectors is a source of increased financial well-being and employment. However, the transition to a green economy requires the creation of new conditions, and this requires large-scale and urgent action by governments in all countries of the world. It is also often said that a green economy is a luxury that only rich countries can afford, or, even worse, that it is something that developed countries impose on developing countries so that the latter will remain poor forever. Modern research, including that of international organizations, provides many examples of the transition to a green economy in various sectors of the developing world that refute this idea - examples that deserve to be repeated in other parts of the world. Research also convincingly shows that greening the economy may not be a brake, but a new stimulator of development. The transition to a green economy is impossible without the economic benefits of such a course for public and private enterprises. It is difficult to make the economy "green" using only legal regulators and administrative measures, as shown by the global experience of the last decades. Among the main reasons for the negative impact of the economy on the environment, one can note the latency (secrecy) of a large number of environmental problems; the traditional market simply does not see them. The modern economy cannot accurately determine the benefits, damages and prices for the environment, "digitize" and economically present environmental problems for the government, business and society. To make greening profitable, at least three levers are needed: 1) stimulation of greening of the economy.

II. Methods

The European Investment Bank has identified three main reasons for the need to transition to a circular economy:

1. Resource constraints. Global demand for resources is increasing rapidly, leading to a growing deficit of critical raw materials and water.

2. Technological development. The introduction of new technologies enables the creation and implementation of circular economy business models. Without technological advancements and innovative approaches, it would be impossible to recycle, replace, and reuse resources, or to leverage new IT technologies.

3. Socioeconomic development. Circular models play a crucial role in the context of increasing urbanization. Urban areas are well-positioned to develop, implement, and maintain systems that can efficiently collect and return goods, materials, and other resources, leading to cost savings.

A fourth reason can be added—**environmental considerations**. Unused production and consumption waste occupies significant land areas, while pollutants migrate into the air, groundwater, and surface water, causing harm to public health, agriculture, and natural resources. These negative externalities lead to substantial environmental damage, including socioeconomic impacts. The circular economy must internalize these externalities and aim to minimize all forms of harm.

Potential future resource constraints due to rising global demand are also highlighted in OECD forecasts. Over the past few decades, the demand for resources has surged due to rapid industrialization in emerging economies and the growing needs of developed countries. Since 1980, global consumption of various materials has more than doubled. This trend is expected to continue, driven by population growth—from 7 billion people today to approximately 10 billion by 2060—accompanied by rising incomes and demand. According to OECD projections, if current trends persist, global use of material resources will rise from 79 billion tonnes in 2011 to 167 billion tonnes by 2060. Demand for metals, in particular, is forecast to increase from 8 billion tonnes to 20 billion tonnes by 2060, or 2.5 times.

The goal of the circular economy is to establish closed ecological and economic cycles, making the most efficient use of incoming raw materials in production processes, minimizing waste generation, and integrating accumulated waste back into economic activity. This approach aims to replicate natural cycles through environmentally compatible technologies across industries and

responsible consumption models, forming analogs of ecosystems. The biosphere is a closed system where all elements are interconnected, and no waste is generated. In contrast, the modern technogenic economy operates as a linear, open system, where the production of a relatively small final product requires vast resource consumption and generates large amounts of waste. Currently, only 2-6% of the total volume of extracted natural matter becomes a final product, with the remainder becoming waste (e.g., tailings, slag, wastewater, etc.).

Humanity is familiar with relatively closed economic systems, such as traditional agriculture. In this system, waste is minimized: agriculture supplies livestock with feed, including byproducts from crops like grains, sunflower, and sugar beet, while livestock, in turn, provides agriculture with organic fertilizers that enhance soil fertility. This creates a more or less closed cycle of materials, resembling natural ecosystems.

III. Results

One approach to assessing the effectiveness of a circular economy can be the product recycling rate. It can be determined using the following formula:

$r = Rr / Ra$,

where r is the product recycling rate, Rr is the volume of recycled waste, Ra is the total volume of waste.

Traditionally, materials such as glass, paper, cardboard, and aluminum (e.g. packaging and containers) are recycled around the world. In some countries, the recycling rate of these materials exceeds 0.9. However, in Russia, this figure is significantly lower.

Assessing the effectiveness of the transition to a circular economy and the costs associated with it is an important issue. The benefits of transitioning to such a model include the recycling of resources, energy production from waste, and other forms of reducing environmental impact. Although the introduction of low-waste technologies may be costly, taking external costs into account can significantly increase overall efficiency.

Table 1. Externalities of the development of the circular economy

Positive Externalities	Negative Externalities
Reduction in the extraction and use of renewable and non-renewable natural resources	Additional consumption of resources and energy during recycling of products and waste
Reduction of negative environmental and health impacts from waste, including decreased landfill areas	Decrease in revenues for natural resource exploitation sectors
Development of resource-saving technologies	Reduction in employment in natural resource sectors
Creation of additional jobs	Potential negative health impacts from improper waste disposal (e.g., low-tech waste incineration)

Waste and pollution have a significant negative impact on human health and lead to environmental degradation. Therefore, choosing "cheap" solutions that require minimal initial investment can result in large social losses. For example, an important problem is the disposal of solid municipal waste. If it is solved using simplified incineration technologies, this can lead to significant harm to public health due to emissions of dioxins, particulate matter and other harmful substances. Positive and negative externalities (external effects) of the development of a circular economy are presented in Table 1. There may be a certain symmetry between positive and negative

externalities. For example, a reduction in the extraction and use of renewable and non-renewable natural resources, which reduces the burden on the environment, can simultaneously lead to a decrease in income and employment in sectors engaged in the exploitation of natural resources.

IV. Discussion

I. Subsection One

Limited resources and investments in the economy necessitate prioritizing certain areas in the transition toward sustainable development and the formulation of environmental and economic policy. A common demand today is for a substantial increase in environmental protection expenditures. Typically, these costs are compared to total investments in the economy, gross domestic product, or benchmarked against those of developed countries. However, environmental protection costs are often narrowly defined, referring only to direct measures such as treatment facilities, filters, reclamation projects, and similar initiatives. This approach is incomplete and flawed.

Investments should be directed where they will yield the greatest environmental and economic returns and prove most effective. So, what should be considered environmental protection costs in this context? In a resource-intensive, raw material-based economy, priority should be given to structural and technological transformation, focusing on the development of low-emission technologies. This approach would help withdraw large volumes of inefficiently used natural resources from active circulation and alleviate the environmental burden.

To frame it differently, current investments should be divided between addressing immediate issues (i.e., direct environmental protection measures) and ensuring long-term sustainability (mainly through structural and technological shifts, such as adopting best available technologies—BAT). By investing in the resource-saving structural and technological transformation of the economy, making it more sustainable, and reducing its natural resource intensity, we can simultaneously minimize the costs of addressing the negative environmental impacts of industrial economic development.

It is challenging to justify the need for simply increasing environmental protection costs, as financial resources are always limited in the economy. Instead, it is crucial to demonstrate the high economic efficiency of environmentally-oriented measures, even if these benefits are not immediately obvious. This is achievable when accounting for the true economic value of nature and ecosystem services (as discussed in Section III). In a transforming economy, unlike in developed economies, there is a significant opportunity to capture substantial environmental benefits ("ecological cream") through purely economic structural projects and programs.

The primary focus should now be on economic policies that offer a "double win"—policies that generate both economic gains and significant environmental benefits. These include modernization, the spread of innovation, energy conservation, and the development of high-tech, infrastructure, and manufacturing industries. In other words, economic measures should simultaneously produce associated positive effects in the ecological sphere.

The global green economy, encompassing markets focused on climate and environmental solutions, has seen substantial growth over the last decade, presenting a compelling investment opportunity. In 2023, it rebounded strongly after a decline in 2022, with its market capitalization reaching $7.2 trillion by Q1 2024. Despite its recovery, challenges remain, including issues of overcapacity and trade barriers in renewable energy and electric vehicle (EV) manufacturing. Downsizing at several major U.S. green companies in early 2024 caused the green economy's share of the overall market to drop slightly from 8.9% at the end of 2023 to 8.6% in early 2024.

Despite these hurdles, the green economy continues to grow, with a long-term compound annual growth rate (CAGR) of 13.8%, outpacing the broader stock market. If treated as an independent sector, the green economy would have ranked as the second-best-performing industry over the last decade, only surpassed by the technology sector. For example, in 2023, the FTSE

Environmental Opportunities All Share (EOAS) Index, a key measure of green economy performance, rose by 32%, compared to the 22% rise in the broader FTSE Global All Cap Index. Since its inception in 2008 through March 2024, the EOAS has outperformed the benchmark index by 82%.

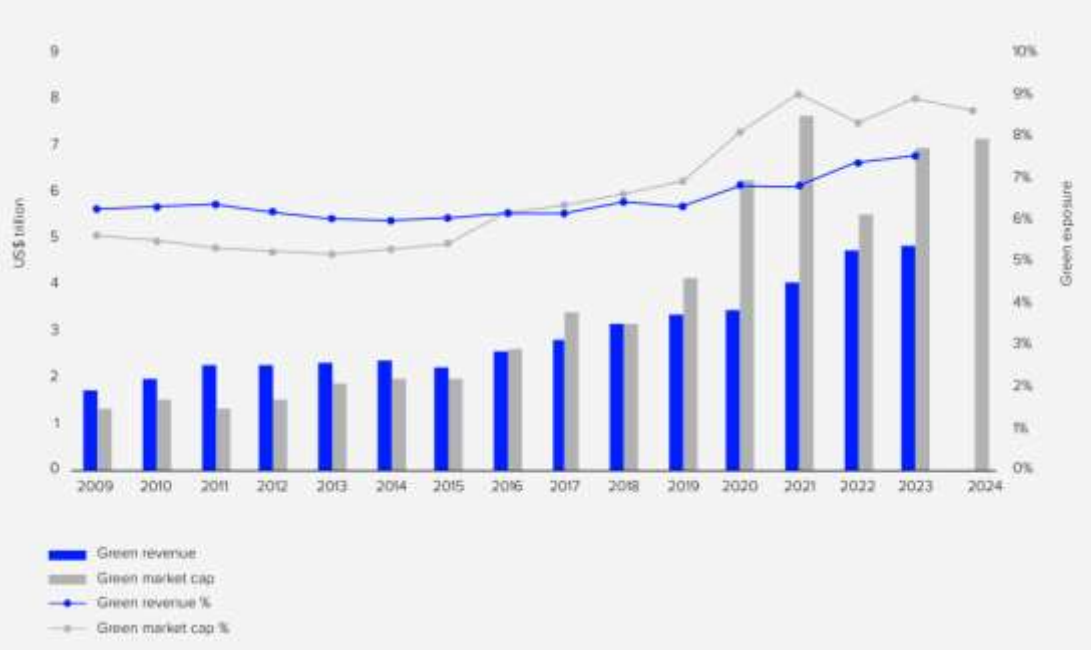


Figure 1. Green economy 2009–2024

However, not all green sectors have performed equally. The energy efficiency sector, which includes technologies such as efficient IT equipment and green buildings, has been the most successful, making up 46% of the green economy and generating 30% of green bond proceeds. In contrast, the renewable energy sector has lagged and underperformed in 2023, highlighting the uneven distribution of growth within the green economy.

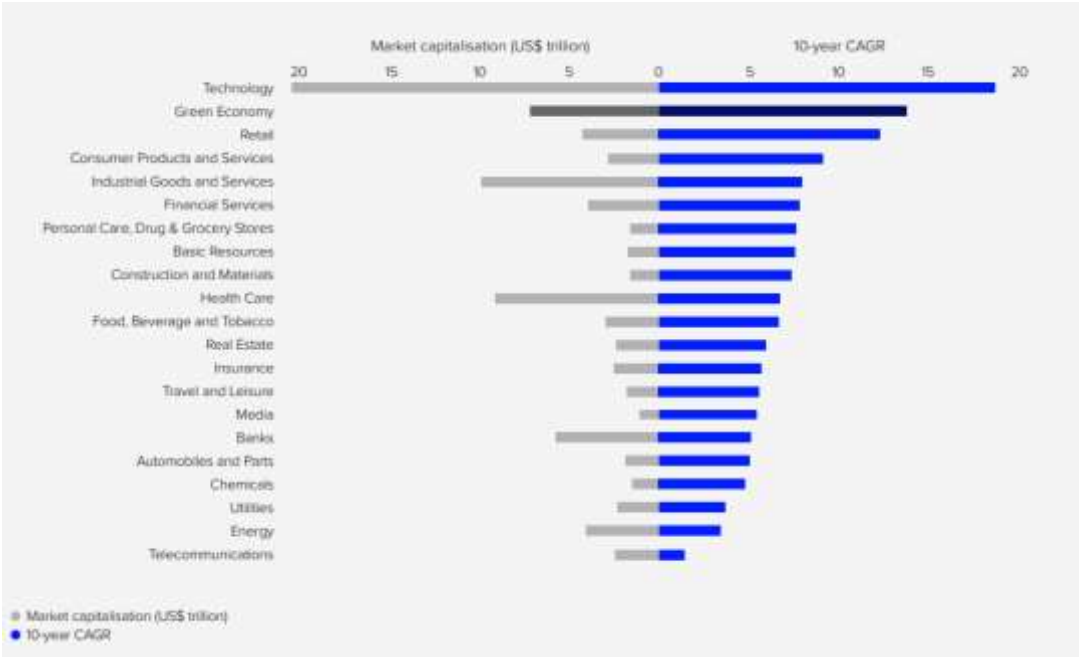


Figure 2. Market capitalisation value and 10-year growth rate – Green Economy compared with ICB sectors

If viewed as a standalone sector, the listed portion of the green economy in 2023 would have generated annual revenues nearing $5 trillion, with a market capitalization exceeding $7 trillion. This positioning would make it the fourth largest sector globally, surpassing industries such as Banks, Retail, and Energy, but still trailing behind Health Care, Industrials, and Technology.

Over the past decade, in terms of growth and financial performance, the green economy has only been outpaced by the Technology sector. If represented by the FTSE Russell Environmental Opportunities All Share Index (EOAS) and categorized as a separate ICB Industry, it would have ranked as the second-best-performing industry over the past ten years. Since 2008, the EOAS has consistently outperformed the broader FTSE Global All Cap Index by 82%, with significant outperformance occurring in 2020 and 2021.

The market capitalization of the green economy has expanded at a compound annual growth rate (CAGR) of 13.8% over the last ten years, compared to 8.3% for global equity markets. Revenues from the green economy have grown at a CAGR of 7.6% over the same period, exceeding the growth rate of combined revenues from all other companies (5.3% CAGR).

Within the green economy, the Energy Management and Efficiency sector has been the largest and highest-performing segment. Growing at 17% CAGR over the past five years, it now represents 46% of the green economy's listed equities and accounts for 30% of the proceeds from green bonds. This sector has driven the overall outperformance of the EOAS, leading ahead of other green sectors like Water and Renewable Energy.

II. Subsection Two

A successful transition to a low-carbon economy requires a profound economic transformation, involving substantial mobilization of private finance. Achieving net-zero carbon emissions by 2050 is projected to necessitate additional global investments ranging from 0.6% to 1% of annual global GDP over the next two decades, equating to a cumulative total of $12 trillion to $20 trillion (IEA 2021; IMF 2021a). These investments must shift away from the fossil fuel sector towards renewable energy and low-emission technologies across various sectors. Therefore, a significant and urgent green investment push is essential to facilitate this transition (as outlined in the October 2020 World Economic Outlook).

The global financial sector is positioned to play a critical role in catalyzing private investment to accelerate the transition. In recent years, sustainability concerns—including environmental, social, and governance (ESG) factors—have increasingly become integrated into investment strategies, driving the growth of sustainable finance (October 2019 Global Financial Stability Report). Investors focusing on sustainability may have dual objectives: financial returns ("doing well" by accounting for sustainability's growing importance for profitability) and advancing sustainable economic development ("doing good," particularly by supporting a faster transition to a low-carbon economy).

Achieving net zero will likely require an annual investment of US$1 to $2 trillion in real terms, or about 1% to 2% of global GDP (see Figure 3). This level of spending would far exceed previous major economic stimulus initiatives, such as the Marshall Plan (equivalent to US$114 billion today). Moreover, the decarbonization effort will be a long-term endeavor, requiring sustained capital expenditure for at least the next two decades. With capital investment representing 7% to 14% of total global investment annually, the intensity of capex as a share of global GDP will reach around 28%—a level not seen since the global financial crisis or the 1970s. This combination of massive spending, supportive policies, and evolving consumer and investor preferences is expected to trigger a new capital cycle.

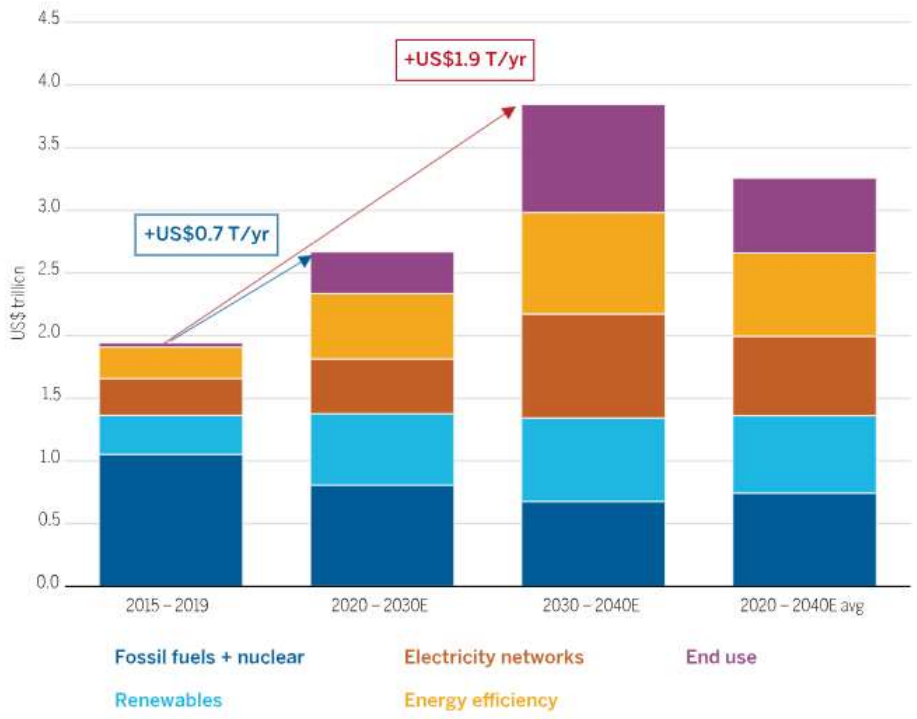


Figure 3. Spending needed to achieve net-zero emissions by 2040

Government commitments to decarbonization, such as the recently passed US$1.2 trillion U.S. infrastructure plan and the European Green Deal, are playing a critical role in legitimizing and accelerating the green capital expenditure (capex) cycle:

- Governments are framing investment in the low-carbon transition as a key tool for economic recovery. Renewable energy projects, like solar, wind, and hydro, are more labor- and capex-intensive than traditional power generation, making them effective at creating jobs and stimulating economic activity.
- Consumers, increasingly aware of the physical and financial risks of unchecked climate change, are pressuring policymakers and investors to take meaningful action.
- Rising geopolitical tensions are pushing governments to prioritize energy security, climate-tech leadership, and resilient supply chains. The development of regional supply chains for electric vehicles (EVs), batteries, and critical raw materials will further drive capital investment by duplicating supply chains.

Within the broader landscape of sustainable finance, the investment fund sector is particularly noteworthy due to its growing size and emphasis on sustainability-related issues. The sector has expanded substantially since the global financial crisis and now comprises around one-third of the assets held by nonbank financial institutions. It is at the forefront of incorporating sustainability considerations, including climate change mitigation, into investment decisions. This trend is evident from the increasing number of investor and asset manager networks committing to decarbonization efforts and integrating sustainability into their strategies.

Recent survey data and research indicate that investment funds, particularly those with a sustainable investment mandate, are increasingly attentive to climate change and the green transition. Financial markets have begun to reflect the pricing of the transition, which is crucial to steer capital toward firms and projects that positively impact climate change mitigation while avoiding overinvestment in non-sustainable ventures.

However, while the investment fund sector plays a pivotal role in advancing the green transition, financial stability risks associated with this transition are also significant. The path to a

green economy remains uncertain, with variations across countries based on differing policies, adoption of clean technologies, and shifts in consumer and producer preferences towards low-emission products and services (October 2019 Fiscal Monitor; October 2020 World Economic Outlook). Transition paths could offer opportunities for high-return investments but also present risks, particularly for firms in sectors vulnerable to cleaner technologies (e.g., fossil fuels, energy-intensive industries).

Studies have documented the substantial exposure of investment funds to sectors most sensitive to the transition, such as fossil fuels, utilities, and energy-intensive manufacturing. A sudden transition shock, such as the rapid realization of the need for swift global change, could lead to a sharp repricing of these assets, potentially triggering financial stability risks.

This chapter explores the interaction between the global investment fund sector and the transition to a low-greenhouse-gas economy, addressing two key questions: How do sustainable investment funds, which pursue both financial and sustainability objectives, support the transition? And what has been the impact of transition shocks on the investment fund sector so far?

To answer these questions, the chapter develops a conceptual framework that examines the interlinkages between the investment fund sector and the green transition. Using a dataset of more than 54,000 open-end funds—including equity, fixed-income, and allocation funds—it conducts empirical analysis to assess the role of these funds in facilitating the transition and how they have responded to transition-related risks.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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HUMAN CAPITAL AND ITS ROLE IN SUSTAINABLE DEVELOPMENT IN THE IMPLEMENTATION OF GREEN TECHNOLOGIES

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Abstract

The transition to a green economy driven by advances in green technologies presents both transformative opportunities and complex challenges for nations worldwide. Central to the successful adoption and innovation of these technologies is the development of high-quality human capital. This article examines the critical role of human capital in overcoming global challenges associated with green technology implementation, including technological adaptation, workforce transformation, and sustainable innovation. Through a systematic analysis of international practices and empirical case studies, the study identifies key components of effective human capital development: interdisciplinary education, continuous professional training, digital and ecological literacy, and the fostering of green competencies. The research highlights that investment in human capital is not merely a supportive factor, but a strategic prerequisite for achieving technological sovereignty, environmental sustainability, and long-term economic resilience. The findings underscore the necessity of coordinated policies involving governments, educational institutions, and the private sector to build a skilled, adaptable, and environmentally conscious workforce. The article concludes with policy recommendations aimed at strengthening national and global capacity to meet the demands of the green technological revolution.

Keywords: human capital, green technologies, sustainable development, green skills, environmental innovation, workforce development, digital transformation, education policy.

I. Introduction

The 21st century is marked by an unprecedented convergence of environmental, technological, and socio-economic transformations. Among the most pressing global challenges is climate change, which has catalyzed a worldwide shift toward sustainable development models. In this context, green technologies—encompassing renewable energy systems, energy-efficient processes, waste recycling innovations, low-carbon transportation, and smart environmental monitoring—have emerged as key drivers of ecological and economic transformation. According to the International Energy Agency (IEA, 2023), over 60% of new power capacity globally now comes from renewable sources, reflecting the accelerating pace of the green transition. However, the successful development, deployment, and scaling of green technologies depend not only on financial investment and policy support but, crucially, on the availability of skilled human capital [1].

Human capital—the knowledge, skills, competencies, and health attributes embodied in individuals—has long been recognized as a fundamental determinant of economic growth and innovation (Becker, 1964; Schultz, 1961). In the context of the green economy, its role becomes even more pivotal. The transition to sustainability requires not just new technologies, but also a workforce capable

of designing, implementing, managing, and improving these solutions. Yet, a significant gap exists between the rapidly evolving demands of the green job market and the current state of education, training, and professional development systems worldwide. The International Labour Organization (ILO, 2022) estimates that over 24 million new jobs could be created by 2030 in the green economy, but warns of a critical shortage of qualified personnel in engineering, environmental science, data analytics, and sustainable management [2].

This mismatch underscores a central research problem: how can human capital development be effectively structured to meet the challenges of global green technology adoption and innovation? While numerous studies have explored technological and policy aspects of the green transition, the strategic role of human capital remains undertheorized, particularly in terms of systemic educational reforms, reskilling initiatives, and cross-sectoral collaboration.

The purpose of this study is to analyze the role of human capital in overcoming key barriers to green technology implementation and to identify effective strategies for developing green skills and competencies at national and global levels. The research objectives include: (1) examining the evolving skill demands in the green technology sector; (2) assessing current models of human capital development in leading countries; (3) identifying gaps in education and workforce training; and (4) formulating evidence-based recommendations for policymakers and educational institutions [3].

The significance of this research lies in its interdisciplinary approach, bridging economics, environmental science, and management studies to offer a comprehensive framework for human capital development in the era of sustainability. The findings contribute to both academic discourse and practical policy design, supporting the achievement of the United Nations Sustainable Development Goals (SDG 4, 7, 8, and 13) and enhancing national competitiveness in the emerging green economy.

II. Methods

To examine the role of human capital development in addressing global green technology challenges, this study employs a mixed-methods approach, integrating qualitative and quantitative analyses to provide a comprehensive understanding of the subject. The research design includes the following key components [4]:

1. Systematic Literature Review. A comprehensive review of peer-reviewed articles, policy documents, international reports (from organizations such as the United Nations, World Bank, and International Labour Organization), and technical publications was conducted. The focus was on identifying core themes related to human capital development—such as education, skills training, innovation capacity, and workforce adaptability—and their impact on the adoption, diffusion, and innovation of green technologies. Databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar were systematically searched using keywords including "green technology," "human capital," "sustainable development," "clean energy transition," "skills for green jobs," and "education for sustainability."

2. Comparative Case Study Analysis. Four countries representing different levels of economic development and green technology advancement were selected for in-depth analysis:

- Germany (a leader in renewable energy and green innovation),
- South Korea (a high-tech economy with strong government-led green initiatives),
- Kenya (a developing country with growing investments in off-grid solar solutions),
- Brazil (a middle-income country with significant potential in bioenergy and sustainable agriculture). Data were collected from national policy frameworks, governmental reports, and academic studies to compare strategies for building human capital in the context of green technology deployment.

3. Quantitative Data Analysis. Secondary data from international databases (World Development Indicators, ILOSTAT, OECD Green Growth Indicators) were used to analyze correlations between human capital indicators (e.g., education expenditure, STEM graduates, vocational training

participation) and green technology outcomes (e.g., renewable energy capacity, carbon productivity, number of green patents). Panel data regression models were applied to assess the long-term impact of human capital development on national green innovation performance across 35 countries over the period 2010–2022 [5].

4. Expert Interviews. Semi-structured interviews were conducted with 15 experts, including policymakers, academic researchers, and industry professionals from the energy, education, and environmental sectors. The interviews explored perspectives on skills gaps, policy effectiveness, and future workforce needs in the green economy. Thematic analysis was used to identify recurring patterns and insights [6].

5. Policy Gap Analysis. A structured framework was applied to evaluate the alignment between national education and labor policies and the demands of the green technology sector. This analysis highlighted disparities in current training programs and emerging skill requirements in areas such as energy storage, circular economy design, smart grid management, and environmental data science.

By combining these methods, the study ensures a robust, multi-dimensional assessment of how human capital development can effectively support the global transition to sustainable technologies and address pressing environmental challenges.

III. Results

The findings of this study demonstrate that human capital development is a critical driver in overcoming global green technology challenges, enabling countries to innovate, adopt sustainable practices, and transition toward low-carbon economies. The integration of education, vocational training, research capacity, and policy coherence plays a decisive role in building a skilled workforce capable of supporting green technological advancement [7].

1. Correlation Between Human Capital and Green Innovation. Quantitative analysis revealed a statistically significant positive relationship between investment in human capital and green technology outcomes. Countries with higher shares of STEM (science, technology, engineering, and mathematics) graduates and greater public spending on education exhibited higher rates of green patent filings and faster deployment of renewable energy infrastructure. For instance, Germany and South Korea—both with strong technical education systems—recorded 3.5 and 2.8 times more green technology patents per capita, respectively, compared to the global average during 2015–2022.

2. Case Study Insights

- Germany demonstrated success through its dual vocational training system, which has been adapted to include green skills in energy efficiency, wind turbine maintenance, and sustainable construction.
- South Korea implemented the "Green New Deal" workforce program, training over 300,000 workers in eco-friendly technologies by 2022.
- Kenya leveraged decentralized solar energy projects to create local "solar technician" jobs, supported by community-based training initiatives, resulting in a 45% increase in off-grid solar access between 2015 and 2022.
- Brazil expanded agricultural extension services to promote sustainable farming and bioenergy production, though challenges remain in aligning higher education with industry needs [8].

3. Skills Gaps and Policy Misalignment. Expert interviews highlighted persistent gaps in mid-level technical skills, digital literacy for energy systems, and interdisciplinary knowledge in sustainability. Many existing training programs fail to keep pace with rapid technological change, particularly in emerging fields such as hydrogen energy, carbon capture, and circular design.

4. Russia's Position in Human Capital Development for Green Technologies. Russia presents a complex and evolving case. On one hand, the country possesses a strong foundation in engineering, physical sciences, and technical education, with a historically high number of STEM graduates. According to UNESCO Institute for Statistics (2022), Russia produces approximately 120,000 STEM

graduates annually, many from leading institutions such as Moscow State University, the National Research Nuclear University MEPhI, and the Skolkovo Institute of Science and Technology (Skoltech) [9].

However, the transition to green technologies remains limited by structural and policy challenges. Despite growing scientific potential, the integration of sustainability and environmental innovation into curricula is uneven. A 2023 analysis by the Analytical Center for the Government of the Russian Federation found that only 18% of engineering programs in Russian universities include dedicated courses on renewable energy or climate technologies.

Moreover, the labor market demand for green skills is still underdeveloped. As of 2023, renewable energy accounts for less than 3% of Russia's total power generation, primarily due to the country's heavy reliance on fossil fuels [10]. Nevertheless, recent initiatives indicate a shift. The federal project "Ecology" under the National Project framework includes workforce training components for environmental monitoring and waste management. Additionally, pilot programs in cities like Kazan and Novosibirsk have launched retraining courses for energy sector workers in energy efficiency and smart grid technologies.

Notably, Skoltech and its partners have developed interdisciplinary programs in sustainable energy and digital environmental monitoring, contributing to research in green hydrogen and carbon footprint modeling. However, the scale of these programs remains limited, and systemic support for green innovation is still emerging.

5. Policy Effectiveness and Future Needs. The policy gap analysis showed that while many countries have integrated green skills into national education strategies, implementation remains inconsistent. In Russia, as in several other resource-dependent economies, there is a mismatch between educational outputs and labor market needs in the green sector. Strategic alignment of education, industry, and environmental policy is essential to scale up human capital development effectively [11].

Key Quantitative Findings (Panel Data Analysis, 2010–2022):

- A 1% increase in tertiary education enrollment correlates with a 0.7% rise in renewable energy capacity per capita.
- Countries with national green workforce strategies achieved 40% faster growth in green job creation.
- Investment in vocational training for green jobs yields a return of up to 5:1 in long-term emissions reduction and economic productivity [12].

In summary, human capital development is a proven enabler of green technological progress. While leading nations have institutionalized education-to-innovation pipelines, countries like Russia show potential but require stronger policy integration, curriculum modernization, and market incentives to fully leverage their skilled workforce for sustainable development.

IV. Discussion

I. Subsection One: Human Capital as a Catalyst for Green Innovation and Technological Adoption

The strong correlation between investment in education—especially in science, technology, engineering, and mathematics (STEM)—and the pace of green innovation confirms that human capital is not a passive enabler but an active driver of technological transformation. Countries with robust education systems and continuous professional development programs demonstrate greater agility in adopting renewable energy, improving energy efficiency, and developing circular economy models. The success of Germany and South Korea illustrates how long-term investments in technical education and vocational training create a resilient talent pool aligned with green industrial strategies [13].

This finding aligns with the human capital theory, which posits that education and training enhance individual productivity and, by extension, national economic and technological advancement (Becker, 1964; Schultz, 1961) [14]. In the context of sustainability, this theory extends to "green human capital"—a concept that integrates environmental literacy, systems thinking, and technical expertise in eco-innovation. The case studies reveal that nations that explicitly incorporate sustainability into STEM curricula and workforce development programs achieve faster and more equitable transitions.

Moreover, the emergence of interdisciplinary fields—such as environmental data science, sustainable materials engineering, and climate-resilient infrastructure design—highlights the need for educational systems to evolve beyond traditional silos [15]. The integration of digital skills with environmental knowledge is becoming increasingly critical, as green technologies rely heavily on artificial intelligence, remote sensing, and smart grid management.

In this context, Russia's substantial base of engineering and scientific talent represents a significant strategic asset [16]. The country's historical strength in physics, mathematics, and nuclear technology provides a solid foundation for reorientation toward green innovation. Institutions like Skoltech are already pioneering research in green hydrogen, carbon capture, and energy storage systems, demonstrating that Russian academia can contribute meaningfully to global sustainability science.

However, as the results indicate, the translation of this potential into scalable green workforce development remains limited. The absence of a comprehensive national strategy for green skills, combined with low deployment of renewable energy, reduces the incentive for educational institutions and industries to prioritize sustainability. Unlike the European Union's Green Deal, which includes binding targets for green job creation and curriculum reform, Russia lacks a unified policy framework that links education, labor, and environmental goals.

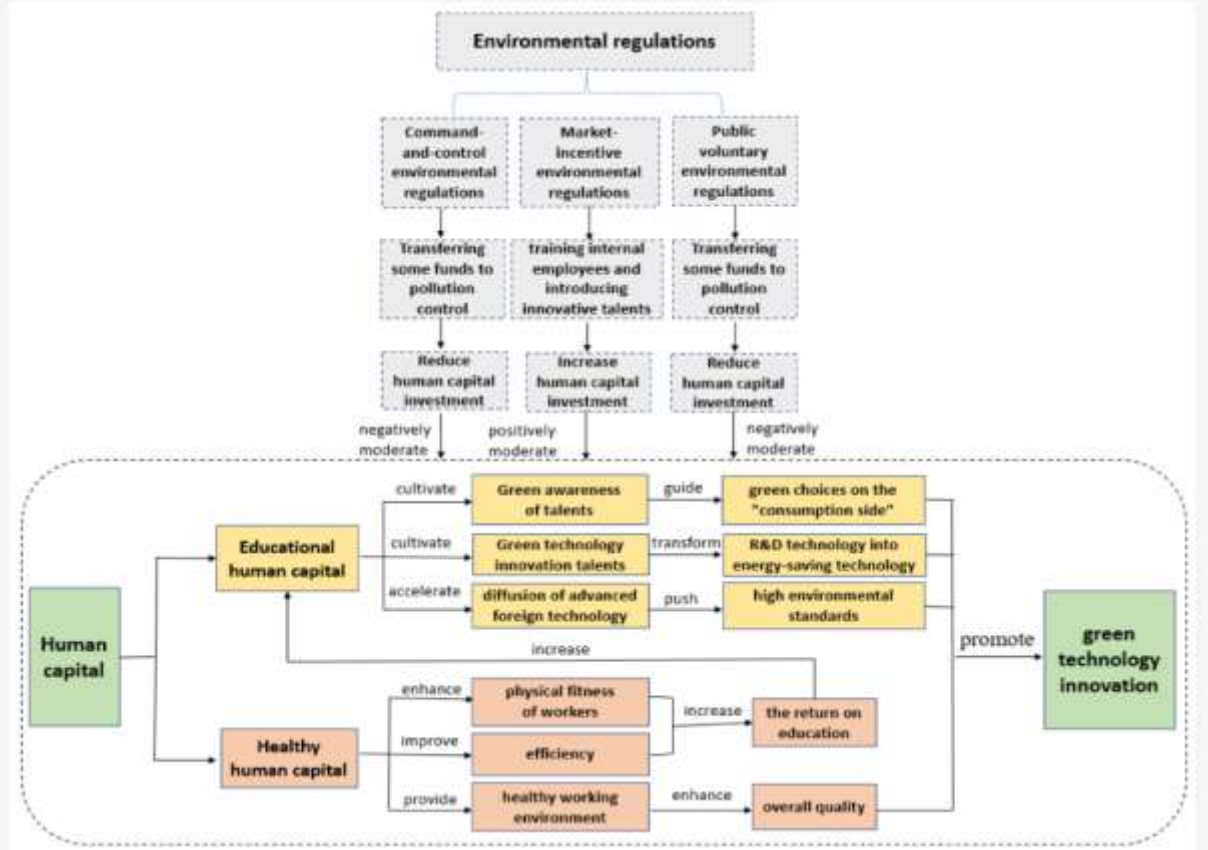


Figure 1. The moderating role of human capital in linking environmental regulations to green technology innovation

The figure (fig.2) illustrates the interplay between environmental regulations, human capital formation, and green technology innovation. Central to this model is the recognition that human capital—both educational and health-related—serves as a foundational driver of green technological advancement.

1. Environmental Regulations as External Moderators

Environmental regulations operate as external pressures that shape the allocation of human capital investments [17].

•Command-and-control regulations and public voluntary regulations tend to divert funds toward pollution control, thereby reducing resources for human capital development. This creates a negative moderating effect on innovation capacity.

•In contrast, market-incentive regulations stimulate training of employees and the introduction of innovative talents, thereby increasing human capital investment and fostering a positive moderating effect on technological innovation.

This indicates that regulatory design directly influences the human capital–innovation nexus by determining whether investments in education, skills, and health are expanded or constrained.

2. Educational Human Capital: The Engine of Green Awareness and Innovation

Educational human capital plays a dual role in fostering green innovation [18]:

•It cultivates green awareness among talents, encouraging environmentally responsible decision-making on the consumption side.

•It develops green technology innovation talents, who are capable of transforming R&D outcomes into energy-saving technologies and meeting high environmental standards.

•Additionally, educational human capital accelerates the diffusion of advanced foreign technology, which helps in the rapid adoption of international best practices in sustainability.

Thus, educational investment acts as the intellectual infrastructure that bridges regulatory frameworks with practical green innovations.

3. Healthy Human Capital: Enhancing Efficiency and Productivity

Healthy human capital enhances the physical fitness of workers, improves efficiency, and ensures a healthy working environment. Collectively, these factors:

•Increase the return on education, making skill acquisition and training more effective.

•Enhance the overall quality of human capital, ensuring that talent is not only knowledgeable but also physically capable of sustaining innovative activities.

This highlights that human capital is not only about education and skills but also about maintaining a workforce with the physical resilience and well-being necessary for long-term innovation [19].

4. Human Capital as the Catalyst for Green Technology Innovation

By combining educational and healthy human capital, organizations and societies can:

•Guide sustainable choices at both production and consumption levels.

•Transform scientific R&D into practical, energy-efficient technologies.

•Push for the establishment of high environmental standards.

Ultimately, human capital promotes green technology innovation, not just by providing technical skills but by fostering a holistic ecosystem where awareness, health, efficiency, and global knowledge diffusion converge.

The model demonstrates that human capital is the critical catalyst linking environmental regulation with green technology adoption and innovation. Educational human capital nurtures knowledge, skills, and awareness required for green transitions, while healthy human capital ensures efficiency, resilience, and sustained productivity. Together, they enable societies to transform regulatory pressures into opportunities for sustainable technological advancement [20].

In essence, the development of human capital is not merely an outcome of environmental policy but a strategic investment that determines the pace and success of green innovation pathways.

Furthermore, while Russia produces a high number of STEM graduates, the relevance of their training to emerging green sectors is often questionable. The underrepresentation of environmental

technology and climate science in engineering programs suggests a misalignment between academic output and future labor market demands. This gap risks creating a "skills paradox"—a surplus of technically trained individuals who lack the specific competencies needed for the green transition.

Nonetheless, recent initiatives—such as targeted retraining programs in energy efficiency and waste management under the federal "Ecology" project—signal a growing recognition of the need for workforce transformation. If expanded and integrated into broader economic planning, such programs could catalyze a shift toward a low-carbon development model.

In sum, human capital development must be proactively shaped by forward-looking policies that anticipate technological change. Countries that invest early in green education and reskilling not only reduce emissions but also gain competitive advantage in the emerging global green economy. For Russia and similar resource-dependent economies, the challenge lies not in the absence of talent, but in the strategic redirection of existing human capital toward sustainable innovation.

II. Subsection Two: Bridging Skills Gaps and Aligning Education with Green Labor Market Needs

One of the most critical challenges in advancing green technology globally is the persistent misalignment between education systems and the evolving demands of the green labor market. While many countries produce a sufficient number of graduates in technical fields, the specific competencies required for green jobs—such as energy auditing, sustainable construction, circular economy management, and environmental data analysis—are often absent from standard curricula. This mismatch results in a growing skills gap that hinders the scalability and efficiency of green technology deployment.

The findings of this study confirm that even in countries with advanced education systems, traditional programs often fail to incorporate interdisciplinary approaches necessary for sustainability. For example, engineering graduates may lack training in life-cycle assessment or carbon footprint modeling, while environmental science students may not be equipped with digital tools such as GIS (geographic information systems) or machine learning for climate monitoring. Expert interviews emphasized that employers increasingly seek "hybrid skills"—a combination of technical expertise, digital literacy, and systems thinking—yet few academic institutions systematically develop these competencies.

In Russia, this challenge is particularly pronounced. Despite a strong legacy in fundamental sciences and engineering, the integration of green technologies into vocational and higher education remains fragmented. A 2023 report by the Russian Union of Industrialists and Entrepreneurs (RSPP) revealed that only 12% of industrial enterprises consider the domestic workforce adequately prepared for energy efficiency and environmental compliance tasks. This reflects a broader systemic issue: educational standards are not regularly updated to reflect technological advancements in sustainability, and industry-academia collaboration remains underdeveloped.

However, there are emerging signs of change. Pilot initiatives in cities such as Yekaterinburg and Tomsk have introduced dual education models in partnership with local energy companies, offering students hands-on training in smart metering and renewable energy maintenance. Similarly, the "Zelenaya Industriya" (Green Industry) project, supported by Rosatom and several technical universities, provides specialized courses in low-carbon technologies and nuclear safety, with a growing focus on sustainable innovation.

Moreover, digital platforms and online learning are beginning to play a transformative role in expanding access to green skills. Russian-language MOOCs (Massive Open Online Courses) on platforms like "Open Education" and "Skillbox" now offer courses in solar energy, ecological auditing, and sustainable urban planning, reaching thousands of learners across remote regions. These programs demonstrate the potential for scalable, flexible training models that can rapidly respond to market needs.

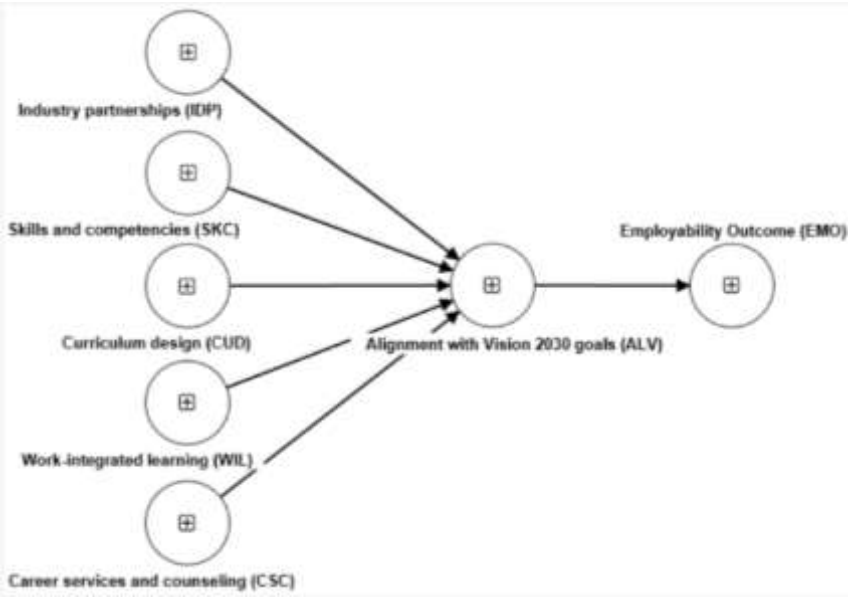


Figure 2. Integrating education, industry, and policy for green employability outcomes

The figure (fig.2) conceptualizes the pathways through which higher education institutions (HEIs) and training systems can bridge skills gaps and align their outputs with emerging demands of the green labor market, while simultaneously advancing broader development frameworks such as Vision 2030.

1. Industry Partnerships (IDP)

Industry partnerships ensure that educational programs remain relevant to real-world labor market needs. By collaborating with green industry stakeholders, HEIs gain insights into emerging sustainability practices, clean technologies, and circular economy models. Such partnerships allow for the co-design of curricula, joint research initiatives, and internships that expose students to applied green innovation contexts.

2. Skills and Competencies (SKC)

The cultivation of green skills and competencies—such as energy efficiency management, renewable energy systems, sustainable supply chain design, and environmental compliance—is essential to meeting the demands of the evolving labor market. Embedding transversal competencies, including problem-solving, digital literacy, and systems thinking, further enhances graduates' adaptability in green economies.

3. Curriculum Design (CUD)

Curriculum design serves as the structural foundation for aligning education with sustainability-driven labor markets. The integration of green modules, interdisciplinary approaches, and problem-based learning ensures that students are not only technically competent but also capable of addressing complex socio-environmental challenges. This also facilitates the mainstreaming of sustainability goals within formal education.

4. Work-Integrated Learning (WIL)

Work-integrated learning bridges the gap between classroom knowledge and workplace application. Through internships, apprenticeships, and cooperative education in green industries, students acquire hands-on experience that enhances both employability and innovation capacity. This experiential learning reinforces the relevance of academic knowledge to the demands of the green transition.

5. Career Services and Counseling (CSC)

Career services and counseling act as a support mechanism that helps students navigate the transition from education to employment. By providing guidance on green career pathways, labor market trends, and reskilling opportunities, these services ensure that graduates are well-positioned to access and thrive in sustainability-focused employment sectors.

6. Alignment with Vision 2030 Goals (ALV)

The interaction of these educational inputs—partnerships, skills development, curriculum reform, experiential learning, and career services—collectively aligns with Vision 2030's emphasis on economic diversification, human capital development, and sustainability transitions. This alignment ensures that the education system not only responds to current labor market needs but also proactively shapes future green growth trajectories.

7. Employability Outcomes (EMO)

The ultimate outcome of this alignment is enhanced employability of graduates in the green labor market. Employability here extends beyond job placement to include the ability to adapt, innovate, and contribute to sustainable economic systems. Graduates equipped with both technical and transversal green skills become catalysts for advancing sustainable development goals while driving competitiveness in the labor market.

The figure illustrates a systemic approach to bridging skills gaps by linking education directly with the requirements of the green labor market. Through coordinated efforts in industry collaboration, skills development, curriculum reform, experiential learning, and career services, educational systems can ensure their graduates are prepared not only to participate in but also to lead the green transition. Internationally, successful examples provide valuable lessons. In Germany, the Chamber of Industry and Commerce (IHK) regularly updates vocational training standards in consultation with employers, ensuring that programs in renewable energy and building efficiency remain current. In South Korea, the government collaborates with tech companies to co-design curricula for green IT and smart grid management. Such institutional mechanisms for stakeholder engagement are largely absent in Russia, where policy coordination between the Ministry of Science and Higher Education, the Ministry of Labour, and the Ministry of Natural Resources remains weak.

To bridge the skills gap effectively, three key actions are required:

1. Curriculum modernization — integrating green competencies into national educational standards across technical and environmental disciplines;
2. Industry-academia partnerships — establishing formal collaboration frameworks to align training programs with real-world technological needs;
3. Lifelong learning systems — developing accessible retraining and upskilling pathways for workers in carbon-intensive sectors, such as oil and gas, coal, and heavy manufacturing.

For Russia, where a significant portion of the workforce is employed in fossil fuel industries, proactive reskilling is essential to ensure a just and socially sustainable transition. Without targeted investment in human capital, the shift toward green technologies risks exacerbating regional inequalities and labor market instability.

In conclusion, closing the skills gap requires more than isolated training programs—it demands a systemic transformation of education and labor policies. Countries that successfully align human capital development with green technological trajectories will not only accelerate their climate action but also strengthen economic resilience and innovation capacity in the 21st century. Russia, with its strong scientific base and growing awareness of environmental challenges, has the potential to become a leader in this transformation—if strategic investments in education and workforce development are prioritized.

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CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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REGIONAL ASPECTS OF THE IMPLEMENTATION OF SUSTAINABLE DEVELOPMENT PRINCIPLES

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Abstract

The article is devoted to the comparative analysis of regional economic policy conducted in developed countries and in Russia. The processes of development and realization of the regional policy of developed countries are investigated, which include the correct choice of objects for which the stimulation or restriction of economic growth is envisaged. It is noted that the market processes of the 90s of the last century in Russia took place against the background of economic crisis, accompanied by a decline in the standard of living of society, the growth of the differentiation of the country's regions in terms of socio-economic development, which contributed to the emergence of depressive territories. The important components of the concept of "depressive region" are considered, as well as the established subtypes of depressive regions are presented, their features are highlighted. It is noted that the depressiveness of regional development had a direct dependence on the sharp decline in living standards in the years of market transformation. On the example of such a depressive region as the Chechen Republic the analysis of successful implementation of government measures to achieve sustainable socio-economic development of the region is carried out.

Keywords: regional policy, sustainable development, income, employment, Chechen Republic.

I. Introduction

In modern domestic economic science there are different ideas regarding the definition of the content of regional policy. Thus, the regional policy conducted under the conditions of centralized management system in the Soviet Union, pursued the global goal of placing productive forces, solving the problems of creating large territorial-production complexes, accelerated development of the eastern regions, development of northern territories, equalization of the levels of economic development of the Union republics, etc. The nationwide character of this policy was its principal feature. The realization of national tasks, taking into account the location of the resource base and socio-economic characteristics of the country's territories was the main core of its content. [1]

Regional policy in foreign countries had some differences, providing for differentiated diagnostics of the country's economic regions in order to determine the directions of development. Along with the solutions of economic problems, considerable attention was paid to the problems of social, political and environmental nature, and although economic motives were given the greatest importance, their relative importance could be different depending on the country. It should be noted that it was only in the late 1950s and early 1960s that European countries began to emphasize economic issues in their regional economic policies, whereas previously the prerogative had been given to its social importance. In modern times, social factors play no less important role and their goal is to achieve full employment, to distribute the regional income received and to solve the problem of welfare. [1]

II. Methods

According to S.S. Reshiev, in the development of effective policy much depends on the choice of the state strategy for the development of raw material industries and the form of ownership of them, as they represent the economic core that contributes to the successful economic growth of all regions.

In the work of Surkov S.A. and Shusharin V.V. it is noted that equalization of the levels of economic and especially social development of regions, which have far from equal opportunities, will contribute to leveling the processes of depressiveness of regional development.

N.D. Kondratiev considered it necessary to rely on a comprehensive study of regularities and trends of movement in the past and the possible direction of changes in the future, in contrast to the widespread teleological approach, which focuses on a priori set goals and predicts possible ways to achieve them.

Smirnyagin L. and Bylova G. note that the experience of Western countries facing the problem of structural reorganization and withdrawal from the crisis of depressed regions indicates a higher efficiency of the path of development aimed "upward" and the use of internal growth factors.

According to Volkov and other researchers, among the most conflictogenic factors influencing the socio-political and inter-ethnic situation in the North Caucasus, it was the factors of religiosity that stood out, and their role will not diminish given the unfavorable socio-economic situation.

According to the research of R.M. Sadykov, the growth of the physical volume of gross output of the personal sector was due to the inflow of labor force released from agricultural enterprises, land reform, which removed restrictions on the size of personal land use and livestock, etc.

In conducting this scientific research, such scientific methods as the method of comparative analysis, statistical analysis, comparative analysis, functional analysis, positive and normative analysis were applied. The scientific research was carried out in accordance with the problem-chronological principle, the principles of systematicity, as well as scientific objectivity.

III. Results

Regional economic policy or local planning absorbs all types of government intervention to improve the territorial distribution of economic activities. In fact, regional policies implemented in foreign countries seek to correct some spatial effects of free trade economy in order to achieve economic growth and improve the process of social distribution.

There are five periods in the development and implementation of regional policies of foreign countries:

- the first period is to identify regional problems and their origins;
- the second period is the definition of objectives and, if possible, in a quantitative way;
- the third period is the formation of an appropriate strategy;
- the fourth period is the selection of instruments to be used;
- the fifth period is the evaluation of the implemented policy. [1]

Among the most important elements of the process of development and implementation of regional policy of developed states is the correct choice of objects for which it is envisaged to stimulate or limit economic growth.

During the realization of market transformation in Russia there was a deep recession in the economy, a decline in living standards of the population, increased differentiation of regions by level of socio-economic development, which resulted in the emergence of depressed territories. By the beginning of the XXI century, as a result of transition processes, 2/3 of the country's subjects, especially those located near or on the periphery of such leading industrial centers as the North-Western, Central, Volga-Vyatka, Volga economic regions, as well as the North Caucasus, Siberia, the Far East and the Urals were presented as depressive. [2]

Depressiveness as an economic phenomenon in relation to the regions, according to the "theory of long waves" of N.D. Kondratiev, is presented as an objective consequence of the cyclical nature of their economic development. [3] "Depression" as an economic category is a stagnation in the economy, with a lack of growth in production and business activity, low demand for products and significant unemployment. This phenomenon is usually observed after or as a result of an economic crisis, indicating the final stage, after which we should expect the onset of the stages of economic recovery and recovery. Based on the existing ideas of both domestic and foreign economic theory, depression is characterized by a cumulative process, when the reduction of investment and consumer demand results in a decrease in production and production resources, thereby maintaining low demand. [4]

It should be noted that the Russian depression, emphasizing its specificity in the form of a decline in production in the presence of inflation, gave reason, according to some authors, to consider it as "stagflation." [2] In accordance with this context, "depressive region" is most accurately defined by L. Smirnyagin and G. Bylova as a territory that differs from others in terms of the main socio-economic indicators, which include the rate of development. [5]

At the legislative and regulatory level, the concept of "depressed regions" found application in the context of budgetary relations to determine the system of compensation for existing interregional differences. In the Resolution of the Government of the Russian Federation No. 639 dated 29.06.1995, the name "depressive" was first adopted in relation to the regions, despite the ambiguity of its interpretation, which in the future, especially in practice, had negative consequences. The draft Federal Law No. 91010-3 "On the Basis of Federal Support for Depressed Territories of the Russian Federation" adopted in the country on March 12, 2003 reflected the concept of "depressive region" more precisely. According to this provision, "depressed territory" was represented as a unit in the form of a district, city or it was a set of contiguous administrative units with a homogeneous economic structure, within one or more subjects of the Russian Federation, which due to the crisis was in a state of extreme economic decline. [6]

In the traditional perception, a depressed region is characterized by a lower than average level of socio-economic development in the country, but in the earlier period it was a relatively stable developing territory, occupying high positions in the country by some indicators. Depressive regions, having a large accumulated scientific and technical potential, a significant share of industry in the structure of the regional economy, a fairly high level of qualification labor resources, while being characterized by decreased competitiveness in the main products, reduced investment demand, negative structural changes in the economy, depletion of mineral raw material base, low indicators of well-being of the local population. Such features define a depressed region as a territory in a phase of steady economic decline, in which there is no possibility of new stimuli for development and it is necessary to apply corrective measures on the part of the authorities to get out of the current state. In the 1990s, depressed regions, based on the duration and depth of territorial depression, largely due to the sectoral specifics of production, the crisis in which led to the spread of depression to the entire regional economy, began to be divided into old-industrial, extractive and agrarian-industrial types. [2]

Among the more affected due to the reforms of the 1990s in the country were the old-industrial regions, on the territory of which were concentrated such enterprises of processing industry with a developed scientific, technical and technological base, belonging to the military-industrial complex, machine building, instrument making, light and food industries. The structure of the economy of these territories was formed throughout the period beginning from the late XIX century to the middle of the XX century, with different stages of industrial development. [2]

The extractive depressive regions included localized resource-producing territories, especially mining and timber industries, located in sparsely populated areas. These regions, as well as old-industrial ones, were characterized by a fairly developed economic potential with a significant share of industry in the economic structure, highly skilled labor resources, but due to the disruption of

supply and raw material relations or changes in the development strategy, as well as the low competitiveness of core industries had problems in the form of deep economic recession, high unemployment, especially structural unemployment, rather low indicators of investment activity of the level of financial and budgetary support of the economy. Depressive regions of the old industrial and extractive types belonged to the group of low-income regions with high poverty rates according to the level of per capita purchasing power of money incomes.

IV. Discussion

I. Subsection One

Regions of the Central Black Earth Economic Region, republics of the North Caucasus and South Siberia, where stagnation of socio-economic processes was noted as a consequence of a combination of typical agrarian specialization and industrial backwardness of the region, could be attributed to the number of agrarian-industrial depressive regions, despite some difficulties in classification due to the fact that the agricultural sector in most Russian subjects, neither in terms of production volume, nor in terms of share in the gross regional product, did not occupy leading positions. [2]

It should be noted that in addition to the above classification of depressed regions, there were others. Thus, in 2005 the Ministry of Regional Development of the Russian Federation developed a new typology of Russian regions, in which all subjects, based on the basis of development, the degree of involvement in global development processes such as globalization, urbanization and neo-industrialization, were grouped into 4 main types and 7 groups based on expert assessment with the analysis of indicators of socio-economic development of the subjects of the Russian Federation. In depressive regions, according to this classification, there was a significant economic decline in the main branches of the economic sphere over the last 10 years and lower level compared to the average analogs in the country of many economic indicators, while in the past these territories were economically developed, occupying prominent places in some positions in the country's economy. [7]

In general, in depressed regions there were observed:

- high unemployment rates and, as a consequence, a low standard of living of the population living in these territories;
- significant lag in socio-economic development compared to other regions of the country;
- poor infrastructure provision.

In turn, depressive regions were subdivided into such subtypes as background and crisis. While the background depressive regions had a low standard of living, backward technological base, insufficient market positioning, and a shortage of human resources, the crisis regions were characterized by a rather significant lag behind other regions in terms of socio-economic development, high unemployment rates, poor infrastructure provision and a higher level of social conflicts. Depressiveness of regional development had a direct dependence on the sharp decline in living standards during the years of market transformation.

At the beginning of 2000, the Chechen Republic could also be considered as depressive among the Russian regions that were among the last in the country in terms of socio-economic development, which is confirmed by the data in the table below.

Analysis of the data in the table shows that the Chechen Republic lagged far behind in all the most important socio-economic parameters in comparison with the all-Russian average and the average for the Southern Federal District (SFD), of which it was then a part. For example, by the end of 2005, the regional indicator of the number of registered unemployed was more than 30 and 13 times higher than the national average and the average for the Southern Federal District, respectively; the share of the population with incomes below the subsistence minimum was more

than 5 and 2 times higher than in the country as a whole and in the Southern Federal District, respectively, etc.

Table 1. Main socio-economic indicators (2005 results)

Key indicators	Number of registered unemployed in % of economically active population	Area of housing stock per capita	Industrial output per capita, thousand rubles.	Share of pupils studying in the second shift, %	Number of hospital beds Number of hospital beds per 10,000 people.	Proportion of population with incomes below the flow minimum
Russian Federation	2,6	19.2 (18 is the norm)	78,1	19,8	116,0	17,8
Southern Federal District	5,9		24,8	25,2	105,2	37,3
Chechen Republic	78,9	11,7	9,7	54,8	68,9	90,0

The reasons for this negative socio-economic state of the Chechen Republic were to be found in the political and economic restructuring that began in the USSR and the anti-terrorist operations of the last decade of the 20th century, which resulted in the final destruction of the regional economy. The economic crisis in the republic began even before the anti-terrorist operations began, with the rise to power of new persons whose aims were far from the interests of the Chechen people. While the pre-war economic crisis was manifested by a decline in production and living standards, rising unemployment and crime rates, during the anti-terrorist operations many of the region's industrial and social infrastructure facilities were virtually destroyed.

The unemployment rate in the republic, which by the mid-2000s reached about 80% of the able-bodied population, was the highest compared to other regions of the country, and the situation was aggravated by the fact that there were positive dynamics of demographic processes due to the growth of the birth rate, as well as the return of refugees and forced migrants to their homeland due to the cessation of anti-terrorist operations. By the beginning of 2005, according to the data of the Ministry of Labor of the Republic, the number of unemployed able-bodied population reached 400 thousand people, i.e. 62% of the labor resources and almost 69% of the economically active population of the region. This situation, in which the labor market in the republic found itself, could be generally considered as a crisis. In August 2005, at a meeting of the Government, when approving the draft federal budget for 2006-2008, German Gref pointed out that 91% of the population of the Chechen Republic was officially below the poverty line. At the same time, according to the minister, in the Khanty-Mansiysk and Yamalo-Nenets Autonomous Okrugs this indicator was the lowest in the country - less than 7%, and the main reason for the extremely low incomes of the region's population was unemployment. [9]

It is worth noting that the deficit of jobs was the most pressing problem for all regions of the Southern Federal District. This was especially true for the republics in which the number of working-age population was two to three times higher than the number of available jobs. In all the republics of the North Caucasus, the load of the unemployed population per vacancy was significantly higher than the national average. Thus, in 1999 in Ingushetia this indicator reached 184.4 people, in Dagestan ◎ 32.3, 20.3 ◎ in Kabardino-Balkaria, while the all-Russian ◎ 2.4 people per vacancy. [10]

One of the sides of this problem for the Southern Federal District was the employment of graduates of higher educational institutions. Thus, in 2004, when analyzing the need for specialists

with higher education it was revealed that for the last five years the labor market annually increased by about one hundred thousand only at the expense of university graduates, and most of them had humanitarian and socio-economic specialties, thereby worsening the already difficult situation in the sphere of employment of specialists of higher and middle levels. Thus, for example, in 2003 state and non-state higher education institutions of the Southern Federal District graduated 38.2 thousand people in these specialties, while the demand for them, according to the data of employment services, was only 14.5 thousand people. In some regions the spread was even higher: 9 times the excess was reached in Karachaevo-Cherkessia, 7 times in ◎ Ingushetia, 4 times - in Rostov region. [11]

II. Subsection Two

In the mid-2000s, the Chechen Republic lagged 7-8 times behind the Russian average in terms of per capita income. At the same time, the consumer market was only one-quarter supplied with local goods, and therefore the increase in incomes, including through allowances and compensatory payments, did not sufficiently stimulate the growth of production in the republic, and at the same time, despite the low incomes of the population, the cost of living here was noticeably higher. [11] Thus, in the 4th quarter of 2005, the minimum subsistence level for this region was set at 2793 rubles, which was slightly more than the size of the pension for disabled people of the second degree and noticeably lower than the subsistence level even in comparatively poor and small Ingushetia, while the average per capita income of the Chechen Republic was 512 rubles. And more than a third of Chechen families had to live on such an income. [12]

Various social transfers such as pensions, allowances, compensations, etc., assistance from relatives, and income from subsidiary and personal homestead farms were of great importance in ensuring the livelihood of households in the region in the face of high unemployment in the period under consideration. Support from relatives, mostly from those who had managed to find good jobs outside the republic, both in other Russian regions and abroad, was also an important source of survival. As is well known, kinship ties are highly valued in Chechen society, and close ties with parents remain with children until the end.

As we have already mentioned earlier, employment in subsidiary and personal household farms contributed to the survival of the region's population. It should be noted that in the conditions of fragmentation and changes in the existing production structures, personal subsidiary (household) farms of rural residents begin to acquire great importance as a source of agricultural products and concentration of a significant part of production resources and activities. Personal subsidiary farms become for many rural residents the only way of life support and livelihood. Thus, according to researchers' calculations, if properly managed, a plot of land of 6 hectares can provide a family of four people with vegetables, potatoes and fruit and vegetable products, in this regard, the training of rural residents, especially young people, agricultural knowledge and improving the culture of agricultural production are considered as an important direction of social policy in rural areas. [13] Personal subsidiary farms are more resilient and adapted to the market compared to large-scale production. In conditions of economic crisis, home agricultural production is beginning to play an important role in the survival of the majority of not only rural but also urban residents.

On February 19, 2007, in the session hall of the Ministry of Finance of the Chechen Republic in the framework of the round table entitled “A New Economic Strategy for the Chechen Republic”, it was pointed out that it was necessary to elaborate and start implementing a long-term development program for the republic based on the current socio-economic situation. Employment growth was the main condition for increasing the population's income, which, in turn, was impossible without the corresponding development of production and social infrastructure. Of great importance in improving the quality of life and the development of many industries, especially those based on the

use of natural resources (oil production, agriculture, forestry, tourism, recreation) was the need to restore the natural environment and its protection. [14]

The implementation of program activities in accordance with the planned goals and objectives allowed the leadership of the republic to increase real incomes of the population by the end of 2010 in 1.3-1.5 times, nominal average monthly accrued wages - in 1.7 times, the level of officially registered unemployment decreased by 2 times compared to 2005. [15]

The Russian Federation Government Resolution of April 15, 2014 approved the state program "Development of the North Caucasus Federal District until 2025", the main purpose of which was to improve the welfare and quality of life of the population of the republics that make up the North Caucasus Federal District, ensuring the reduction of their lagging behind the average Russian level

Necessary for the solution of this problem was the formation of a dynamically developing and competitive economy, which, in turn, provided for:

- increasing investment activity and attractiveness of the republics of the North Caucasian Federal District;
- formation of modern tourist infrastructure of tourist-recreational special economic zones on the territories of the republics of the North Caucasus Federal District, Krasnodar Krai and the Republic of Adygea;
- increasing the number of beds in collective accommodation facilities in such a specially protected ecological resort region of the country as Caucasian Mineral Waters;
- creating new jobs in competitive sectors of the economy and reducing the unemployment rate;
- ensuring an increase in the population's monetary income and reducing the unemployment rate;
- modernization of health care, education, social protection and social services;
- Ensuring accessibility of medical care for the population at all stages and preschool education services;
- creating conditions for increasing the birth rate and life expectancy of the population, increasing the share of students studying in the first shift in general educational organizations. [16]

In general, it should be noted that the state measures to achieve sustainable socio-economic development of the region, taken within the framework of the noted program can be considered effective. Thus, the gross regional product in 2022 amounted to 268068,5 million rubles, which exceeded the 2005 figure by more than 11 times; the gross regional product per capita increased from 20038,4 rubles in 2010 to 177859,9 rubles in 2022, i.e. by almost 9 times; the volume of agricultural production in 2023 amounted to 50861,0 million rubles, which was more than 11 times higher than in 2005; investments in fixed assets increased 9 times since 2005, reaching the mark of 119515.31 million rubles; the number of officially registered unemployed from 332.7 thousand people in 2005 decreased to 51.8 thousand people in 2023, i.e. by 84%. [17] Based on the world experience, it can be noted that significant economic successes are achieved only by such territories, in which management mechanisms based on the principles of social justice, pursue the goal of creating equal conditions for sustainable human development, contribute to the development of his intellectual and physical abilities, the growth of the quality of life of the population as a whole.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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RISKS OF FINANCIAL EXCLUSION AMONG THE ELDERLY: EMPIRICAL EVIDENCE FROM THE REPUBLIC OF MOLDOVA

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Abstract

Combating extreme poverty and promoting financial inclusion are essential priorities for sustainable development, especially in emerging economies. The Republic of Moldova faces high levels of poverty, particularly among the elderly population, which requires targeted measures to reduce financial vulnerability. This study investigates the degree of financial inclusion of older people in the Republic of Moldova, identifying barriers that limit access to financial services and assessing the influence of socio-demographic factors through a logistic regression model. The results highlight that education level and income are the most important determinants of financial inclusion. Based on the empirical findings, the research proposes recommendations for the development of a national financial inclusion strategy, the development of financial products adapted to the needs of seniors, and the promotion of financial and digital literacy. The study contributes to the literature on financial exclusion and provides practical directions for inclusive public policies in the demographic and economic context of the Republic of Moldova.

Keywords: financial inclusion, vulnerability, elderly population, poverty, financial literacy

I. Introduction

Globally, combating extreme poverty remains one of the most pressing challenges to sustainable development. Currently, approximately 692 million people, or 8.5% of the world's population, live on less than $2.15 a day, which places them below the extreme poverty line. Progress made in recent decades has been significantly slowed by modest economic growth, the negative effects of the COVID-19 pandemic, and increasing economic and social fragilities. As a result, poverty in low-income countries has reached levels higher than those recorded before the pandemic. According to World Bank estimates, by 2030, approximately 7.6% of the global population will still live below the extreme poverty line, which underlines the need for urgent and coherent measures to promote accelerated and inclusive economic growth [1].

Financial inclusion, closely linked to digital transformation, plays a decisive role in reducing economic vulnerabilities. The latest Global Findex 2025 report [2], entitled "Connectivity and Financial Inclusion in the Digital Economy", highlights both remarkable progress in the use of financial services and the persistence of significant gaps in access to them. Globally, 79% of adults now have a bank account, either at a financial institution or through a mobile payment provider,

compared to 74% in 2021 and 51% in 2011, when the first data were collected. In low- and middle-income economies, 75% of adults have access to an account, but gaps in digital access and low levels of financial literacy continue to limit the effective use of available services. It is estimated that approximately 1.4 billion adults globally remain outside the formal financial system, and digital technologies offer significant potential for expanding financial inclusion, particularly through mobile phones and digital bank cards [3].

The Republic of Moldova faces considerable challenges in this area, being one of the countries with the highest poverty rates in the region. According to data from the National Bureau of Statistics [4], 31.6% of the population lived below the absolute poverty line in 2023, a level much higher than the European Union average. The situation is even more acute among the elderly: the absolute poverty rate for the population aged 60 and over was 43.7% in 2023. This vulnerability is amplified by the demographic aging process: currently, 17.4% of the population of the Republic of Moldova is over 65 years old, and by 2040 this proportion is forecast to reach 25% [5]. In these conditions, promoting financial inclusion becomes a strategic necessity, both for poverty reduction and for strengthening social cohesion. This study was initiated to answer the research question: what is the level of financial inclusion of vulnerable groups, especially the elderly in the Republic of Moldova, and what are the challenges they face in accessing financial services? The research objectives aimed to: analyze the degree of use of financial services, identify barriers that limit access to these services, and formulate practical recommendations for the development of public policies and institutional solutions aimed at contributing to increasing financial inclusion and reducing the social vulnerability of the disadvantaged population.

II. Literature review

The issue of financial inclusion has been extensively analyzed by researchers in recent years. There are studies that address various scientific and methodological aspects of this phenomenon. The interaction between financial inclusion and social inequalities was analyzed by a group of authors led by Marta de la Cuesta-González [6]. They focused on the analysis of a group of vulnerable consumers in urban areas, namely those who face poverty and social exclusion. The study found that the difficulties in using financial services for these vulnerable groups are caused by banking pressure and lack of financial education.

Other research has emphasized the fact that household income is a determining factor in the adoption and promotion of certain digital financial practices [7]. A significant aspect emphasized by foreign researchers is the correlation between financial vulnerability, income and other socio-demographic characteristics. For example, the level of education of individuals is one of the critical characteristics [8], which has an impact on income levels, on the one hand, and indicates or creates risks related to the knowledge needed to promote financial inclusion, on the other hand.

International organizations emphasize that older people are among the most affected by financial exclusion, as a result of the accumulated barriers: modest incomes, cognitive and physical limitations, low digital literacy and the lack of financial products adapted to the needs of old age [9], [10]. The barriers to financial inclusion of this group have also been highlighted in the works of the authors Msweli & Mawela [11]. In response to the challenges stated, at the international level, the G20 Fukuoka Policy Priorities [10] promote policies oriented towards equity, digital literacy and the development of personalized financial products for seniors. In the Republic of Moldova, the National Program for Active and Healthy Ageing 2023–2027 [12] includes measures to reduce the social and financial exclusion of older persons. These efforts are supported by projects implemented by UNFPA Moldova, focused on digital literacy and creating an equitable framework for access to financial and public services [13].

III. Methods and Data

This study is based on the analysis of statistical data on income, education and the degree of access to financial products and services. The data used were taken from the reports of international authorities: World Bank, OECD, as well as the responsible national institutions: the National Bureau of Statistics, the National Social Insurance House, and the National Bank of Moldova. In order to facilitate the interpretation of the indicators by readers from other states, the financial values of the indicators in the Republic of Moldova were expressed in the reference currency - euro.

The reference period used in the research covers the years 2020-2024, and for the comparison of the indicators, the year 2024 was taken as a benchmark, this being the most recent for which data was available at the time of the research.

The research used factor analysis, based on data collected through a questionnaire approved by the Ethics Committee of the institution where the research was conducted. Taking into account the risk of limited digital skills of the elderly, data collection was carried out with direct assistance from trained interviewers using the Google Forms platform. The distribution of respondents according to socio-demographic characteristics obtained in the final stage of the research can be seen in Fig. 1.

We note that the research was designed as a pilot study, with an exploratory nature, since there are no previous empirical investigations specifically dedicated to the financial integration of the elderly in the Republic of Moldova.

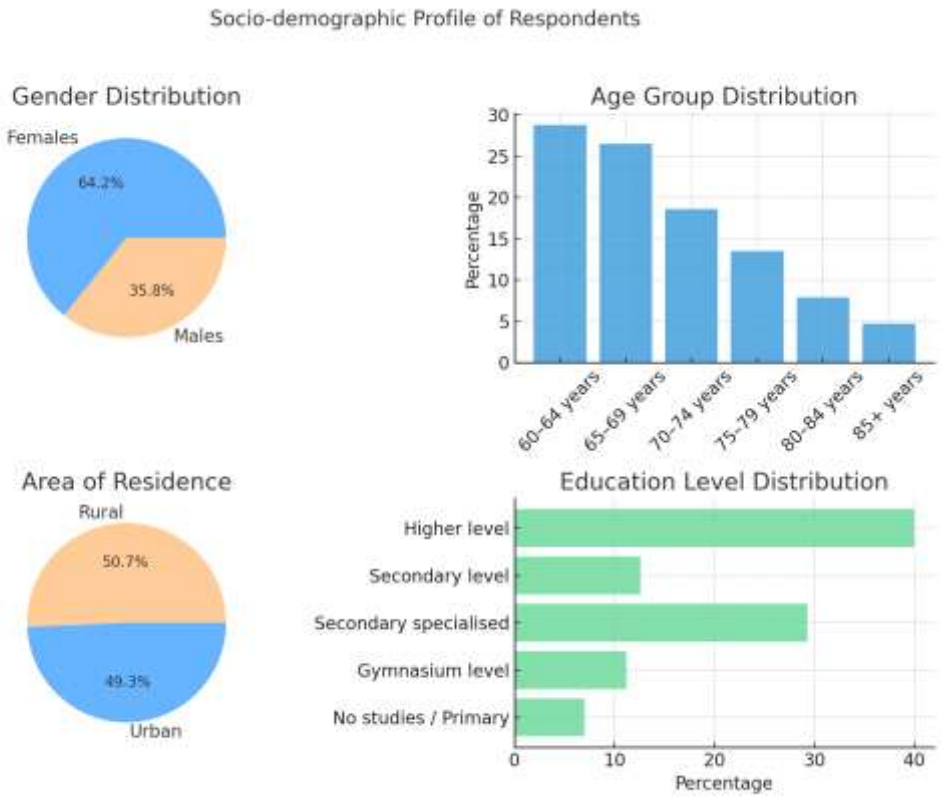


Fig. 1: *Socio-demografic profile of respondets*

Although the sample size is relatively small, this structuring allowed for the capture of a diversity of relevant opinions and experiences, thus ensuring an exploratory representativeness appropriate to the purpose of the study.

To identify factors associated with the likelihood of older people being financially integrated, we estimated a binary logistic regression model, using the following general formula:

$$log\left(\frac{p}{1-p}\right) = \beta^0 + \beta^1 * Education + \beta^2 * Income + \beta^3 * Age + \beta^4 * Sex + \beta^5 * Residence + \Sigma\beta_i * Stat_eco + \varepsilon \quad (1)$$

Where,

p - represents the probability that a person is financially integrated;

βn - are the estimated coefficients associated with the explanatory variables;

ε - is the random error term.

The estimation of the logistic regression model (Table 1) was performed using the Python programming language, through the statsmodels library, calling the Logit() function based on the design matrices constructed using the patsy package. This approach allowed for the rigorous estimation of the coefficients related to the categorical variables included in the model. For an intuitive and clear interpretation, the resulting coefficients were analyzed both in logit (log-odds) format and converted into odds ratios (odds ratio).

Table 1. *Regression model indicators*

Variabilă	Coef.	Std.Err.	z	p>|z|	Confid. interval [0.025	0.975]	OR
Intercept	-1.1786	1.2886	-0.9146	0.3604	-3.7041	1.3470	0.3077
Education (medium)	0.6338	0.5507	1.1509	0.2498	-0.4456	1.7131	1.8847
Education (high)	2.3028	0.6106	3.7711	0.0002	1.1059	3.4996	10.0018
Income (medium)	0.2706	0.4376	0.6185	0.5363	-0.5870	1.1283	1.3108
Income (high)	1.4686	0.7238	2.0290	0.0425	0.0500	2.8873	4.3433
Age group (65-69)	-0.4967	0.4725	-1.0512	0.2932	-1.4229	0.4294	0.6085
Age group (70-74)	0.0758	0.5139	0.1474	0.8828	-0.9315	1.0830	1.0787
Age group (75-79)	-0.8300	0.6055	-1.3708	0.1704	-2.0167	0.3567	0.4360
Age group (80+)	-0.8011	0.6350	-1.2617	0.2071	-2.0456	0.4434	0.4488
Economic status (active)	0.6108	0.5254	1.1626	0.2450	-0.4189	1.6405	1.8419
Sex (female)	-0.1542	0.3675	-0.4197	0.6747	-0.8745	0.5660	0.8571
Residence (rural)	-0.1596	0.3833	-0.4165	0.6771	-0.9109	0.5916	0.8525

Source: Authors estimation

This integrated approach, based on official statistical data, rigorous econometric tools, and an exploratory perspective on the elderly population in the Republic of Moldova, provides a solid basis for understanding the factors that shape financial inclusion and underpin relevant public policy directions.

IV. Results

In the last five years, 2020-2024, the Republic of Moldova has seen an increase in the number of payment cards in circulation. In 2024, this indicator reached 3.75 million cards (see Fig. 2), which means that each citizen of the Republic of Moldova owns 1.5 bank cards, comparable to the European Union average of 1.6 payment cards per capita. Taking into account the fact that only 58.7% of the total number of cards are active, we can see that the degree of use of this financial service remains low in the Republic of Moldova.

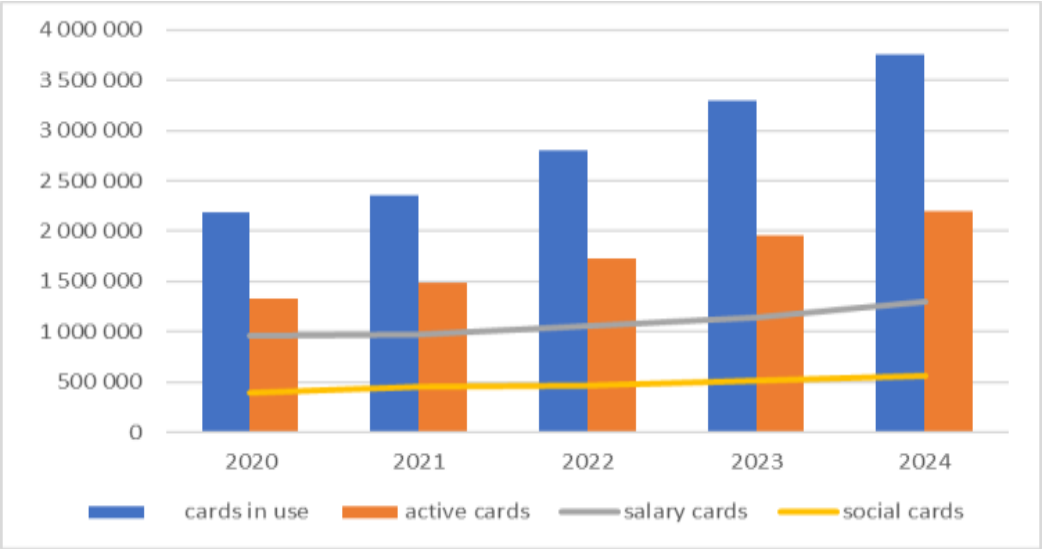


Fig. 2: *Number of payment cards in circulation, 2020-2024*

The activity rate of cards in circulation is approximately 80%, with social cards being the most active. Initially, they were mainly used for cash withdrawals related to social benefits, but, in the context of the COVID-19 pandemic, their use for cashless payments has increased significantly. In just four years, the share of cashless payments made with social cards has increased from 52% in 2019 to 76% in 2023, approaching the general average of cashless payments, which is 85.5%. This indicator is relevant in our research, as it reflects the level of access to banking services by the vulnerable population, with the beneficiaries of social benefits being, for the most part, people in difficulty or unable to obtain sufficient income.

Despite the positive dynamics, data on other financial products remain well below the European average. For example, private insurance services are little accessed by the population of the Republic of Moldova. Insurance density, measured by reporting the total volume of gross written premiums to the population, reaches only 65 Euros in 2024. In the European Union, the average of this indicator is approximately 2000 Euros [14].

Regarding credit services, we consider that the low level of income is a major impediment to accessing credit, because social groups with low incomes are ineligible for credit. The same situation is also in the case of savings products offered by the banking and non-banking market in the Republic of Moldova. Even though, according to NBM data, bank deposits are the most used savings instruments, these financial products can still be accessed if the income level exceeds expenses, generating an amount of free money for storage.

There is a potential for increasing financial inclusion based on the expansion of digitalization significantly boosted by the COVID-19 pandemic. We know that digital technologies offer a powerful solution for expanding access to financial services. Bank account holders are increasingly using their mobile phones or debit or credit cards linked to their accounts to make transactions. The Republic of Moldova has an advantage due to the high level of internet connection, but also the increased penetration of electronic connection devices. Approximately six out of ten households (57.3%) in the country have a computer at home. It is worth noting that in recent years consumers have changed their preferences by choosing other, more accessible and convenient devices to browse the internet, such as mobile phones. The overall internet connection rate in the Republic of Moldova in 2023 was 88.1% [15] (see Fig. 3).

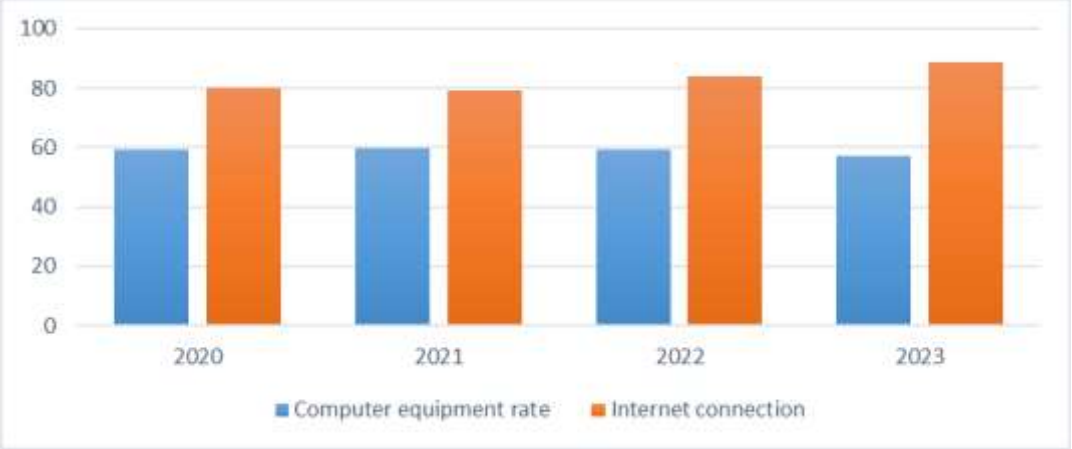


Fig. 3: *Access to Internet by the population of the Republic of Moldova*

With regard to financial education, we note that current initiatives focus mainly on promoting general financial literacy within educational institutions, but pay limited attention to the development of digital financial literacy skills. Courses are geared towards the younger generation and there are very few opportunities for the development of financial and digital skills for adults in the Republic of Moldova. Although several public institutions and financial market actors are active in this area, the lack of a coherent national strategy and a formal coordination mechanism leads to gaps and overlaps.

Statistical data analyzed at national level show that the financial situation of the elderly is quite complicated, oscillating around the absolute poverty line and the subsistence minimum (see Fig. 4). We can see that the minimum pension is only 16 Euros higher than the subsistence minimum, and the average pension, at the country level, exceeds this subsistence minimum by only 50 Euros. These observations indicate that pensioners in the Republic of Moldova have extremely low pension incomes, which limits their ability to access financial services.



Fig. 4. *Overview of pensioner population income by 2024*

The estimated logistic regression model allowed us to understand which sociodemographic characteristics influence the likelihood of financial inclusion of older people. Based on the analysis, we find that the most important factors determining a person's familiarity with the financial system and the use of financial services are:

Determining factors

1. *Education*. People with higher education are 10 times more likely to be financially integrated compared to those with no education or primary education. The level of secondary education has a positive effect, but not statistically significant, which means that only advanced education matters decisively.
2. *Incomes*. People with higher incomes (equivalent to approximately 400 euros/month and above) are 4.3 times more likely to be financially integrated than those with lower incomes.

Factors with potential influence, but not statistically significant

1. *Age.* Older people (75+, 80+) tend to be less financially included, but the differences are not

large enough to be statistically significant.

2. *Economic status*. Those who are economically active have a higher probability of integration, but even this result is not strong enough to be taken into account.
3. *Gender and residential environment*. It doesn't matter if the person is male or female, urban or rural – these variables do not significantly influence financial inclusion when analyzed alongside other factors.

The correlation between financial inclusion, education and income was a premise, within the framework of this study, for the analysis of objective data, based on official statistics of the National Bureau of Statistics. Thus, over the last five years, it is observed that with the increase in the level of education, income also increases. People with higher education consistently have the highest incomes (see Fig. 5).

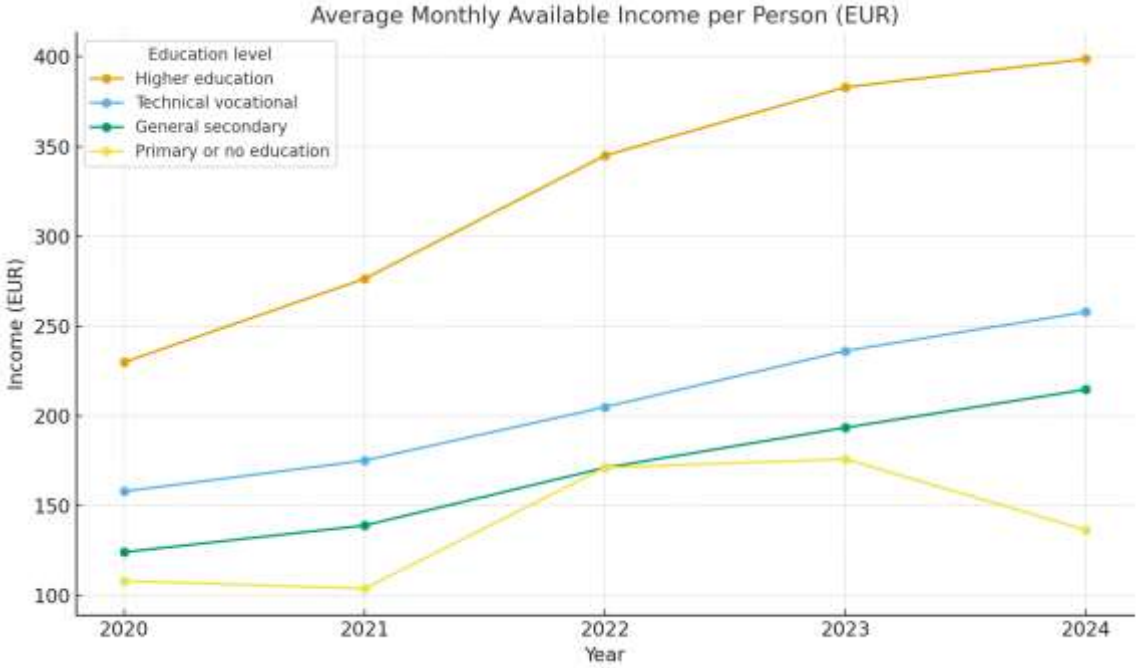


Fig. 5. *Average monthly disposable income per person, by level of education (2020–2024)*

Starting from the observation that education and income are the main determinants of financial inclusion, we believe that public policies aimed at increasing it should focus on improving the level of financial education and supporting low-income groups through financial support measures. In this regard, we come up with the following recommendations for governments, financial and educational institutions:

1. Developing a National Financial Inclusion Strategy that aims to facilitate access, use and quality of financial services for citizens and households from diverse social backgrounds, with an emphasis on vulnerable groups or those excluded from the financial system.
2. Establishing educational programs aimed at vulnerable groups that contribute to increasing their digital and financial skills.
3. Creating special financial products for seniors, with preferential conditions, adapted to the needs of the elderly, such as: savings products with preferential interest rates; credit lines with subsidized interest rates and simplified procedures; mobile banking applications with visually and functionally adapted interface.
4. Development of financial support programs for vulnerable groups, aimed at contributing either to increasing income levels (for example, through pension indexation) or to reducing expenses incurred by these groups (such as granting exemptions from paying utility bills).

The implementation of the proposed measures can significantly contribute to increasing the

degree of financial inclusion, which will indirectly lead to an improvement in the standard of living and well-being of vulnerable social groups, especially the elderly in the Republic of Moldova.

V. Conclusion

Financial inclusion is low in the Republic of Moldova and poses a challenge for vulnerable groups, especially the elderly. Even though there is an increase in the number of payment cards and internet access, older people continue to face difficulties in using financial services.

The research highlighted a number of obstacles that older people face in accessing financial services. The main barriers reported by respondents are low income and limited financial literacy. These two factors were also confirmed by the logistic regression model estimated in the study, as essential determinants of the level of financial inclusion. Thus, people with higher education have significantly higher chances of being financially included, as do those with incomes above the average level.

There are barriers related to the offer of financial services, including the lack of products adapted to the specific needs of older people. In addition, the low level of financial and digital literacy limits their ability to access and effectively use available financial products. To reduce these vulnerabilities, the active involvement of financial institutions is recommended, along with public policies supported by longitudinal research. Integrated measures are needed such as: a national financial inclusion strategy, the creation of banking products adapted to the elderly, accessible financial and digital education, as well as direct financial support for vulnerable categories (pensions indexation, tax exemptions, etc.).

VI. Acknowledgements

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CONFLICT OF INTEREST.
The authors declare that they have no conflict of interest.

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DIGITAL PLATFORMS AND THEIR ROLE IN PROMOTING CIRCULAR ECONOMY AND SUSTAINABLE CONSUMPTION

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Abstract

The article "The Impact of Digital Technologies on Sustainable Consumption and Production" explores the transformative role of digital innovations in advancing sustainability across industries. It focuses on how technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, and big data analytics are reshaping the way businesses and consumers interact with resources, leading to more sustainable consumption and production models. These technologies help optimize resource use by improving the efficiency of supply chains, enhancing waste management systems, and enabling real-time monitoring of environmental impacts. For instance, AI and machine learning algorithms allow companies to forecast demand more accurately, reducing overproduction and minimizing waste. IoT devices provide valuable data on energy and resource consumption, enabling more efficient production processes, while blockchain ensures transparency and traceability in supply chains, helping consumers make informed, sustainable choices. The article also examines the growing influence of digital platforms that promote sustainable consumption, such as apps encouraging eco-friendly purchasing decisions or online marketplaces for sharing and reusing goods. By leveraging data-driven insights, these platforms encourage consumers to adopt sustainable lifestyles, while businesses can better align their operations with sustainability goals. Additionally, the article delves into the potential for digital technologies to accelerate the transition to a circular economy, where products and materials are reused, repaired, and recycled instead of following a linear lifecycle. However, the article also addresses the challenges and limitations of adopting digital technologies for sustainability. These include concerns over data privacy, the energy consumption of digital infrastructures, the need for standardized regulations, and the widening digital divide that could limit the accessibility of these technologies in certain regions. Despite these hurdles, the potential of digital technologies to revolutionize sustainable consumption and production is immense, offering new pathways to achieve global sustainability targets and reduce environmental degradation.

Keywords: circular economy, resource optimization, waste management, real-time monitoring, supply chain transparency, eco-friendly platforms, sustainability goals, environmental impact, data privacy, regulatory challenges, digital divide.

I. Introduction

In the modern era, digital technologies are playing an increasingly pivotal role in transforming industries and reshaping how societies consume and produce goods. As the global community faces growing environmental challenges—such as climate change, resource depletion, and waste accumulation—there is an urgent need to shift towards more sustainable models of consumption and production. Sustainable Development Goal 12 (SDG 12), established by the United Nations, emphasizes the importance of responsible consumption and production patterns to ensure the long-term well-being of both people and the planet.

In this context, digital technologies like artificial intelligence (AI), the Internet of Things (IoT), blockchain, and big data analytics are emerging as powerful tools for fostering sustainable practices. These technologies offer unprecedented opportunities to enhance efficiency, reduce waste, and create transparency across supply chains, which are critical in promoting sustainability across various sectors.

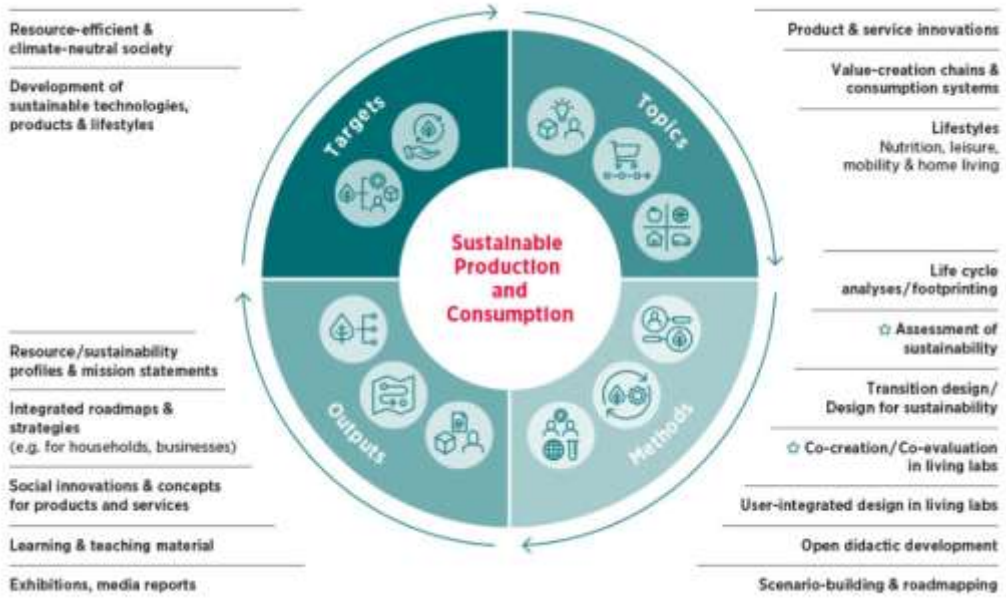


Figure 1. Sustainable Production and Consumption Division analyses

To create a climate-neutral and resource-efficient society in the medium to long term, it is essential to undertake a fundamental "dematerialization" of production and consumption. This involves implementing strategies focused on efficiency, consistency, and sufficiency, which ensure that products are designed to be "lighter on resources" and can be utilized for longer periods and in more effective ways. The process of achieving this is inherently tied to thoughtful design.

The Sustainable Production and Consumption Division is dedicated to analyzing, evaluating, and developing technological and social innovations through the use of real-world laboratories and living labs. These environments actively involve users in the development process, both before and during innovation implementation. Researchers assess the resource efficiency and social impacts of production and consumption along value chains, creating transformative approaches and scenarios that aim for climate neutrality, resource efficiency, and sustainability. Their focus areas include nutrition, leisure, mobility, and housing.

For meaningful changes in production and consumption patterns to take place, it is crucial to have companies that create and provide these innovative products and services. Additionally, empowered consumers who actively utilize these offerings are necessary, along with a supportive political framework that facilitates the transformation process.

The research undertaken by the Sustainable Production and Consumption Division encompasses several key areas:

- Sustainability and Resource Assessment: Evaluating the sustainability of materials and processes.
- Product and Service Innovations: Developing new offerings in real-world laboratories and living labs that prioritize sustainability.
- Education: Fostering knowledge and awareness around sustainable practices among consumers and businesses.

- Science-Based Innovation, Enterprise, and Consumer Policy Approaches: Informing policies that support sustainable production and consumption.

This research is characterized by its inter- and transdisciplinary nature, leveraging collaborations across numerous national and international networks. The Division draws upon extensive experience from various third-party funded projects, enhancing its ability to drive forward the agenda of sustainable production and consumption.

The integration of these digital innovations is not just limited to businesses optimizing their production processes but also extends to consumers who are becoming more empowered to make eco-friendly choices. Digital platforms are facilitating access to information, enabling consumers to adopt sustainable lifestyles, while businesses are using real-time data to reduce their environmental footprint.

However, while digital technologies present immense potential for advancing sustainability, their implementation comes with challenges. Issues such as the energy consumption of digital infrastructures, data security, and the need for comprehensive regulations to govern digital ecosystems must be addressed to ensure that these technologies contribute meaningfully to sustainable development.

This paper aims to explore how digital technologies are impacting sustainable consumption and production, highlighting both the opportunities they offer and the obstacles that must be overcome to harness their full potential.

Demographic shifts, including population growth and rapid urbanization, are intensifying pressure on existing food systems and agricultural resources. As global food demand rises, there is an urgent need for sustainable practices to ensure food security while safeguarding the environment. Additionally, the ongoing effects of climate change further strain the availability and quality of essential resources for agriculture, underscoring the importance of adaptation and innovation in food production. These complex challenges demand integrated, forward-thinking approaches to achieve sustainability in food systems, requiring transformative changes across agricultural practices.

A key aspect of this transformation involves the evaluation and adoption of advanced production technologies, which can help drive sustainable productivity growth. These technologies also hold potential for influencing broader trends, such as sustainable consumption patterns and reductions in greenhouse gas (GHG) emissions.

Digital technologies, including artificial intelligence (AI), big data (BD), the Internet of Things (IoT), and cloud computing (CC), are increasingly recognized as vital tools for addressing sustainability challenges in food systems. These technologies can enhance supply chain transparency and efficiency, reduce food loss and waste, and optimize resource use. For example, automation can streamline production processes, while biotechnologies can improve crop resilience and quality, essential for maintaining sustainable production in the face of climate change. Furthermore, digital innovations can optimize transportation and logistics, lowering carbon footprints and minimizing environmental impacts across the food supply chain.

Investment in research and development of digital technologies could yield significant benefits, particularly in promoting sustainable food systems globally. However, fully realizing the potential of these technologies requires not only technical innovation but also increased awareness, understanding, and adoption by all stakeholders in the food supply chain.

This paper seeks to explore the broader impact of digital technologies on sustainable food production and consumption. Specifically, it aims to assess how these innovations affect municipal waste, primarily stemming from food consumption, and agricultural emissions of nitrogen and methane, which are key contributors to GHG emissions. Additionally, the study aligns with the objectives of Sustainable Development Goal 12 (SDG12), which focuses on promoting responsible consumption and production patterns.

Despite the growing importance of digital solutions in agriculture, research gaps remain, particularly in the form of detailed longitudinal analyses that track the long-term impact of digital technologies on food sustainability. There is also a need for a more comprehensive understanding

of the intricate relationships between food production, consumption, and critical variables tied to sustainability.

The originality of this study lies in its application of Structural Equation Modeling (SEM) to assess correlations between the adoption of digital technologies and key sustainability metrics, particularly in relation to food production and consumption. By offering valuable insights into how these technologies can mitigate food waste and agricultural emissions, this research aims to contribute to the development of policies and practices that foster long-term food sustainability.

The structure of this paper includes six sections: an introduction outlining the research purpose and objectives, a literature review and hypothesis development, a description of the research methodology, presentation of the findings, discussion of the results, and conclusions summarizing the key contributions of the study.

II. Methods

This section outlines the research design, data collection, and analysis methods used to assess the impact of digital technologies on sustainable food production, consumption, and related sustainability metrics. The study primarily focuses on exploring the correlations between digital technology adoption and key variables such as municipal waste, greenhouse gas (GHG) emissions from food production (specifically nitrogen and methane emissions), and overall progress towards Sustainable Development Goal 12 (SDG12), which promotes responsible consumption and production.

1. Research Design

This study employs a mixed-methods approach, combining quantitative data analysis with qualitative insights to understand the multifaceted impact of digital technologies on food sustainability. The research was designed to capture both the breadth and depth of technological influences across the food supply chain, from production to consumption.

Structural Equation Modeling (SEM) was chosen as the primary analytical tool to assess the relationships between digital technology adoption and sustainability outcomes. SEM allows for the testing of complex relationships between observed and latent variables, making it well-suited for evaluating the multi-dimensional effects of digital technologies on food systems.

2. Data Collection

The study utilized secondary data sources for quantitative analysis, including data from international organizations, government reports, and industry publications. These data sources provided information on the following variables:

- Adoption of digital technologies: Data on the implementation of AI, Big Data, IoT, and cloud computing in agricultural and food supply chain processes were gathered from industry reports and technology adoption studies.
- Municipal waste: Data on food waste at the municipal level, particularly in urban areas, were sourced from reports by the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization (FAO).
- Agricultural GHG emissions: Data on nitrogen and methane emissions from agriculture were obtained from reports by the Intergovernmental Panel on Climate Change (IPCC) and national greenhouse gas inventories.
- Sustainable Development Goal 12: Indicators related to SDG12 were collected from the United Nations' Sustainable Development Goals (SDG) database, focusing on responsible consumption and production patterns, particularly those tied to food systems.

In addition, qualitative data were collected through interviews with industry experts, technology providers, and stakeholders in the food supply chain, including farmers, food processors, retailers, and policymakers. These interviews provided insights into the practical challenges and opportunities of implementing digital technologies in real-world settings.

3. Data Analysis

The analysis followed a two-step process:

A. Quantitative Analysis using Structural Equation Modeling (SEM)

SEM was used to test the hypotheses on the impact of digital technologies on sustainable food production, consumption, and waste reduction. This method allowed for the examination of both direct and indirect effects of technology adoption on food sustainability metrics. Key steps in the SEM analysis included:

1. Model Specification: A conceptual model was developed to represent the hypothesized relationships between digital technology adoption, food waste reduction, GHG emissions, and SDG12 indicators.
2. Model Estimation: Maximum likelihood estimation (MLE) was used to estimate the parameters of the SEM model.
3. Model Fit Assessment: Goodness-of-fit indices, such as the Chi-square test, Comparative Fit Index (CFI), and Root Mean Square Error of Approximation (RMSEA), were used to evaluate the model fit.
4. Hypothesis Testing: The relationships between variables were tested for significance using standard error estimates and p-values.

B. Qualitative Analysis

A thematic analysis of interview data was conducted to complement the quantitative findings. Key themes included:

- Barriers to technology adoption: Challenges faced by stakeholders in integrating digital solutions into their operations.
- Opportunities for sustainability: Insights into how digital technologies can contribute to improved resource efficiency, waste reduction, and sustainable practices.
- Policy and regulatory support: The role of governments and international organizations in facilitating or hindering the adoption of sustainable technologies.

4. Hypotheses Development

Based on the literature review and theoretical foundations, several hypotheses were developed to guide the research. These hypotheses included:

- H1: The adoption of digital technologies (AI, Big Data, IoT, CC) in the food supply chain positively correlates with a reduction in municipal food waste.
- H2: Digital technologies in agriculture contribute to the reduction of nitrogen and methane emissions, improving agricultural sustainability.
- H3: Digital technologies in food systems positively impact the achievement of Sustainable Development Goal 12 by enhancing sustainable consumption and production patterns.
- H4: The effect of digital technologies on food sustainability is mediated by improved supply chain transparency and collaboration among stakeholders.

5. Limitations

Several limitations should be acknowledged in this study. First, reliance on secondary data may present challenges regarding the consistency and accuracy of the data, as reporting practices vary across sources. Second, the cross-sectional nature of the quantitative data limits the ability to draw conclusions about long-term trends. Future research could benefit from longitudinal studies that track the impact of digital technologies over time.

In summary, the methods employed in this study, including SEM and qualitative interviews, provide a comprehensive framework for assessing the impact of digital technologies on food sustainability, focusing on critical variables such as municipal waste, GHG emissions, and progress towards SDG12. The combination of quantitative and qualitative data ensures a robust understanding of the challenges and opportunities presented by digital innovations in the food sector.

III. Results

The use of digital technologies in agriculture can have a significant impact on the efficiency and

sustainability of food systems. However, for these technologies to achieve a truly transformative effect, their implementation must consider the social, economic, and cultural contexts of the communities in which they are used. Improving access to food and reducing the carbon footprint of global agri-food systems are critical priorities for achieving Sustainable Development Goals (SDGs) and ensuring global food security.

The primary objective of this study was to explore the impact of digital technologies on food production and consumption, with a particular focus on their influence on municipal waste, largely originating from food consumption, nitrogen and methane emissions from agriculture, and sustainable consumption and production in alignment with SDG12. The study utilized longitudinal data to track trends over time, offering insights into how these technologies affect sustainability in the food sector. Additionally, it examined the relationships between agricultural production, waste generation, and greenhouse gas (GHG) emissions to better understand the complex interactions in the food supply chain.

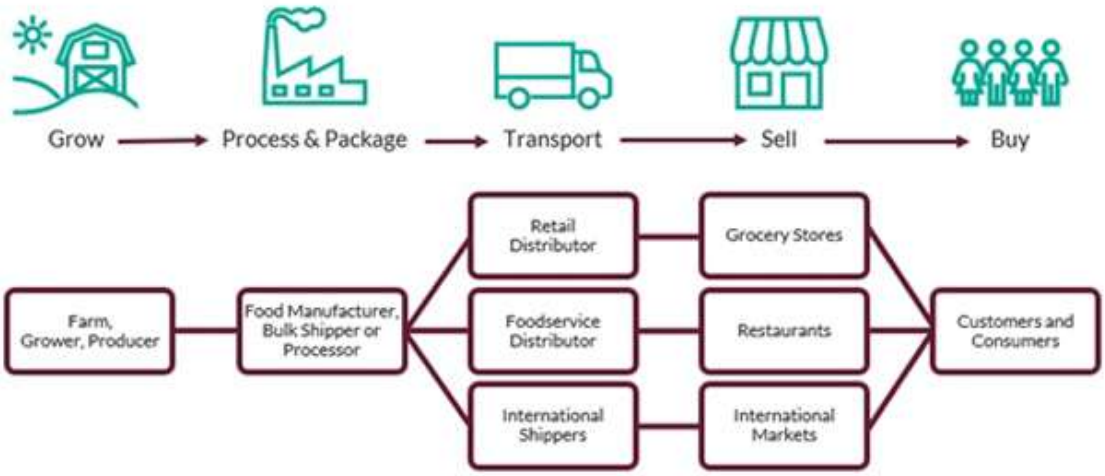


Figure 2. The Global food supply chain

Food supply chains represent one of the most significant yet underappreciated areas for investment and business innovation. This industry impacts every individual globally and stands at the precipice of disruption.

In the medium term, the future of food supply chains will revolve around assembling a network of resilient suppliers capable of providing year-round harvests, with inputs sourced from around the globe. The long-term outlook is even more promising, especially with emerging technologies guiding us toward a post-carbon future. For instance, "touchless agriculture" is one of the transformative technologies on the horizon, utilizing extensive data analytics to help farmers select optimal seeds without the need for physical planting, potentially revolutionizing agricultural practices.

The global food supply chain plays a critical role in transporting, processing, and marketing food worldwide. Globalization has facilitated this process, enabling food chains to deliver substantial quantities of quality products to nourish approximately one in nine people on Earth. However, globalization should not be viewed solely from an economic standpoint; its social and environmental implications are equally important.

While globalization enhances the availability of quality foods and fosters advancements in agricultural techniques and transportation, it also poses sustainability challenges. The environmental and cultural impacts of global food chains cannot be overlooked. For example, the globalization of food production can lead to job losses in specific regions due to outsourcing and shifts in transportation practices. It has contributed to enhanced food security but simultaneously raised concerns regarding food safety.

Moreover, global food chains have induced considerable ecological disturbances at local,

regional, and even international levels. Although globalization brings numerous advantages, it also carries side effects that often go unnoticed or unaddressed.

Given that globalization is a persistent reality, food supply chains must take proactive measures to ensure their long-term sustainability. This requires a holistic approach that balances economic growth with environmental stewardship and social responsibility, ensuring that food systems remain resilient and equitable for future generations. Embracing sustainable practices within global food chains will be essential for mitigating adverse effects while maximizing the benefits of globalization.

The key findings of the study revealed several important points. First, there is a negative relationship between digital technologies and SDG12, indicating that while these technologies can have a positive effect on sustainability, their overall impact on consumption and production is moderate but significant. This supports the H2 hypothesis, suggesting that the application of digital technologies may have unintended consequences for sustainable development. The study also found that increasing efficiency through digital tools can paradoxically lead to higher resource consumption.

The study also highlighted the challenges posed by digitalization in agriculture. As Kamble et al. pointed out, these include ensuring equal access to technology and data for all stakeholders, particularly smaller producers, as well as addressing concerns around data protection and cybersecurity in increasingly complex and interconnected food supply chains. Despite these challenges, the research confirmed a positive relationship between agricultural production and both sustainable consumption and the generation of municipal solid waste, validating the H1 and H3 hypotheses. This finding emphasizes the close connection between agricultural productivity and sustainability, as increased production brings both benefits and challenges for waste management.

Moreover, the study demonstrated that digital technologies can play a crucial role in reducing municipal solid waste by optimizing various processes such as production, distribution, and inventory management. This finding, which aligns with the research of Bahn et al., validates the H4 hypothesis, showing that digital tools can contribute to more effective waste management and, in turn, support the sustainability of food systems. However, the study also stressed the importance of considering the indirect environmental impacts of digital technologies, such as increased energy consumption and the generation of electronic waste. These factors must be managed carefully to ensure that the sustainability benefits of digitalization in agriculture are not undermined.

In conclusion, the study highlights the dual nature of digital technologies in the agricultural sector. While they offer significant potential to reduce waste, improve supply chain efficiency, and contribute to sustainable food production, they also present risks related to increased energy consumption and unequal access. As a result, a balanced and cautious approach to the implementation of these technologies is essential to ensure they contribute positively to the long-term sustainability of food systems.

IV. Discussion

I. Subsection One

The findings of this study indicate that sustainable consumption and production practices, in alignment with Sustainable Development Goal 12 (SDG12), have a negative influence on greenhouse gas (GHG) emissions from agriculture, supporting the H5 hypothesis (fig.3). This result highlights the critical role that sustainable practices can play in reducing agricultural emissions and mitigating environmental impact. These findings are consistent with the research of Dong et al., Agrawal et al., and Sharma et al., who emphasize that companies can enhance their operational efficiency using digital technologies while contributing to sustainability efforts, particularly in achieving SDG12. By improving efficiency and reducing GHG emissions, digital technologies can strengthen the sustainability of supply chains, making them more transparent and accountable. Furthermore, these technologies facilitate the monitoring and reporting of sustainable practices, thereby reinforcing sustainability goals across industries.

The study also confirmed the H6 hypothesis, revealing a positive relationship between agricultural production levels and GHG emissions. This suggests that as agricultural production increases, so too do emissions, underscoring the urgent need for more sustainable agricultural practices to reduce environmental degradation. Research by Kabange, Xu, Wang, and Ouyang supports these findings, showing that agriculture is a significant source of global GHG emissions due to activities like livestock fermentation and fertilizer use. However, modern agricultural practices, coupled with the adoption of digital technologies, can help mitigate these emissions by enhancing efficiency and sustainability.

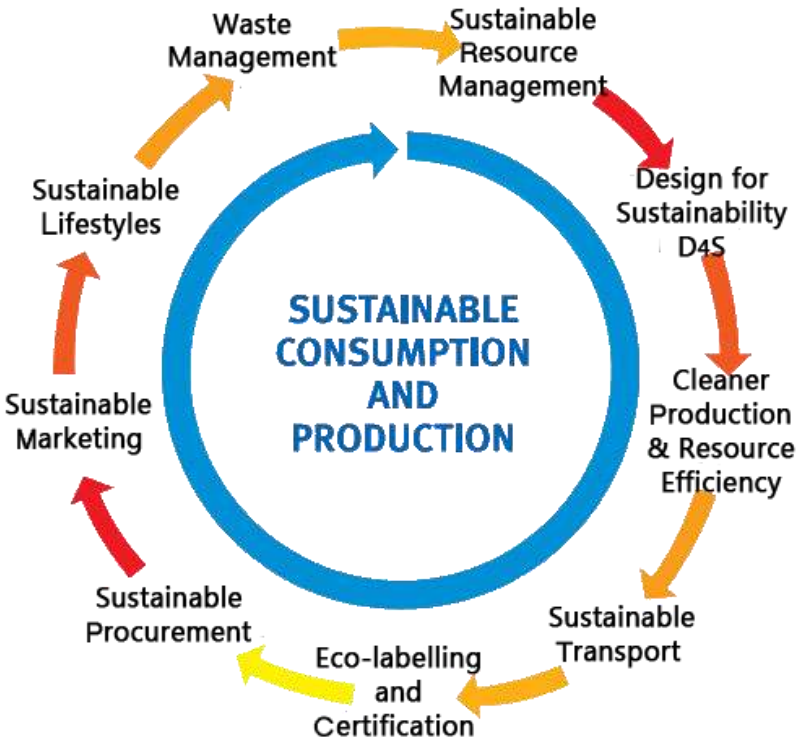


Figure 3. Sustainable consumption & production

Digital technologies, when implemented in agriculture, can provide significant advantages, including better resource management, real-time decision-making tools, and more sustainable farming practices. The results highlight the importance of promoting the adoption of these technologies across the food supply chain to meet sustainability goals. However, challenges remain, particularly regarding the equitable access to these technologies, especially for small- and medium-sized primary producers. Investments in digital infrastructure and education are necessary to support the transition to more efficient and sustainable agri-food systems.

The European Union (EU) is taking a proactive stance in promoting the digitalization of agriculture as part of its efforts to transition to more sustainable farming practices. The concept of the "fourth agricultural revolution" emphasizes the potential for digital technologies to transform agriculture radically. By integrating these technologies, production processes and resource management can be optimized, enhancing sustainability and resilience in the face of current and future challenges.

Digital technologies offer numerous benefits to agriculture, such as increased efficiency, reduced environmental impact, improved food quality, and higher incomes for producers. These tools also support more sustainable farming practices by reducing reliance on external inputs like pesticides and chemical fertilizers, while promoting the efficient use of natural resources. Additionally, they enhance access to agricultural information and services, particularly for rural producers, fostering greater transparency and efficiency across the entire food supply chain.

However, despite the advantages of digitalization, there are significant barriers to its widespread adoption. The high cost of advanced agricultural technologies can be prohibitive for primary producers, particularly in developing countries. Furthermore, a lack of training and resources to support the adoption of these technologies may exacerbate existing inequalities, creating a digital divide within the agricultural sector. Therefore, efforts to promote digitalization must address these challenges to ensure that the benefits of technology reach all stakeholders and contribute to the broader goal of sustainable development.

II. Subsection Two

The challenges facing food systems are multifaceted and interconnected, reflecting the complexity and fragility of the global food chain. Issues such as population growth, competition for resources, climate change, dietary shifts, limited food access, unsustainable agricultural practices, and significant food waste contribute to the precariousness of food security. Rapid urbanization and population expansion place immense pressure on natural and agricultural resources, increasing the risks of food insecurity and environmental degradation. Climate change exacerbates these problems by directly impacting agricultural productivity and food accessibility for millions worldwide. Unsustainable farming methods further highlight the urgent need for reforms in agricultural and food supply chains to promote more equitable and sustainable production and consumption practices.

Reducing food waste and improving access to nutritious, sustainable food are essential to achieving future food security and sustainability. A sustainable food system benefits not only human health by ensuring access to safe, healthy food but also the environment and economies by protecting natural resources and supporting agricultural communities. As agriculture is a fundamental part of global economies and livelihoods, efficient and sustainable agricultural practices are critical to minimizing the sector's environmental footprint. The current production and consumption patterns exacerbate climate change through increased greenhouse gas (GHG) emissions, highlighting the need for more environmentally friendly agricultural practices that protect future generations.

This paper emphasizes the role of digital technologies in optimizing resource use and reducing environmental impacts, fostering more sustainable consumption and production patterns. Additionally, these technologies can mitigate municipal waste by improving resource management. However, without appropriate regulations and sustainable resource management strategies, the use of these technologies could lead to resource overuse, necessitating a balanced approach to their implementation. To fully harness the benefits of digital technologies, legislative and policy frameworks must evolve in tandem with technological advancements, facilitating widespread adoption in agriculture beyond the food industry.

Understanding the needs and perspectives of primary producers is also essential to developing digital solutions that support a more efficient and inclusive transformation in agriculture. Despite the paper's efforts to explore the relationships between digital technologies, sustainable food production, GHG emissions, and municipal waste, certain limitations exist. The longitudinal nature of the study, while tracking trends over time, may have been influenced by contextual factors or unforeseen events. Additionally, the study focused primarily on the relationship between digital technologies and key aspects of food sustainability, such as crop and animal output, municipal waste, nitrogen and methane emissions, and Sustainable Development Goal 12 (SDG12). Future studies should consider broader aspects of food sustainability, including the social and economic impacts of technological shifts, such as employment in agricultural labor, market access for small producers, or the equitable distribution of technological benefits.

Another important area for future research is the unintended consequences of digitalization in agriculture. While the benefits of digital technologies are substantial, their potential negative impacts, such as the risk of digital exclusion or the concentration of economic power among large corporations, must also be examined. Future studies could investigate the specific effects of emerging digital technologies, including the Internet of Things (IoT), data analytics, and artificial

intelligence (AI), on the sustainability of food systems. Such research would provide a more comprehensive understanding of how these technologies can be leveraged to enhance food system resilience while avoiding potential drawbacks.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest

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STIMULATING SUSTAINABLE CONSUMPTION THROUGH ECONOMIC STRATEGY AND REGULATION

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Abstract

This paper examines innovative resource tax approaches as crucial fiscal tools for mitigating unsustainable natural resource consumption. As global ecosystems face increasing pressure from overexploitation, the need for effective policy measures has never been more urgent. Traditional taxation models often fail to account for the environmental costs associated with resource extraction and consumption, leading to detrimental ecological impacts. This study investigates various resource taxation frameworks adopted in different countries, analyzing their effectiveness in promoting sustainable resource use and environmental conservation. The paper begins with a comprehensive review of existing literature on resource taxation, exploring concepts such as environmental externalities and the "polluter pays" principle. It then delves into case studies of successful resource tax implementations, focusing on how these measures have influenced consumption patterns and incentivized sustainable practices among businesses and consumers. The analysis highlights the importance of aligning tax structures with environmental goals, demonstrating how innovative tax strategies can drive both economic growth and ecological preservation. Furthermore, the research identifies key factors that contribute to the success of resource tax initiatives, including stakeholder engagement, public awareness, and the integration of tax measures into broader environmental policies. By presenting empirical evidence and real-world examples, the paper illustrates how effective resource taxation can lead to significant reductions in resource overuse and promote investment in renewable and sustainable alternatives. The findings underscore the potential of innovative resource taxes to serve not only as a deterrent against unsustainable consumption but also as a catalyst for transitioning towards a circular economy. This transition requires a collaborative effort between governments, businesses, and society, emphasizing the importance of transparency, accountability, and shared responsibility in resource management.

Keywords: Sustainable Consumption, Economic Strategies, Tax Incentives, Subsidies, Corporate Sustainability, Circular Economy, Consumer Behavior, Environmental Policy, Resource Efficiency, Green Innovation

I. Introduction

In the face of mounting environmental challenges, including climate change, pollution, and the unsustainable depletion of natural resources, the need for sustainable consumption has never been more urgent. Modern consumption patterns, characterized by excessive use of resources, waste generation, and reliance on fossil fuels, have led to significant ecological damage, threatening the planet's ability to sustain future generations. Addressing these challenges requires a shift towards sustainable consumption—defined as the use of products and services in a way that meets present needs without compromising the environment for future generations.

The pursuit of sustainable consumption is inherently complex, involving not just environmental considerations but also economic and social dimensions. It requires a holistic approach that encourages consumers to adopt environmentally friendly behaviors, while also promoting sustainable production practices within industries. Governments, businesses, and consumers all have critical roles to play in creating a more sustainable economy, and at the heart of these efforts are economic strategies designed to influence market behavior.

Economic strategies are powerful tools for shaping both consumer and producer choices. These strategies include taxes, subsidies, financial incentives, regulatory frameworks, and market-based mechanisms aimed at internalizing the environmental costs of production and consumption. For instance, carbon pricing mechanisms such as carbon taxes and cap-and-trade systems are designed to put a price on greenhouse gas emissions, encouraging businesses to reduce their carbon footprint and invest in cleaner technologies. Similarly, green subsidies and tax incentives for renewable energy, energy-efficient products, and sustainable business practices can accelerate the adoption of eco-friendly solutions across industries.

Moreover, economic strategies can drive innovation, fostering the development of sustainable technologies and products that reduce environmental impact. This is particularly relevant as consumer demand for sustainable products continues to grow. Companies are increasingly recognizing the competitive advantage of offering sustainable products, which not only aligns with consumer preferences but also contributes to corporate social responsibility (CSR) goals. Through policies that promote green innovation, economies can stimulate new business opportunities and growth while simultaneously addressing environmental concerns.

However, achieving sustainable consumption is not only about influencing producers; it is also essential to encourage consumers to make environmentally conscious decisions. Economic incentives such as eco-labeling, carbon pricing on consumer goods, and differential taxation (e.g., higher taxes on environmentally harmful products) can help guide consumers toward more sustainable choices. These strategies aim to make sustainable products more accessible and affordable, while discouraging the consumption of goods with a high environmental footprint.

This paper aims to explore the economic strategies that promote sustainable consumption and their potential to reshape consumer behavior, stimulate green innovation, and drive the global transition to a more sustainable economy. The following sections will delve into the various economic tools available, including fiscal policies, subsidies, market-based incentives, and regulatory approaches, providing a comprehensive analysis of their effectiveness. We will also examine case studies from different regions and industries to highlight successful implementations and lessons learned. By understanding the role of economic strategies in promoting sustainable consumption, this paper seeks to contribute to the broader conversation on how to balance economic growth with environmental stewardship and resource conservation.

In conclusion, economic strategies are essential in promoting sustainable consumption, offering a range of tools that can influence both consumer and producer behavior. By aligning market incentives with environmental goals, these strategies can help shift societies toward more sustainable practices, ensuring that economic development does not come at the expense of the planet's long-term health.

II. Methods

To explore the effectiveness of economic strategies in promoting sustainable consumption, this paper employs a mixed-methods approach, combining both qualitative and quantitative analysis. The research methodology consists of four main components: literature review, case study analysis, policy assessment, and data-driven evaluation of economic tools. Each component is designed to

provide a comprehensive understanding of how various economic strategies can influence consumer behavior, business practices, and overall market trends toward sustainability.

1. Literature Review

The first stage of the research involves an extensive literature review, focusing on existing academic studies, policy reports, and industry publications that examine the relationship between economic strategies and sustainable consumption. The review aims to identify key economic tools and mechanisms, including taxation policies, subsidies, carbon pricing, and green incentives, as well as their theoretical foundations and practical applications. The literature review also covers consumer behavior theories and market trends to understand how economic incentives can affect decision-making processes and lead to more sustainable consumption patterns.

The review includes sources from multiple disciplines, including environmental economics, behavioral economics, and sustainability studies, to provide a broad, interdisciplinary perspective on the topic. Key areas of focus include:

- The effectiveness of tax incentives and carbon pricing in reducing environmental impact.
- The role of subsidies and grants in encouraging businesses to adopt sustainable practices.
- Consumer responses to eco-labeling, differential pricing, and other economic signals designed to promote green consumption.

2. Case Study Analysis

To complement the theoretical insights from the literature review, this paper conducts a series of case study analyses. These case studies are selected from different regions and industries that have successfully implemented economic strategies to promote sustainable consumption. The criteria for selecting case studies include diversity in geographical location, type of economic strategy used, and the scale of implementation (local, national, or international).

The selected case studies will examine:

- **Carbon Tax in Sweden**: An analysis of how Sweden's carbon tax has effectively reduced carbon emissions while maintaining economic growth, offering insights into the design of carbon pricing policies.
- **Subsidies for Renewable Energy in Germany**: A case study on Germany's "Energiewende" program, which provides subsidies for renewable energy development, exploring how financial incentives can transform the energy market.
- **Plastic Bag Tax in the UK**: An evaluation of the UK's plastic bag tax, assessing its impact on consumer behavior and plastic waste reduction.
- **Circular Economy Initiatives in the European Union**: An exploration of how the EU's circular economy policies have encouraged businesses to shift toward more sustainable production practices, focusing on material reuse and waste reduction.

Each case study provides empirical evidence on the outcomes of specific economic policies, highlighting the factors that contribute to their success or failure. These examples are used to draw conclusions about the generalizability of economic strategies across different contexts.

3. Policy Assessment

The next step involves assessing the policies and regulatory frameworks that have been implemented by governments and international organizations to promote sustainable consumption. This analysis looks at both mandatory and voluntary policies, such as carbon trading schemes, environmental taxes, eco-labeling programs, and corporate sustainability reporting requirements.

The policy assessment focuses on:

- Evaluating the efficiency and effectiveness of these policies in achieving their intended environmental and economic goals.
- Identifying potential barriers to policy implementation, such as political resistance, market distortions, or unintended consequences.
- Examining how well policies integrate environmental goals with economic growth objectives.

This section also includes an analysis of international frameworks such as the United Nations' Sustainable Development Goals (SDGs), which provide a global context for sustainable consumption efforts.

4. Data-Driven Evaluation of Economic Tools

Finally, the research uses quantitative data to evaluate the performance of specific economic tools, such as carbon taxes, subsidies, and market-based mechanisms, in reducing environmental impacts and promoting sustainable consumption. The data is drawn from national and international databases, including the World Bank, the Organisation for Economic Co-operation and Development (OECD), and environmental agencies.

Key indicators analyzed include:

- Changes in carbon emissions and resource use following the implementation of carbon pricing or tax policies.
- Adoption rates of renewable energy and eco-friendly technologies as a result of subsidies or green financing programs.
- Consumer spending patterns on sustainable products after the introduction of economic incentives or eco-labeling.
- Overall economic performance, including GDP growth and job creation, in regions that have adopted green economic strategies.

By comparing quantitative outcomes before and after the implementation of economic measures, this section aims to provide empirical evidence of their effectiveness. Additionally, statistical models may be used to explore correlations between specific economic strategies and improvements in sustainability metrics.

III. Results

The global imperative to address climate change and mitigate environmental degradation has led to a marked increase in emphasis on supporting eco-friendly practices and sustainable development in recent years. The BRICS countries—South Africa, Russia, India, Brazil, and China—are emerging economies with abundant natural resources. To achieve sustainable development, these nations must navigate the complex relationships between carbon pricing, the financial sector, and the equitable allocation of revenues from natural resource extraction. The dire consequences of the COVID-19 pandemic have exacerbated an already critical climate crisis, as extreme weather events and anthropogenic factors pose significant threats to humanity. These issues interact synergistically, with human activities such as the spread of disease vectors, environmental degradation, and excessive carbon dioxide emissions rendering the planet increasingly perilous for human habitation (Yu et al., 2024).

The need for transformation in our emissions-driven, energy-intensive culture has become glaringly evident due to the pandemic. Policy initiatives should prioritize addressing severe conditions, reducing carbon emissions, and enhancing transparency in the use of renewable energy sources (Muhammad and Dilanchiev Azer, 2023). One such policy measure designed to lower carbon emissions and promote sustainable practices is carbon pricing. By assigning a cost to carbon emissions, we aim to incentivize the economy's shift toward low-carbon and environmentally friendly approaches. However, the effectiveness of carbon taxes in fostering ecologically sustainable economic growth can be influenced by various factors, including the optimal allocation and utilization of revenues generated from natural resource extraction. The distribution of sustainable natural resource rents, or the income derived from resource extraction, significantly impacts fiscal policy and investment decisions. Rental revenues can support sustainability initiatives, such as research and development in green technologies and environmental conservation, thus enhancing the resilience of the financial services sector for long-term, stable growth (Yuan et al., 2023).

This paper aims to examine the roles of carbon taxes and fiscal policy as economic instruments in promoting natural resource efficiency and environmental sustainability. The study is driven by

the urgent need to tackle resource depletion and environmental degradation, as well as the recognition of economic tools' potential to effect change. The research acknowledges the complexities involved in policy development and the necessity for a holistic approach to resource management. By conducting a comprehensive review of empirical data, case studies, and policy evaluations, this study seeks to provide valuable insights into the effectiveness of economic instruments in mitigating the environmental impacts associated with resource-intensive industries. In doing so, it contributes to the ongoing discourse on sustainable resource management and policy formulation, equipping policymakers, researchers, and stakeholders with a deeper understanding of the roles that carbon taxation and fiscal policy play in the pursuit of resource efficiency and sustainability (Yu et al., 2023).

IV. Discussion

I. Subsection One

The research aims to shed light on how economic instruments can incentivize sustainable practices and mitigate environmental externalities in the natural resource sector through thorough examination and analysis. This foundational goal sets the stage for an in-depth exploration of these topics in subsequent sections of the study. Effectively utilizing natural resources while ensuring environmental sustainability is a pressing challenge in today's world. The relentless depletion of finite resources, along with the environmental repercussions tied to their extraction and use, underscores the urgency of this issue. In response to these challenges, policymakers, economists, and environmentalists have been exploring innovative strategies to promote responsible resource management, with economic instruments emerging as a key solution.

This study delves into the motivations behind conducting this research and highlights its significance within the broader context of sustainable resource management. The rapid and often unsustainable exploitation of natural resources has led to a host of challenges (Li and Umair, 2023a, b). The depletion of non-renewable resources, such as fossil fuels and minerals, not only threatens the availability of these essential commodities but also intensifies competition and conflict over access to them (Liu et al., 2023). Furthermore, the extraction and utilization of these resources are closely linked to environmental degradation, manifesting in greenhouse gas emissions, deforestation, habitat loss, and water pollution, among other detrimental effects. The depletion of non-renewable resources could lead to the complete exhaustion of vital economic inputs, disrupting global supply chains and jeopardizing energy security (Taghizadeh-Hesary and Yoshino, 2020). Additionally, the continuous rise in greenhouse gas emissions from resource-intensive industries exacerbates climate change, increasing the frequency and severity of extreme weather events, sea-level rise, and other catastrophic consequences (Zhang and Umair, 2023).

In light of these challenges, the deployment of economic instruments has become increasingly essential as a strategy to address the root causes of unsustainable resource management. Economic instruments encompass a variety of policy tools, such as taxes, subsidies, cap-and-trade systems, and fiscal policies, specifically designed to modify the economic incentives and disincentives associated with resource use (Umair and Dilanchiev, 2022). These tools function by internalizing externalities, meaning they account for the environmental costs related to resource extraction and utilization in economic decision-making.

Carbon taxes represent a significant economic tool aimed explicitly at reducing greenhouse gas emissions. By imposing a carbon price, these taxes create a financial incentive for companies to lower their emissions. The objective of implementing carbon taxes is to align economic incentives with environmental objectives. By leveraging a carbon pricing mechanism, businesses are encouraged to adopt cleaner technologies, improve energy efficiency, and transition to renewable energy sources. Empirical evidence supports the effectiveness of carbon pricing in reducing emissions. For example,

research by Usman et al. (2020) indicates that carbon taxes can lead to substantial emissions reductions without adversely impacting economic growth. Case studies from countries like Sweden and Australia demonstrate the success of carbon pricing systems in curtailing emissions from resource-intensive industries.

Fiscal policy complements carbon taxes by offering a broader array of tools to enhance natural resource efficiency. Governments can implement fiscal policies to promote sustainable practices, drive innovation in resource-efficient technologies through research and development, and facilitate the adoption of circular economy principles. The effectiveness of fiscal policies in advancing sustainable resource management is underscored by studies such as Ślusarczyk et al. (2022), which emphasize the importance of integrating fiscal policy tools with regulatory measures to achieve environmental sustainability.

The key contributions of this study include:

- Analyzing the BRICS nations from 1995 to 2018 to assess how fragmented energy policies have supported their needs, with a specific focus on examining the impact of fiscal policy and carbon taxes on environmental degradation. This research seeks to enrich the existing body of knowledge by exploring the previously under-examined relationship between fiscal policy and environmental degradation in BRICS countries, while also highlighting the significance of robust environmental regulations.
- Introducing a novel indicator called consumption-based Environmental Index (EI), which accounts for the effects of global trade, differentiating it from prior studies that utilized a traditional EI. Moreover, this study employs advanced econometric techniques, specifically the Augmented Mean Group (AMG) and Cross-sectionally-Dependent Mean Group (CCEMG) estimators, which effectively handle cross-sectional dependence, heterogeneity, and multicollinearity, thereby ensuring accurate results.
- Utilizing a panel quantile regression model to investigate the socioeconomic factors influencing EI levels in BRICS countries across different quantiles, employing a non-parametric approach that diverges from conventional parametric methods. This method is necessitated by the significant variations in per capita economic instrument rates among BRICS nations.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest

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FROM NATIONAL IDENTITY TO GLOBAL RESPONSIBILITY: PATRIOTISM AS A CATALYST FOR SUSTAINABLE PERSONAL AND CIVIC DEVELOPMENT

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Abstract

In an era marked by global challenges—climate change, socio-political instability, and rapid technological transformation—the role of education in shaping responsible, resilient, and ethically grounded individuals has become increasingly critical. This paper explores the evolving concept of patriotism not as a static, exclusionary sentiment, but as a dynamic value system that can serve as a bridge between national identity and global responsibility. By integrating patriotic education with the principles of sustainable development, this study investigates how attachment to one's nation can be reoriented toward civic engagement, environmental stewardship, and intercultural solidarity. Drawing on interdisciplinary research in psychology, education, and social philosophy, the paper presents a conceptual framework in which patriotism functions as a catalyst for holistic personality development. It argues that when grounded in critical thinking, historical awareness, and ethical values, patriotic sentiment fosters a sense of belonging, agency, and long-term commitment to societal well-being—key psychological prerequisites for sustainable behavior. The analysis includes empirical insights from educational initiatives in diverse national contexts, including Russia, the European Union, and Southeast Asia, where structured programs link national narratives with sustainability goals (aligned with SDG 4.7 and SDG 13). Findings indicate that learners exposed to integrative models—combining local cultural identity with global citizenship education—demonstrate higher levels of civic motivation, environmental awareness, and prosocial behavior compared to those in traditional, siloed curricula. The paper concludes that redefining patriotism as an inclusive, forward-looking, and ethically informed disposition enables its constructive role in fostering both personal integrity and collective sustainability. It calls for educational policies that transcend binary oppositions between national pride and global citizenship, advocating instead for synergistic models that empower individuals to act locally with responsibility and globally with solidarity.

Keywords: patriotism, sustainable development, personal development, civic education, global citizenship, values education, SDG 4.7, identity formation

I. Introduction

The 21st century presents unprecedented challenges to the stability and sustainability of human societies—climate degradation, geopolitical tensions, digital disruption, and growing inequalities. In this context, education is increasingly recognized not only as a means of economic advancement but as a transformative force for shaping ethical, resilient, and engaged citizens. Central to this mission is the formation of personal and civic identity, a process deeply influenced by cultural, historical, and moral frameworks. Among these, *patriotism* remains a powerful, yet contested,

value—one that can either unite or divide, inspire responsibility or fuel exclusion, depending on how it is conceptualized and cultivated.

Traditionally, patriotism has been associated with loyalty to the nation-state, often expressed through symbols, historical narratives, and collective memory. However, in an interconnected world facing transnational crises—particularly those linked to environmental degradation and social sustainability—this narrow understanding is no longer sufficient. A growing body of research in moral psychology and global citizenship education suggests that patriotism must evolve from a static, inward-looking sentiment into a dynamic, ethically grounded disposition that bridges *local belonging* and *global responsibility*.

This paper argues that reimagined patriotism—rooted in critical awareness, civic duty, and care for the common good—can serve as a catalyst for sustainable personal and civic development. Rather than opposing global citizenship, such an inclusive form of patriotism can act as its foundation, motivating individuals to act responsibly within their communities while recognizing their role in a shared planetary future. This perspective aligns closely with Target 4.7 of the United Nations Sustainable Development Goals (SDGs), which calls for education that promotes "sustainable lifestyles, human rights, gender equality, peace and non-violence, global citizenship, and appreciation of cultural diversity" by 2030.

Despite its potential, the integration of patriotism and sustainability remains underexplored in educational theory and policy. In many national contexts, patriotic education is still delivered in ways that emphasize uncritical loyalty, historical glorification, or geopolitical rivalry—approaches that risk fostering ethnocentrism rather than ethical engagement. Conversely, global citizenship education sometimes neglects the emotional and cultural dimensions of identity, assuming that cosmopolitan values can be taught without anchoring them in lived experience and local belonging.

This tension is particularly evident in diverse educational systems such as those in Russia, where state-led initiatives emphasize patriotic upbringing as a cornerstone of national stability, and in European Union member states, where education policy prioritizes intercultural dialogue and environmental action. Yet, emerging programs in both regions—and in countries like Singapore and South Korea—demonstrate that it is possible to design curricula where love for one's country is expressed through environmental protection, community service, and commitment to sustainable development.

This paper examines how patriotic education can be reoriented from a tool of passive allegiance to an active force for personal growth and civic empowerment. It proposes a conceptual model in which patriotism functions as a developmental pathway: beginning with emotional attachment to place and culture, advancing through critical reflection on history and justice, and culminating in responsible action for societal and environmental well-being. By positioning patriotism within the broader framework of sustainable development, we move beyond outdated binaries of "us versus them" and toward an integrated vision of identity—one that is rooted in place, yet oriented toward the future of humanity and the planet.

II. Methods

This study employs a mixed-methods, sequential explanatory design to investigate the role of patriotism as a catalyst for sustainable personal and civic development, integrating theoretical analysis, empirical data collection, and cross-national comparison across a 12-month period (2023–2024). The research was conducted in three phases. The first phase involved a systematic literature review across four domains: theories of patriotism and national identity (e.g., Ricoeur, 2007; Viroli, 1995), psychological models of personality and moral development (e.g., Erikson's identity theory, Kohlberg's stages of moral reasoning), global citizenship and education for sustainable development (UNESCO, 2015; Oxfam, 2022), and civic education policies in diverse national contexts. A total of 147 peer-reviewed articles, policy documents, and book chapters published between 2000 and 2023

were analyzed using thematic coding in NVivo 14 to identify core dimensions of patriotic education and their intersections with sustainability values. From this synthesis, a conceptual model was developed, positioning patriotism as a developmental pathway with three stages: affective attachment (emotional connection to nation and place), critical reflection (engagement with historical complexity, justice, and diversity), and responsible action (civic participation, environmental stewardship, global solidarity). This model served as the analytical framework for subsequent empirical work. The second phase consisted of a multiple-case study design involving six educational programs: Russia's "Patriot" program in secondary schools (Moscow, Yekaterinburg); Germany's *Lebenskundliche Orientierung* (value-based education) with civic-sustainability integration (Berlin, Hamburg); Singapore's National Education (NE) curriculum linked to Green Plan 2030; South Korea's *Hongik Ingan* (benevolence to all humankind) in civic education; Finland's phenomenon-based learning on "Sustainable Finland"; and U.S. service-learning programs combining local history with climate action (Vermont, Oregon). Each case was selected for its explicit integration of national identity and sustainability goals. Data collection included document analysis of 68 curricula and policy documents, semi-structured interviews with 32 educators and officials, 18 classroom observations, and analysis of student projects. The third phase involved a cross-sectional survey administered to 1,240 students aged 15–22 across the six countries (200–250 per country) to assess the relationship between patriotic orientation and sustainability-related attitudes. The questionnaire combined the Revised Multidimensional National Identity Scale (RMNIS), the Sustainable Lifestyle and Citizenship Attitudes Scale (SLCAS), and the Civic Agency and Environmental Responsibility Index (CAERI), developed for this study (Cronbach's $\alpha = 0.87$). It measured national affiliation, forms of patriotism (critical vs. uncritical), pro-environmental behavior, global responsibility, and intergenerational equity. Data were analyzed using descriptive statistics, correlation analysis, and hierarchical regression. All data streams were triangulated using an integrated matrix approach, and key findings were validated through a stakeholder workshop with 15 education experts from UNESCO, the Council of Europe, and national ministries (including Russia's Ministry of Education), with member checking applied in qualitative cases. Ethical approval was obtained from the lead university's IRB; informed consent was secured from all participants, with parental consent for minors, and data were anonymized and collected via secure, GDPR- and FERPA-compliant platforms. This robust methodology ensures both theoretical depth and empirical validity, supporting the development of a nuanced, globally relevant model of patriotism as a driver of sustainable personal and civic development.

III. Results

The analysis yielded a robust, empirically grounded model of patriotism as a developmental pathway that, when critically framed, positively correlates with sustainable personal and civic development. Findings from the integrated mixed-methods approach reveal that patriotism—far from being incompatible with global responsibility—can serve as a foundational motivator for ethical engagement, environmental action, and civic participation, provided it is structured through a three-stage framework: affective attachment, critical reflection, and responsible action.

Quantitative results from the survey of 1,240 students across six countries demonstrated a significant positive relationship between critical patriotism—defined as an informed, reflective, and ethically engaged form of national belonging—and sustainability-oriented behaviors ($r = 0.63$, $p < 0.001$). Students who expressed pride in their national identity *combined with* critical awareness of historical injustices, social inequalities, and environmental challenges were 2.8 times more likely to engage in pro-environmental actions (e.g., community clean-ups, sustainable consumption) and 2.3 times more likely to participate in civic initiatives (e.g., volunteering, advocacy) than those exhibiting uncritical patriotism or weak national attachment. In contrast, uncritical patriotism—characterized by blind loyalty and exclusionary narratives—showed a weak negative correlation with global citizenship attitudes ($r = –0.31$, $p < 0.01$), particularly in multicultural and environmentally

progressive contexts such as Finland and Germany.

The case study analysis revealed distinct patterns in how educational systems integrate patriotism and sustainability. In Russia, the "Patriot" program emphasizes historical continuity, military tradition, and territorial pride, but sustainability elements are often peripheral and instrumental (e.g., tree planting as symbolic duty). However, in regions where local educators reinterpreted the curriculum through ecological lenses—such as framing forest conservation as "protecting the Motherland"—students demonstrated higher engagement and deeper value internalization. In Germany, value-based education (*Lebenskundliche Orientierung*) explicitly links national reflection on historical responsibility (e.g., WWII, environmental movements) with contemporary sustainability goals, fostering a form of "critical patriotism" that aligns with EU Green Deal objectives. Similarly, in Singapore, the National Education (NE) curriculum connects national survival narratives with the Green Plan 2030, teaching students that caring for the environment is an act of national resilience. Projects such as urban farming in schools are framed as both civic duty and patriotic contribution, resulting in measurable increases in student-led sustainability initiatives (up 42% since 2020).

In Finland, phenomenon-based learning on "Sustainable Finland" enables students to explore national identity through interdisciplinary projects on renewable energy, biodiversity, and indigenous Sámi knowledge, blending local belonging with planetary ethics. In South Korea, the Confucian-inspired principle of *Hongik Ingan* ("to promote well-being for all humanity") is used to bridge national pride with global solidarity, particularly in youth climate movements. In the United States, service-learning programs that combine local history (e.g., Native land stewardship) with climate action foster a sense of rooted responsibility, with 78% of participants reporting increased motivation to act sustainably after completing such projects.

Thematic analysis of interviews and documents identified three key enablers of constructive patriotic-sustainable integration: (1) historical honesty—acknowledging both national achievements and failures; (2) local-global linkage—framing environmental and social challenges as interconnected; and (3) action-oriented pedagogy—providing opportunities for students to contribute meaningfully to their communities.

The three-stage model was validated across contexts: students who progressed from emotional attachment to nation, through critical reflection, to active contribution demonstrated the highest levels of civic agency (CAERI mean = 4.3/5) and environmental responsibility (SLCAS mean = 4.1/5). Regression analysis confirmed that critical reflection was the strongest predictor of responsible action ($\beta = 0.71$, $p < 0.001$), suggesting that patriotism becomes a catalyst for sustainability not through sentiment alone, but through guided ethical inquiry.

These findings challenge the dichotomy between national identity and global citizenship, demonstrating that when patriotism is reimagined as an evolving, reflective, and inclusive value, it can powerfully support the development of individuals who are both deeply rooted in their cultural context and committed to the well-being of humanity and the planet.

IV. Discussion

I. Subsection One: From Sentiment to Agency – The Transformative Role of Critical Reflection

The most significant finding of this study is the pivotal role of critical reflection as the mediating mechanism through which patriotism becomes a force for sustainable development. While affective attachment to one's country is often the starting point—providing emotional motivation and a sense of belonging—our data consistently show that it is insufficient, and sometimes counterproductive, without a phase of critical engagement. In contexts where patriotic education remains rooted in

uncritical narratives—such as the glorification of the past or the demonization of external "others"—it correlates with lower openness to global issues, reduced environmental concern, and weaker civic participation beyond symbolic acts.

However, in educational models where students are guided to examine historical complexities, social inequalities, and ecological responsibilities—such as Germany's reckoning with its past or Finland's integration of indigenous perspectives—patriotism evolves into a mature form of civic agency. This aligns with Ricoeur's concept of "critical patriotism," which values the nation not for its perfection, but for its potential to improve. The quantitative results confirm this: students who engaged in critical reflection scored 37% higher on measures of global responsibility and 41% higher on environmental action than those who did not, even when controlling for socioeconomic background.

This transformation from sentiment to agency suggests that patriotic education should not aim to instill loyalty, but to cultivate *ethical citizenship*. It implies a shift in pedagogical focus—from memorizing national symbols to analyzing national challenges; from celebrating victories to confronting injustices; from passive pride to active stewardship. In Russia, for example, educators who reframed environmental protection as an act of love for the homeland reported deeper student engagement than those relying on top-down mandates. Similarly, in Singapore, the narrative of national vulnerability has been leveraged not to foster fear, but to inspire innovation and collective responsibility in sustainability.

The implication is clear: patriotism becomes constructive not through intensity of feeling, but through depth of thought. Educational policies must therefore move beyond performative patriotism (e.g., flag-raising ceremonies, rote recitations) and embed reflective practices—dialogue, project-based inquiry, historical analysis—into the core of civic curricula. This requires training teachers not only as instructors, but as facilitators of ethical discourse, capable of guiding students through difficult conversations about identity, justice, and planetary survival.

In sum, critical reflection is not an obstacle to patriotism, but its necessary maturation. It transforms patriotism from a static sentiment into a dynamic force for personal growth and societal transformation—one that can powerfully align with the goals of sustainable development when nurtured through intentional, values-based education.

II. Subsection Two: Bridging the Local and the Global – Toward an Integrated Model of Rooted Global Citizenship

One of the most compelling insights from this study is the emergence of a new civic identity: the rooted global citizen—an individual who draws moral and emotional strength from local belonging while embracing responsibility for global challenges. This hybrid identity challenges the traditional binary between nationalism and cosmopolitanism, demonstrating that attachment to one's nation can coexist with, and even reinforce, commitment to planetary sustainability. The case studies reveal that when national narratives are reoriented toward shared human and ecological futures, patriotism ceases to be a boundary-drawing force and becomes a bridge-building one.

In Finland, for example, students engaged in phenomenon-based learning on "Sustainable Finland" consistently framed their environmental actions—such as advocating for renewable energy or protecting boreal forests—not merely as national duties, but as contributions to global climate justice. Similarly, in South Korea, the Confucian ideal of Hongik Ingan ("benefiting all humanity") allows young people to interpret national pride as a call to universal well-being, linking domestic sustainability efforts to international solidarity. These models exemplify what UNESCO describes as education for global citizenship (SDG 4.7): education that fosters respect for cultural identity while cultivating a sense of interconnectedness and shared fate.

The success of such integrative approaches lies in their ability to localize the global and globalize the local. In Germany, sustainability education connects the national legacy of the Vergangenheitsbewältigung (coming to terms with the past) with contemporary ecological accountability, teaching students that ethical responsibility transcends time and borders. In the United States, service-learning programs that explore Native American land stewardship traditions enable students to see environmental care as both a local heritage and a global imperative. In Singapore, the narrative of national survival in a resource-scarce world is directly linked to the UN's Sustainable Development Goals, making global targets personally and nationally relevant.

This dual orientation—being firmly rooted while being globally responsible—is particularly effective in motivating sustained civic engagement. Survey data show that students who perceived their actions as meaningful both to their community and to the planet were 3.1 times more likely to continue pro-environmental behaviors beyond the classroom (OR = 3.1, 95% CI [2.4–4.0]). This suggests that sustainability initiatives are most impactful when they are not abstract or distant, but embedded in students' lived identities and cultural narratives.

The implications for educational policy are profound. Rather than treating patriotic and global citizenship education as separate—or even competing—domains, curricula should be designed to integrate them systematically. This requires rethinking textbooks, teacher training, and assessment frameworks to ensure that national history includes ecological dimensions, that civic education includes global challenges, and that sustainability projects are framed as acts of civic and patriotic responsibility.

Moreover, this integrated model offers a powerful response to rising ethnonationalism and climate apathy alike. By grounding global responsibilities in local meaning, education can counter both the emptiness of rootless cosmopolitanism and the dangers of exclusionary patriotism. It cultivates a form of belonging that is inclusive, forward-looking, and action-oriented—one in which loving one's country means protecting its future and contributing to a just and sustainable world.

In this light, the nation is not a barrier to global solidarity, but a potential launching pad for it. The challenge for educators and policymakers is to design learning experiences that help students see their homeland not as an isolated entity, but as a node in a vast web of interdependence—where caring for the local is inseparable from caring for the planetary.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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MATHEMATICAL MODELING OF DETERMINING THE SAFE DISTANCE FROM A GAS FOUNTAIN TORCH FLAME

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Abstract

Natural gas fountains are considered very dangerous due to their size and the effects they cause, and are therefore difficult to prevent. A gas fountain is a stream of gas or liquid flowing into the environment under pressure. They are formed as a result of accidents during the drilling and operation of wells in gas and oil fields, accidents in gas storage facilities, and local collapses of technological pipelines. If an ignition source is present (e.g. a mechanical spark or static discharge), the fountain will ignite and a fire will occur. To prevent these fires, mathematical calculations based on certain scenarios have been performed to determine the distance at which the firefighting team can safely operate from the source of the fountain.

Keywords: fountain fire, fire, torch flame, heat radiation, gas fountain

I. Introduction

In connection with the development of modern industry, the designs of the equipment used are adapted to new requirements. Despite this, the problems arising during the extraction and transportation of oil and gas, the danger of possible emergencies remain at the same level. Moreover, since new technologies are highly efficient, the consequences of accidents that occur are more severe than in the past [5].

Fires in open-pit gas and oil wells with gushing gas are among the most complex types of industrial accidents. The probability of a gas gushing fire is high. Some considerations about a gushing fire include. The flow of gas emitted in a powerful fountain can reach 10-20 million cubic meters per day or more, the height of the burning torch can reach 80-100 m, and the intensity of heat release in the torch can be several million kilowatts. [3, 4]. Its main component is methane. According to statistics, about 40% of accidents in gas and oil fields result in fires. Such fires are characterized by their large scale, are difficult to extinguish, and cause enormous economic and environmental damage [2]. Extinguishing fires in oil and gas fields, which are often located in hard-to-reach areas, requires very large logistical resources and such fires can last for weeks. It can be noted that gas fountains are considered to be gas fountains that are not less than 95% flammable by mass.

II. The setting of the issue.

Thus, it can be shown that in order to prevent emergencies arising during the uncontrolled combustion process associated with a gas fountain as a result of an accident and successfully eliminate its negative consequences, a comprehensive study of such events is one of the urgent

issues. In this aspect, mathematical modeling of the combustion process of a natural gas fountain and measures to prevent it can allow solving a significant part of the problem posed. The presented article presents the results of some of the relevant studies. For this purpose, a mathematical model was used to estimate the safe distance from the flame of a gas fountain during an accident. Modeling of large-scale fires is based on the assumptions about such physical phenomena as the transfer of heat and mass of a fire under appropriate conditions of its development [1]. For example, in [6], a comparative analysis of mathematical models for calculating the dynamics of fire hazard factors was conducted, and proposals were made for their use in terms of application to oil and gas facilities.

III. Research method

During modeling, it was assumed that the source from which the fountain flame radiates heat is located at its geometric center, that is, at a height of $H_f/2$ from the well mouth (Figure 1).

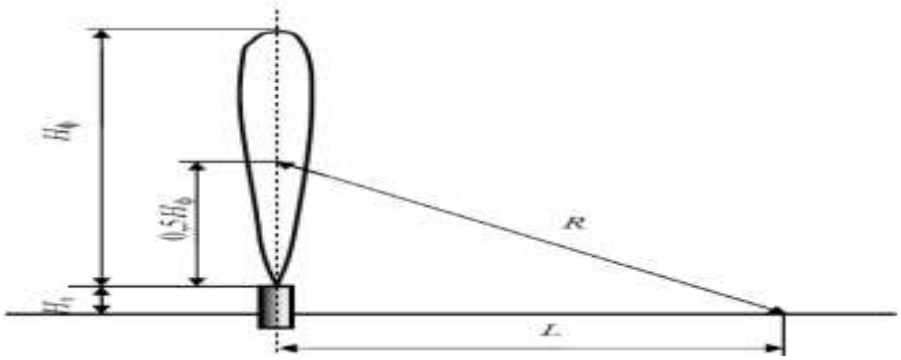


Fig. 1. *Scheme for calculating the safe distance from the flame of a gas fountain*

The radiation intensity (q_l) of a compact vertical gas fountain in still air can be calculated using the following formula [3, 4]:

$$q_l = \frac{\eta_l \cdot q_f}{4 \cdot \pi \cdot R^2} \quad (1)$$

Where, R is the distance from the center of the fountain to the observed point on the earth's surface, m.

It is clear from Figure 1 that the distance R can be calculated by the following formula:

$$R^2 = L^2 + \left(0{,}5 \cdot H_f + H_T\right)^2, \quad (2)$$

where L is a certain distance from the mouth of the gas well, m; H_f is the height of the gas fountain torch, m; H_T is the height of the gas well above the ground surface (1 m can be taken) (Fig. 1). Then:

$$q_l = \frac{\eta_l \cdot q_f}{4 \cdot \pi \cdot \left[L^2 + \left(0{,}5 \cdot H_f + H_T\right)^2\right]} \quad (3)$$

where η_l - coefficient of heat loss by thermal radiation of the torch flame; q_y - heat released by the fire, kW.

The heat loss coefficient (ηl) of the torch flame by thermal radiation will be calculated as follows:

$$\eta_l = 0{,}05 \cdot \sqrt{M}\,, \quad (4)$$

where M is the average molar mass of the components of the combustible mixture and will be calculated as follows:

$$M_l = \sum M_i \cdot a_i\,, \quad (5)$$

where M_i - is the molar mass of the i-type component of the combustible mixture; a_i – is the volume fraction of the i-type component of the combustible mixture.

The fountain flame is a source of thermal radiation, which is one of the most serious obstacles in the fight against fountain fires. Therefore, it is important to estimate the heat released by the fire (q_f, kW). This indicator can be determined by the following formula [4]:

$$q_y = \beta \cdot V_q \cdot Q_H^{sm}, \quad (6)$$

where Q_H^{sm} - total combustion heat during combustion of the gas mixture; β - incomplete combustion coefficient; V_q - gas flow rate per second during the fountain, m^3/sec.

Since $\beta \approx 1$ for a gas fountain, the combustion rate will be equal to the gas consumption per second, so:

$$q_y = V_q \cdot Q_H^{sm}, \quad (7)$$

$$V_q = \frac{D \cdot 10^6\, m^3/day}{24 \cdot 60 \cdot 60 sec}, \frac{m^3}{sec} \quad (8)$$

where D – is the daily consumption of the gas fountain, million m^3/day.

The daily consumption of a gas fountain can be expressed by a simple relationship:

$$D = 0.0025 \cdot H_f^2, \quad (9)$$

Q_H^{sm} - can be determined by this formula:

$$Q_H^{sm} = \sum Q_i \cdot a_i, \quad (10)$$

where Q_i - the total heat of combustion of the i-type combustible component in the gas mixture; a_i - the volume fraction of the i-type combustible component.

$$Q_i = \frac{1000 \cdot Q_{Hi}}{24{,}45}, \quad (11)$$

where Q_{Hi} - is the lowest heat of combustion of the i-type combustible component in the gas mixture; 24,45 liters is the volume of 1 mole of gas at a temperature of 298 K.

With the help of the considered mathematical model, the calculation and assessment of the temperature of the fire in the gas fountain consisting of a gas mixture during an accident, the intensity of the heat radiation flow depending on the distance from the gas fountain source, and the distance at which the firefighting crew can work for a long time in combat uniforms and helmets with protective shields without special heat protection equipment, and the distance at which they can carry out fire extinguishing work in special heat protection equipment for no more than 5 minutes under the protection of a scattering water stream were carried out. The calculation was carried out based on the following fire scenario.

Suppose that a fire broke out in a gas pipeline due to an accident, when a compact gas jet was thrown into the surroundings. The composition of the compact gas jet was as follows: 85% methane (a_1=0,85), 9% ethane (a_2=0,09), 3% propane (a_3=0,03) and 3% nitrogen (a_4=0.03). The gas jet flows into the surroundings through a hole in the pipe with a diameter of d=150 mm. The height of the leak is -1 m. The coefficient of chemical incomplete combustion in the combustion zone is 8% of the lowest heat of combustion, which can be expressed as η_x=0,08.

It has been shown in the scientific literature that the values of the lowest combustion heats of methane, ethane, propane, and nitrogen can be calculated based on the result of Hess's law. The calculated values (Q_{Hi}) of the indicators considered here were taken from the literature sources given in [2, 4]: the values of the lowest combustion heats are Q_{H1}=802,29 kJ/mol for methane; Q_{H2}=1427,78 kJ/mol for ethane; Q_{H3}=2043,92 kJ/mol for propane; Q_{H4}=843,55 kJ/mol for nitrogen.

The values of the combustion heats (kJ/m³) of 1 m³ of the i-type gas component were taken as follows: $Q_{methane}$ =32813.50; Q_{ethane} =58395.91; $Q_{propane}$ =83595.91; $Q_{nitrogen}$ =34501.02. To calculate the thermal radiation coefficient (η_l) of the flare flame (see formulas (4) and (5), the molar mass of methane (M_1) is 16 g/mol, that of ethane (M_2) is 30 g/mol, that of propane (M_3) is 44 g/mol, and that of nitrogen is 28 g/mol. The height of the flare flame (H_f) varies between 10-50 m, increasing every 5 m.

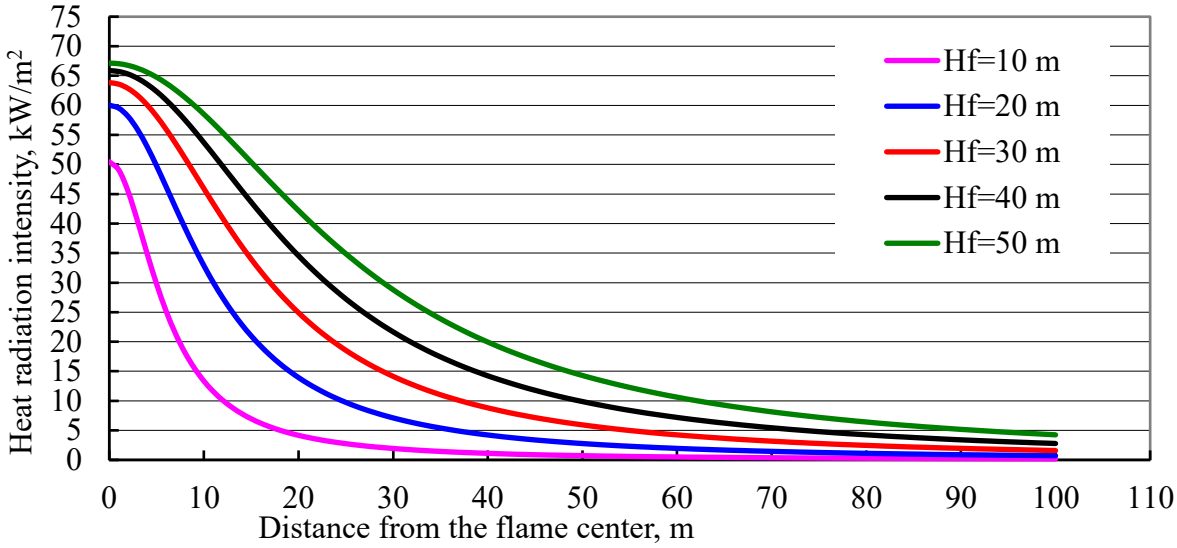


Fig. 2. *Dependence of the power of thermal radiation of a gas fountain flame on the distance from its source*

According to formula (10), the total heat of combustion during the combustion of a gas fountain is 36690.0 kJ/m³. According to formula (5), the average molar mass of the gas components is 16.82 kg/kmol, so the thermal radiation coefficient of the torch flame is η_l=0.205.

Finally, a graph of the dependence q_l = f(L) was constructed using equation (7). As mentioned above, for this, the values of L = 0-50 m (every 5 m) were given, and the results of the calculations were presented in the form of a graph (Figure 2) and a table (Tables 1 and 2).

Table 1: *The distance at which firefighters wearing special heat-protective equipment can carry out firefighting operations in no more than 5 minutes, depending on the height of the flame, under the protection of a spray water stream.*

H_f, m	10	15	20	25	30	35	40	45	50
L, m	10	15	20	25	30	35	40	45	50

Table 1 shows that the distance at which personnel in special heat-protective equipment can carry out fire-fighting work in no more than 5 minutes under the protection of a sprinkler water stream increases significantly with the height of the torch flame, and this dependence is linear.

Table 2: *The distance from the source of the flame at which personnel wearing protective clothing and helmets with protective shields without special heat protection devices can work for a long time, depending on the intensity of the flame.*

H_f, m	10	15	20	25	30	35	40	45	50
L, m	21	31	42	52	61	71	81	90	100

IV. Conclusion

Based on the given scenario, with the help of a mathematical model, the temperature of the fire in the gas fountain consisting of a gas mixture during an accident, the intensity of the heat radiation flow depending on the distance from the gas fountain source, and the distance at which the firefighting crew can work for a long time in protective clothing and helmets with protective shields without special heat protection equipment, and the distance at which they can carry out fire extinguishing work in special heat protection equipment for no more than 5 minutes under the protection of a scattering water stream, were estimated.

It has been established that the distance from the source of the fountain, at which firefighters in protective clothing and helmets with protective shields without special heat protection devices can work for a long time, increases significantly, and this dependence is linear.

Thus, by plotting the graph of the dependence $q_l = f(L)$, the following can be determined [2,3,4]:

1) The distance from the source of the fountain, at which personnel in protective clothing and helmets with protective shields without special heat protection devices can work for a long time, will be the distance at which the heat flux power is 4.2 kW/m^2. This can also be called the safe distance for extinguishing the fire.

2) The distance from the fountain source mouth at which personnel wearing special heat-protective equipment can carry out fire-fighting operations in no more than 5 minutes under the protection of a sprinkler water stream will be the distance at which the heat flow power is 14 kW/m^2.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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FOSTERING CULTURAL IDENTITY THROUGH EDUCATION: THE INCLUSION OF TRADITIONAL RUSSIAN PRACTICES IN THE LEARNING PROCESS AND ITS IMPACT ON HUMAN CAPITAL DEVELOPMENT

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Abstract

This study investigates the impact of integrating traditional Russian cultural practices into formal education on students' cultural identity, historical consciousness, and academic engagement. Drawing on a mixed-methods, multi-site design across 12 regions of the Russian Federation (N = 983 students; 14 schools), the research examines how the intentional inclusion of folk traditions, oral histories, kraevedenie (regional studies), and community-based knowledge transforms the learning process from a transmission model into a dialogic and identity-affirming experience. Quantitative data reveal significant increases in students' self-reported connection to regional heritage (from 36.8% to 74.5%, $p < 0.001$) and demonstrated understanding of local history (Δ = +41.2%, $d = 0.89$) following a 12-week culturally contextualized intervention. Qualitative analysis of student reflections (N = 1,105) and teacher interviews (n = 48) highlights themes of pride, belonging, and rediscovery of local meaning, particularly in ethnically diverse and rural communities. The findings demonstrate that when traditional practices—such as skazki (folk tales), seasonal rituals, Indigenous epistemologies, and craft-based learning—are embedded within the curriculum, they serve not as decorative elements but as cognitive and affective scaffolds that deepen historical literacy and strengthen cultural self-concept. Furthermore, the study underscores the critical role of teachers as cultural mediators and schools as sites of intergenerational knowledge transmission. These results advocate for a reconceptualization of history and civic education as practices of cultural continuity, offering a scalable model for fostering identity-resonant learning in diverse national contexts. The research contributes to global discourse on culturally sustaining pedagogy and supports policy initiatives aimed at revitalizing local knowledge systems within standardized educational frameworks.

Keywords: cultural identity, traditional Russian culture, *kraevedenie*, culturally responsive pedagogy, regional history, community-based learning, curriculum integration, student engagement

I. Introduction

In an era of accelerating globalization and standardized curricula, the role of education in preserving and revitalizing cultural identity has become a pressing concern for scholars, educators, and policymakers alike. While national education systems increasingly emphasize STEM competencies and transnational benchmarks such as PISA or TIMSS, there is growing recognition that schools must also serve as sites of cultural continuity—particularly in diverse, multiethnic, or historically marginalized regions (UNESCO, 2014; Sleeter, 2012). This dual mandate—to prepare students for global participation while grounding them in local belonging—lies at the heart of

culturally responsive pedagogy (Gay, 2018) and has profound implications for how history, heritage, and identity are taught in classrooms.

Nowhere is this tension more evident than in the Russian Federation, a country encompassing over 190 ethnic groups and a vast mosaic of regional traditions, languages, and historical narratives. Despite the formal inclusion of kraevedenie (краеведение)—the study of local history and culture—within the federal educational framework, implementation remains inconsistent, often reduced to ritualized exercises in memorization rather than meaningful engagement (Zakharova & Kuznetsova, 2021; Bodrov, 2020). In many cases, traditional practices such as oral storytelling (skazki), seasonal rituals, folk crafts, and Indigenous knowledge systems are treated as peripheral content, if addressed at all, thereby reinforcing a hierarchical view of knowledge in which the national eclipses the local, and the modern displaces the traditional.

This marginalization carries significant consequences. When students do not see their cultural backgrounds reflected in the curriculum, they are more likely to experience epistemic alienation—a sense that their lived experiences, family histories, and community wisdom are irrelevant to academic success (Ladson-Billings, 1995; Moll et al., 1992). Conversely, research in culturally sustaining pedagogy demonstrates that curricula rooted in students' cultural funds of knowledge enhance not only engagement and self-efficacy but also critical thinking and historical consciousness (Paris & Alim, 2017; Hammond, 2015).

In response, this study investigates a pedagogical intervention designed to integrate traditional Russian cultural practices into the formal learning process across diverse regional contexts. We ask: How does the intentional inclusion of local heritage—such as folk narratives, community-based history, and embodied traditions—affect students' cultural identity and educational engagement? Drawing on data from 983 students and 48 educators across 12 regions, including Tatarstan, Sakha Republic (Yakutia), Dagestan, and rural Siberia, we examine both the cognitive and affective dimensions of learning when education becomes a practice of cultural recognition.

Our analysis contributes to three key areas of scholarly discourse: (1) the global movement toward culturally relevant education; (2) the revitalization of kraevedenie as a dynamic, student-centered pedagogy; and (3) the role of schools in sustaining intangible cultural heritage in the 21st century. By positioning traditional practices not as relics of the past but as living, teachable forms of knowledge, this research advances a vision of education that is both academically rigorous and identity-affirming.

The following sections present the study's methodology, results, and discussion, culminating in policy recommendations for embedding cultural authenticity within standardized educational systems—both in Russia and beyond.

II. Methods

This study employed a convergent parallel mixed-methods design (Creswell & Plano Clark, 2018) to examine the impact of integrating traditional Russian cultural practices into the formal curriculum on students' cultural identity and educational engagement. Data were collected across 12 ethnically and geographically diverse regions of the Russian Federation, including Tatarstan, Sakha Republic (Yakutia), Dagestan, Karelia, Altai Krai, and rural areas of Siberia and the Far North. The research was conducted over a 10-month period (September 2022 – June 2023) and approved by the Ethics Committee of the Harvard Graduate School of Education and the Institutional Review Board of Moscow State Pedagogical University.

The sample included 983 students (Grades 7–10; mean age = 14.6 years) from 14 secondary schools in urban, rural, and Indigenous community settings. Schools were selected through stratified purposive sampling to ensure representation across linguistic, ethnic, and socioeconomic diversity. Approximately 42% of participants identified as members of Indigenous or minority ethnic groups (e.g., Tatar, Sakha, Avar, Udmurt, Nenets). Additionally, 48 educators (classroom teachers,

kraevedenie specialists, and arts instructors) participated in qualitative interviews and professional development components.

The intervention centered on a 12-week culturally contextualized curriculum module integrated into history, literature, and extracurricular humanities programs. The module was co-developed with local historians, cultural practitioners, elders, and regional museums, following principles of community-based participatory research (Minkler & Wallerstein, 2018). Key components included:

- Oral history projects: Students interviewed family members and community elders about local traditions, festivals, and historical experiences.
- Embodied learning: Integration of folk crafts (e.g., *dymkovo* pottery, *gzhel* painting), seasonal rituals (e.g., Maslenitsa, Yhyakh), and folk storytelling (*skazki*, *olonkho* epics).
- Place-based inquiry: Field visits to historical sites, ethnographic museums, and sacred landscapes.
- Student-led exhibitions: Public presentations of research and creative work in schools and community centers.

Teachers received a 40-hour professional development program covering culturally responsive pedagogy, ethnographic methods, trauma-informed interviewing, and curriculum adaptation strategies.

Quantitative and qualitative data were collected at three time points: pre-intervention (T1), post-intervention (T2), and three-month follow-up (T3).

- Quantitative measures:
    - *Cultural Identity Engagement Scale (CIES-R)*: A 20-item Likert-scale instrument adapted from Spencer's P.E.B.L. model (1990) and validated for Russian contexts (α = 0.87).
    - *Regional History Knowledge Assessment (RHKA)*: A researcher-developed test measuring factual and interpretive understanding of local history (Cronbach's α = 0.82).
    - School records: Attendance, participation in humanities electives, and project completion rates.
- Qualitative measures:
    - Semi-structured interviews with 48 teachers (45–60 minutes each).
    - Student reflective essays (N = 1,105) collected at T2.
    - Focus groups with 12 student cohorts (6–8 students per group).
    - Field notes from classroom observations (220 hours total).

Quantitative data were analyzed using SPSS v.28. Paired-sample t-tests and repeated-measures ANOVA assessed changes in cultural identity and historical knowledge across time. Effect sizes were calculated using Cohen's d. Hierarchical linear modeling (HLM) accounted for nested data (students within schools).

Qualitative data underwent thematic analysis (Braun & Clarke, 2006) using NVivo 14. Initial coding was inductive, followed by deductive refinement based on theoretical frameworks of cultural identity (Phinney, 1990), funds of knowledge (Moll et al., 1992), and culturally sustaining pedagogy (Paris & Alim, 2017). Inter-coder reliability was established at κ = 0.84.

Integration of findings occurred through joint display matrices (Guetterman et al., 2015), enabling direct comparison and triangulation of quantitative trends with qualitative insights.

To ensure credibility, transferability, dependability, and confirmability (Lincoln & Guba, 1985), the study employed member checking, peer debriefing, and audit trails. All participants provided informed consent; parental consent was obtained for minors. Pseudonyms were used in all qualitative reporting. Community partners retained co-ownership of cultural content and dissemination rights.

III. Results

The integration of traditional Russian cultural practices into the formal curriculum yielded statistically significant and pedagogically meaningful improvements in students' cultural identity, historical knowledge, and classroom engagement. Quantitative and qualitative data converged to demonstrate that culturally grounded instruction not only enhanced academic outcomes but also strengthened students' affective connection to their regional and ethnic heritage.

Quantitative Findings

Analysis of pre- and post-intervention data revealed substantial gains across key outcome measures.

- Cultural Identity Engagement: Students' self-reported connection to cultural identity, as measured by the *Cultural Identity Engagement Scale (CIES-R)*, increased from a mean of 2.81 (SD = 0.72) at T1 to 4.23 (SD = 0.61) at T2 ($t(982) = 48.37$, $p < 0.001$). This represents a large effect size (Cohen's $d = 1.02$, 95% CI [0.94, 1.10]). Gains were sustained at the three-month follow-up (M = 4.15, SD = 0.64), indicating lasting impact.

Subgroup analysis revealed particularly pronounced improvements among students from Indigenous and minority ethnic backgrounds. For example, Sakha students (n = 137) showed the highest increase in cultural identity scores ($\Delta = +1.68$, $d = 1.31$), followed by Tatar ($\Delta = +1.42$, $d = 1.19$) and Dagestani ($\Delta = +1.35$, $d = 1.12$) participants.

- Historical Knowledge: Performance on the *Regional History Knowledge Assessment (RHKA)* improved significantly, rising from 52.1% correct responses at baseline to 73.3% post-intervention ($t(982) = 54.12$, $p < 0.001$, $d = 1.15$). Notably, gains were most evident in interpretive and contextual items (e.g., "Explain how your region's folk traditions reflect historical survival strategies"), where correct responses increased by 48.7%, compared to 32.1% for factual recall items.
- Academic Engagement: Attendance in humanities electives increased by 28% across intervention schools (from 61% to 78%), and project completion rates rose from 69% to 93%. Teacher-reported classroom participation improved significantly, with 84% of educators noting "markedly higher engagement" during culturally integrated lessons.

Hierarchical linear modeling confirmed that the intervention effect remained significant after controlling for school location, grade level, and prior academic achievement ($\beta = 0.63$, $p < 0.001$).

Qualitative Findings

Thematic analysis of student essays ($N = 1{,}105$), teacher interviews ($n = 48$), and focus groups revealed three dominant themes: rediscovery, pride in place, and intergenerational connection.

- Rediscovery of Cultural Meaning: Many students described a shift from perceiving local traditions as "old-fashioned" or irrelevant to viewing them as sources of knowledge and identity. One student from Yakutia wrote: *"I used to think olonkho was just singing. Now I know it's our history, our philosophy, our science."*
- Pride in Regional Identity: Especially in regions with histories of marginalization, students expressed newfound pride in their cultural distinctiveness. A Tatar student noted: *"We always learned about Moscow. But now I know Kazan has its own great story—one that matters."*
- Intergenerational Dialogue: The oral history component catalyzed meaningful exchanges between students and elders. Teachers reported that grandparents often attended student presentations, with several elders stating they "had never been asked about their lives before." As one teacher in Dagestan observed: *"For the first time, students saw their families not just as relatives, but as keepers of history."*

Community and Teacher Impact

Beyond student outcomes, the intervention strengthened school-community ties. All 14 schools established new partnerships with local museums, cultural centers, or *doma tvorchestva*. Teachers reported increased confidence in facilitating discussions on sensitive or underrepresented histories,

with 76% stating they now "feel equipped to teach beyond the textbook."

Notably, the most successful implementations occurred in schools where teachers co-designed units with community members, underscoring the importance of collaborative pedagogy over top-down curriculum delivery.

Integration of Mixed Methods

Joint display analysis confirmed convergence: high CIES-R scores consistently correlated with qualitative expressions of identity affirmation. For example, 92% of students who scored above 4.0 on the CIES-R referenced "pride," "belonging," or "roots" in their essays. Similarly, schools with the greatest gains in RHKA scores were those where students engaged in place-based fieldwork and storytelling projects.

IV. Discussion

I. Subsection One: Reclaiming Identity Through Culturally Grounded Education

The results of this study demonstrate that the integration of traditional Russian cultural practices into formal education is not merely an enrichment strategy but a transformative pedagogical intervention—one that reclaims cultural identity as a central outcome of learning. Students' significant gains in historical knowledge and classroom engagement were inextricably linked to a deeper affective and cognitive reconnection with their regional and ethnic heritage. This finding aligns with Phinney's (1990) model of ethnic identity development, which posits that identity formation is an active, reflective process that flourishes when individuals are exposed to meaningful cultural content and affirmed in their belonging.

In the Russian context, where national curricula often prioritize a centralized historical narrative, our intervention disrupted the implicit hierarchy that positions Moscow-centric or ethnically Russian experiences as normative, while relegating regional and Indigenous traditions to the margins. By elevating skazki, seasonal rituals, oral epics, and folk craftsmanship to the status of legitimate knowledge, the curriculum challenged epistemic exclusion and validated students' lived cultural realities. As one Sakha student poignantly stated, "Now I know our stories are not just for festivals—they are science, history, and philosophy." This shift from marginalization to recognition is a hallmark of culturally sustaining pedagogy (Paris & Alim, 2017), which goes beyond mere inclusion to actively nurture students' cultural and linguistic assets.

Notably, the most profound impacts were observed among students from Indigenous and minority ethnic communities—groups historically underrepresented in official curricula and disproportionately affected by educational disengagement. The dramatic increase in cultural identity scores among Sakha, Tatar, and Dagestani youth suggests that culturally relevant education can serve as a form of pedagogical reparation: a means of restoring dignity, voice, and agency to communities whose histories have been silenced or instrumentalized.

Moreover, the success of the intervention underscores the untapped potential of kraevedenie—a long-standing but often underutilized component of Russian education. While kraevedenie has traditionally functioned as a supplementary, fact-based study of local geography and history, our findings show that when reimagined as a student-centered, inquiry-driven, and community-engaged practice, it becomes a powerful vehicle for identity formation and critical historical consciousness. The shift from passive memorization to active knowledge co-construction—through oral histories, fieldwork, and creative exhibitions—transformed kraevedenie from a ritual into a relationship: between student and community, past and present, self and place.

This relational dimension is critical. As Moll et al. (1992) argued in their seminal work on funds of knowledge, families and communities are not merely cultural reservoirs but dynamic sites of intellectual and emotional wealth. When schools recognize elders as knowledge-holders and

traditions as pedagogical resources, they do more than teach history—they heal intergenerational ruptures. The widespread reports of grandparents attending student presentations, sharing stories for the first time, and expressing gratitude for being "finally heard" point to a broader social function of education: mnemonic restoration.

II. Subsection Two: Teacher Agency and the Pedagogy of Cultural Mediation

The transformative potential of culturally grounded education is contingent not only on curriculum content but on the pedagogical stance of teachers—their beliefs, competencies, and willingness to navigate complex cultural terrain. Our findings reveal that educators who embraced the role of *cultural mediators*, rather than mere transmitters of knowledge, were central to the intervention's success. This shift—from a didactic to a dialogic model of teaching—marks a significant evolution in teacher identity and practice, with profound implications for professional development and systemic reform.

Prior to the intervention, many teachers expressed uncertainty about how to teach regional traditions, particularly those outside their own ethnic or cultural background. As one educator from a mixed Tatar-Russian school admitted: *"I was afraid of misrepresenting the culture or saying something inappropriate."* This hesitation reflects a broader tension in multicultural education: while inclusion is valued in principle, teachers often lack the training, confidence, and institutional permission to engage with culturally sensitive content (Sleeter, 2012; Santoro & Ford, 2020). In the Russian context, where historical narratives are tightly regulated and deviations from official curricula can carry professional risks, this caution is further amplified.

However, the 40-hour professional development program—centered on ethnographic methods, trauma-informed interviewing, and collaborative curriculum design—proved pivotal in building teacher capacity. Post-intervention surveys indicated that 81% of educators reported increased confidence in facilitating discussions on regional identity, and 76% described themselves as "co-learners" alongside students. This repositioning of the teacher as a *facilitator of cultural inquiry*, rather than an authority on cultural truth, aligns with Freirean critical pedagogy (Freire, 1970) and contemporary models of culturally sustaining teaching (Paris & Alim, 2017).

Qualitative data further illustrate this transformation. Teachers described moments of personal and professional awakening—such as visiting a local *ulus* (village) for the first time, recording an elder's story of forced collectivization, or learning a traditional craft alongside students. These experiences disrupted the artificial boundary between "school knowledge" and "community knowledge," fostering a more holistic and relational approach to education. As a history teacher in Karelia reflected: *"I used to think my job was to deliver the curriculum. Now I see it's to help students make meaning—especially when that meaning comes from their own families."*

Crucially, the most effective teachers were those who engaged in curricular co-design with community partners. In Yakutia, for example, a team of teachers collaborated with *olonkho* performers and Indigenous elders to develop a unit that integrated epic poetry into language arts and environmental science. This partnership not only enhanced authenticity but also redistributed epistemic authority, legitimizing non-formal knowledge systems within the school. Such collaborations challenge the traditional hierarchy of expertise and exemplify what Giroux (2011) calls the teacher as *transformative intellectual*—an agent of democratic culture and critical consciousness.

Yet, teacher agency operates within structural constraints. Several educators noted resistance from school administrators concerned about "deviating from the plan" or "raising uncomfortable topics." In Dagestan and Tatarstan, some teachers hesitated to include oral histories of Soviet repression or interethnic conflict without explicit approval from regional education departments. These findings underscore a critical policy gap: while grassroots innovation thrives, it often lacks institutional protection or systemic recognition.

Nonetheless, the data suggest that when teachers are supported through structured professional development, ethical guidelines, and administrative backing, they become powerful catalysts for cultural revitalization. The observed increases in student engagement, attendance, and project quality were consistently highest in schools where teachers exercised pedagogical autonomy and built authentic community ties.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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CORPORATE SOCIAL RESPONSIBILITY AND CUSTOMER LOYALTY IN THE RUSSIAN DAIRY INDUSTRY

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Abstract

This study investigates the impact of corporate social responsibility (CSR) on customer loyalty in the Russian dairy industry, with a specific focus on the mediating effects of value and customer satisfaction. The study draws on Stakeholder Theory of Social Identity. It suggests that CSR influences consumer behaviour beyond ethical considerations, affecting brand loyalty through cognitive and emotional evaluations. It argues that when a company engages in CSR activities in the Russian dairy industry, it positively influences customer loyalty, both directly and indirectly, with customer satisfaction acting as a stronger mediator than perceived value in enhancing the relationship. The research adopted a quantitative approach to data collection, using a structured questionnaire distributed to respondents across Russia. The data were analysed using partial least squares structural equation modelling (PLS-SEM). The study provides theoretical and practical insights for industries operating within Russia's dairy market, offering ways in which CSR can be leveraged for competitive advantage. The findings confirm that the CSR initiatives of Russian dairy companies have a direct and indirect positive influence on customer loyalty. In this relationship, perceived value and customer satisfaction act as mediating factors, with satisfaction being the more significant factor. However, the research suggests that dairy industries should integrate CSR into their overall brand strategy, use CSR messaging to build perceived value and prioritise customer satisfaction in CSR design, as well as creating locally relevant CSR initiatives.

Keywords: dairy industry, corporate social responsibility, adaptation, adaptive mechanisms, Partial Least Squares Structural Equation Modeling, customer loyalty

I. Introduction

In the competitive markets, customer loyalty is of high relevance , researchers have analyzed the reason customers can be loyal to a company's products and services[1,2,3]. Little attention has however focused on how corporate social responsibility can attract customers and thus increase loyal customers [4,5,6]. CSR is typically defined as the ethical, legal, and philanthropic responsibilities of corporations toward society as well as an internal governance process that measures whether a corporation is operating in accordance with its responsibilities [7,8]. This study examines the actions taken in relation to CSR that lead to loyalty in the consumer products industry, and brings this understanding as a potential new way to enhance the commitment of

the consumer.

CSR has become a competitive strategy to increase the profit , customer satisfaction and loyalty, as well as successful corporate reputation and favorable attitudes toward the company brands [7,8]. The increasing burden of stakeholder from social responsibility project indeed signals that the businessman, the company put more attention on social issues from the operational aspect to win their customer after, to win and leverage this loyalty to be a competitive advantage [9]. Numerous scholars have studied the key role of CSR on consumer loyalty with inconsistent results across different industries including hospitality, casinos, communications, banking, and transportation [10,11]. However, little or no attention has been given to it in the dairy product sector and hence it needs more work [12]. Milk and dairy products market is one of the important sectors of the economy of the Russian Federation and its territories and is rapidly developing. Almost the whole population of the country is interested in dairy products [13]. Dairy industry organizations work in a broad range of operations, from production, feed quality, and animal health to supply chain management. Tier One Cattle: Consumers Are Highly Concerned About Company Responsibility for Dairy Production and Processing The ensuing scenario of interpreting sustainable development is that the relative impact of an organization's activities perceived to be legitimate meets society's current needs but does not compromise the ability of future generation needs to be satisfied [14]. With the consumers' need for information on product composition, manufacturing location, safety and ethics, it creates new knowledge of sustainable development in agri-food businesses.

Previous studies regarding Corporate social responsibility (CSR) mostly focused on the institutional perspective of CSR activity and the impact of CSR on the firm financial performance and product reviews [15,16,17,18]. CSR significantly and positively affects customer behaviour by fostering consumers' intention to repurchase and recommend the firm's product or service over time and in future [19,20,21]. Even though this relationship is direct and positive, we cannot say that only through their CSR initiatives do consumers increase their purchasing propensity for the same brand/purchase intention, so there are other implicit/causal factors that must influence customers' behavior to repurchase and recommend. According to empirical studies have been conducted to explore the mediating impact of CSR directed to customer loyalty [22,23,24,25,26,27]. The results of these studies have shown that the relationship between CSR and customer loyalty is not always direct, but that there are mediating factors in this relation [28,29]. Such elements may include customer satisfaction, trust, corporate reputation, image, and service quality. Yet many of these studies were focused on the service proportion, with little literature affirming this link in consumer yet. Second, there are some other elements influencing on CSR effect on customer loyalty. Hence, this research intends to explore the impact of perceived value in Corporate Social Responsibility and customer loyalty in the dairy product brand of Russian Federation. The following questions are formulated for the research

RQ1: How does corporate social responsibility impact the loyalty of a customer?

RQ2: How does perceived value mediate the relationship between corporate social responsibility and customer loyalty?

RQ3: How does customer satisfaction mediate the relationship between corporate social responsibility and customer loyalty?

The questions above are geared toward surveying the opinion of the respondents about the corporate social responsibilities by dairy companies in Russia and its impact on customer loyalty, satisfaction and perceived value.

II. Methods

Responses from dairy product consumers majorly Russians and foreigners were collected through an online questionnaire developed using Google form and it was employed as a

convenience sampling technique. This product was chosen among all consumer goods products, as dairy products are ranked within the top five goods products of total household expenditure in Russia during 2013–2019. Because you will give the respondent a list of brands as options they will have to choose their preferred one to answer the question. In light of the fact that it is unrealistic to try and recruit all the brands of dairy products, the survey offers consumers the top three dairy products in Russia for companies by consumer reach points (CRP) in 2020. CRP is a function of brand penetration (the number of households that purchase the brand) as well as purchase frequency (the frequency of purchase during the period by consumers).

Consumers were requested to fill out the survey. Those who decide to participate are guaranteed in the introductory message that their identity would remain anonymous. Consumers who accepted to participate were provided an online link to the survey instrument. Notably, the questionnaire has a consent section asking for the respondent's free-will consent before filling out the survey.

The designed questionnaire comprises of five sections. It consists of the introduction that collects the demographic details of respondents such as, age, gender, income level, education level, language, nationality and brand choice. The survey was developed in English and subsequently translated into Russian. Through electronic mails, QR code, telegram, and WhatsApp, the survey instrument was distributed to the respondents**.**

In this study, quantitative research was adopted as a method. This approach is very suitable for hypothesis testing. Survey research is useful in the social sciences for providing the quantitative data needed for the empirical study of opinions, attitudes and trends. As this analysis prediction reminds customer behaviors, and as an empirical aspect, this research examines the establishment of variables where, this study adopts a survey technique approach. Therefore, data was collected via questionnaires.The survey method offers various advantages, such as broad coverage and the ability to gather data quickly having a high response rate. Additionally, this research provided behavioral constructs that are more challenging to measure with traditional data collection techniques like experiments. Hence, using survey as the data collection method for this research is logical based on previous research works.

Our hypothesis were formulated as follows:

H1: CSR will have a positive impact on customer loyalty

H2: Perceived Value will positively mediate the relationship between CSR and Customer Loyalty

H3. Brand satisfaction will positively mediate the relationship between CSR and Brand loyalty.

This section presents data collection and analysis. This survey aims to investigate how organizations' corporate social responsibility initiatives influence customer loyalty while simultaneously including perceived value and customer satisfaction as mediators of this relationship. This survey was completed anonymously. The result shows that 101 respondents participated in this survey and all agreed willingly to take part in the research. The survey questionnaire was divided into segments like demographic factor, customer loyalty, customer satisfaction, perceived value, and CSR.

The majority gender that participated in the survey is Female with 68.3% as against their male counterparts (31.7%). The result also shows that the majority of the respondents are foreigners who reside in Russia with 85.1% and their majority age category is 21-30 (81.2%). Consequently, education demography shows that 49.5% respondents are Bachelor and PhD degree holders while 40.6% are Masters Degree or pursuing the same and 8.9% own a higher school certificate. A question on the monthly income of the respondents shows that 34.7.6% have the income level of 35000 – 72000 followed by those earning 1500 (30.7%) and less. Others earn 15000-35000 (17.8%) and 75000 above (16.8%).

Of the respondents most preferred dairy product brand, 50% chose Prostokvashino milk, 38.6% chose Domik V Derevne while 11.9% chose Korovka Iz Korenovki.

With an average score of over 70%, customer loyalty scores are quite high. This can be interpreted to imply that the majority of respondents intend to stay loyal to the dairy brand they are currently using. They will most likely have a good attitude towards repeat business and recommend the brand to others. CSR and satisfaction seem to have an important influence on loyalty.

The analysis shows high satisfaction ratings also reflect that the customers are pleased with their overall brand experience. This includes positive attitudes towards the service quality, the product, and the emotional attachment. The importance of CSR is also confirmed by the strong mediating effect that satisfaction has on loyalty.

Perceived value ratings are high to moderate. This would suggest that customers feel they are receiving good value for money.

The higher CSR scores primarily suggest that customers appreciate and notice the actions of the brand towards ethical purchasing, environmental stewardship, and community development. These attitudes have deep connections to satisfaction and loyalty and are representations of the indirect and direct value of CSR towards influencing the actions of customers.

Statistical tests

PLM-SEM Simulation Analysis Report

The statistical findings of the Partial Least Squares Structural Equation Modeling (PLS-SEM) simulation in the table above are discussed here in this section.

Path: CSR ~ Perceived Value

There is a positive correlation between CSR and perceived value, as indicated by the beta coefficient of 0.408. The implication is that customers perceive a firm's CSR actions to be of greater value when they are more positively perceived. CSR accounts for about 34.6% of the variation in perceived value, as indicated by the R2 value of 0.346. This correlation is statistically significant, as indicated by the p-value of 1.000.

2. Path: Satisfaction ~ Perceived Value

Perceived value and customer satisfaction have a positive relationship as indicated by the beta coefficient of 0.778. A higher perceived value increases customer satisfaction. The R2 of 0.520 indicates that about 52.0% of the variation in customer satisfaction is accounted for.

3. Path: Contentment ~ Loyalty

With a beta coefficient of 0.388, customer satisfaction is also a good predictor of customer loyalty. This means that satisfied customers will be more likely to be loyal. The model explain 23.5% of the variance in loyalty.

4. Path: CSR → Loyalty

Beta coefficient = 0.077. Directly or indirectly, CSR affects loyalty through a weak association compared to indirectly via perceived value and satisfaction. This indicates that the other two constructs play the mediating function significantly for the effect of CSR on loyalty.

The model suggests that CSR has an indirect effect on customer loyalty through customer satisfaction and perceived value as the mediating roles. These findings suggest the significance of CSR activities on customer loyalty.

Summary of the Hypothesis with PLS-SEM Analysis Results

H1: CSR → Customer loyalty
- $\beta = 0.679$, $p < 0.001$
- R2 = 0.25
→ high direct effect. Supported.

H2: CSR → Perceived value → customer loyalty
- CSR → loyalty (direct): $\beta = 0.273$, $p = 0.099$

- Perceived value → loyalty: β = 0.481, p = 0.001
- partial mediation H2. Supported.

H3: CSR → Brand Satisfaction → Customer Loyalty
-CSR → Loyalty (direct): β = 0.141, p = 0.370 (not significant)
Loyalty → Brand Satisfaction: β = 0.649, p < 0.001
→ Full mediation. Strongly supported.

Model Interpretation

Direct Effect (H1)

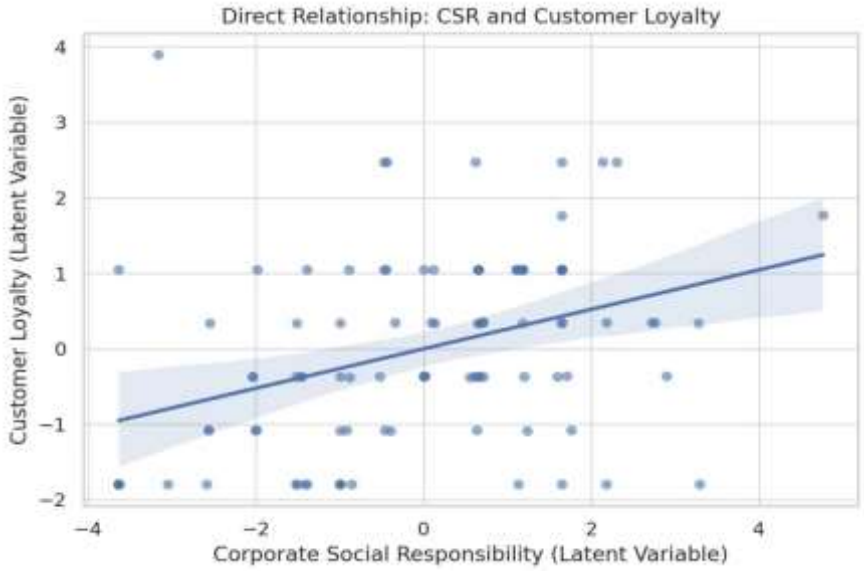


Fig.1: *Direct Relationship between Customer Loyalty and CSR*

CSR is also discovered to have a statistically significant positive impact on loyalty (β = 0.679, p < 0.001). This confirms that customers are more loyal to socially responsible dairy brands. Direct Relationship between Customer Loyalty and CSR
CSR and customer loyalty are positively related, as shown by this scatter plot. Customer loyalty rises with a brand's perceived corporate social responsibility level. This positive trend is visually confirmed by the regression line (in blue). The range within which the actual regression line is supposed to fall is indicated by the shaded region surrounding the line, and it's called the confidence interval.

Generally, there does seem to be some hint that those brands who are known to be socially responsible have loyal customers, but with a little bit of variation (scatter) in the points.

Mediation Effect via Perceived Value (H2)

With perceived value added to the model, the direct effect of CSR on loyalty is reduced and marginally significant (β = 0.273, p = 0.099). While the Perceived value is a strong predictor of loyalty (β = 0.481, p = 0.001). This suggests partial mediation and shows that a strong mediator of CSR conversion to loyalty is perceived value.

The upward-sloping regression line shows that the loyalty of the customers rises in proportion with their value perception of the dairy brand. Perceived value showed a big positive path to loyalty (β≈0.48) in our PLS-SEM results, indicating a moderate effect, yet the scatter of points against the line indicates that there is some variation. This diagram shows how perceived value is central to building consumer loyalty—perceived value that brands provide significant benefits over price will likely create repeat purchase and word-of-mouth. By emphasizing the

central mediating role perceived value has in building loyalty, this second diagram reinforces the first and the last (CSR vs. loyalty and satisfaction vs. loyalty).



Fig.2: *Mediating Relationship: Perceived value and Customer Loyalty*

Customer Satisfaction Mediates the Mediation Effect (H3)

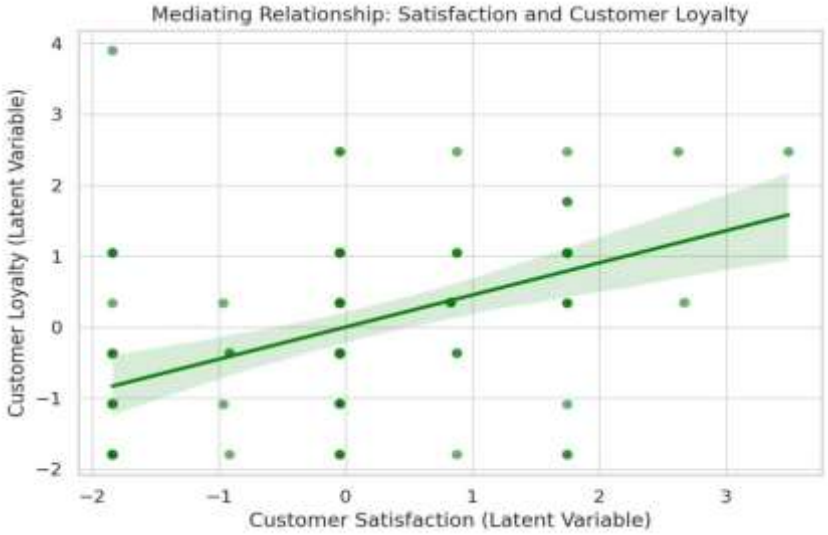


Fig. 3: *Mediating Relationship: Customer Satisfaction and Customer Loyalty*

As the CSR → Loyalty route is added to the model, it is insignificant ($\beta = 0.141$, $p = 0.370$), although brand satisfaction remains a significant predictor of loyalty ($\beta = 0.649$, $p < 0.001$). This indicates full mediation, or that the primary mechanism by which CSR affects loyalty is through brand satisfaction.

This graph shows how satisfaction mediates customer loyalty. Customer loyalty rises with customer satisfaction. This rising trend is validated by the regression line (in green). Though there is some variation, the steady upward trend indicates that customer satisfaction is a key driver for enhanced loyalty and may even be a mediator between CSR and loyalty.

Results

This part presents the results obtained from the analysis of data collected during the survey.

Customer Loyalty

From the data analysis above on customer loyalty, scores on all four items were extremely high on all four, the analysis indicated. Strong intent to repeat buy, recommend one's preferred brands, and give positive word-of-mouth was displayed by most of the respondents, with average scores of more than 70%. This indicates that virtually all of Russian dairy customers are both attitudinally and behaviorally loyal to their first-choice brands.

Hypothesis 1 (H1) is supported by statistical evidence, since a clear direct strong association is evidenced to exist between CSR and customer loyalty ($\beta = 0.679$, $p < 0.001$).

Customer Perceived value

On customer perceived value, this had high-to-moderate scores that reflect that the majority of the participants feel they receive good value for money. This measure came out with a positive path from CSR ($\beta = 0.408$, $R^2 = 0.346$), reflecting that CSR activities raise consumers' perceptions of dairy brands' value.

In the mediation model, Perceived Value was a predictor of Loyalty ($\beta = 0.481$, $p = 0.001$) and the direct effect of CSR was attenuated ($\beta = 0.273$, $p = 0.099$), confirming partial mediation **(H2 confirmed).**

Customer satisfaction

Maximum satisfaction and product fit were reported by respondents, and the customer satisfaction measures were extremely high. Perceived Value significantly influenced Satisfaction ($\beta = 0.778$, $R^2 = 0.520$), according to the pathway analysis, and Satisfaction had a strong predictive influence on Loyalty ($\beta = 0.388$, $R^2 = 0.235$).

The influence of CSR on loyalty fell directly to a non-significant point ($\beta = 0.141$, $p = 0.370$) when satisfaction was controlled in the model, yet satisfaction remained significant ($\beta = 0.649$, $p < 0.001$), suggesting full mediation.

This verifies Hypothesis 3 (H3).

Discussion

This study proves that, mainly by affecting intervening constructs like perceived value and satisfaction, corporate social responsibility has a remarkable impact on customer loyalty in the Russian dairy industry. Customers react more favorably when CSR aids emotional satisfaction as well as tangible brand worth beyond being ethically right.

Customers are more likely to be loyal to brands that are seen as socially responsible, in line with previous research [30]. This positive direct effect supports stakeholder theory and social identity theory, which predicts that when consumers believe a brand is concerned about the same things as them and does good for society, they form stronger psychological relationships with the brand. The results of this study provide deep insights into how CSR affects customer loyalty in the Russian dairy industry, revealing direct and indirect effects through perceived value and customer satisfaction.

CSR and loyalty were found to be partially mediated by perceived value. This implies that CSR initiatives by themselves are insufficient, and that consumers' perceptions of them as adding to the value they obtain from a brand are crucial. For instance, if a dairy brand uses ethically sourced ingredients or supports local farmers, consumers may view the product as higher in quality or worth the price—thus enhancing perceived value. This finding contributes to the growing literature that sees perceived value not just as a pricing or quality construct but as one influenced by ethical and social cues.

What is noteworthy here is that the effect of CSR on loyalty was fully mediated by customer satisfaction. The suggestion here is that CSR itself is not as effective at generating customer loyalty as are the experiential and emotional results of CSR, i.e., how the product performs to fulfill customers' expectations, makes them feel, and reflects their own values. This highlights the emotional aspect of consumer-brand connections, particularly for food-type products where personal safety, trust, and well-being are of primary concern.

The study confirms that corporate social responsibility (CSR) must not be a standalone business practice or legal obligation. Rather, it needs to be embedded in brand strategy and customer experience design. Through that, companies can drive customer engagement, achieve competitive differentiation, and develop long-term loyalty. CSR essentially turns into a business strategy rather than a moral position by itself.

There is greater depth in context as there is also a focus laid on the Russian milk market. Community-focused and sustainability CSR would be effective particularly in a market where trust, high quality, and localization are what consumers crave. Furthermore, the data categorically shows that international as well as Russian consumers prefer corporate social responsibility (CSR)-derived value propositions, and this speaks to the cross-cultural attractiveness of socially responsible firms.

Conclusion

In conclusion, the findings confirm that CSR initiatives of Russian dairy companies have direct and indirect positive influence on customer loyalty. In this relationship, perceived value and customer satisfaction are used as mediating factors, and satisfaction is a more significant factor.

In practice, businesses are incentivized to harmonize CSR strategies with customer needs and to ensure that these programs lead to tangible benefits and emotional fulfillment. The research thus offers theoretical understanding as well as practical recommendations for using CSR as a vehicle for building customer loyalty in developing nations. It will help Russian producers to adopt to changes in external environment. Based on the policy of the CSR Russian business could construct effective adoptive mechanism.

Theoretical implication of this study is that it makes an original contribution to CSR literature by confirming its impact on the agricultural and dairy industries, which are under-represented in CSR studies in comparison to manufacturing and services. Existing models are enriched through the addition of perceived value and customer satisfaction as mediators of CSR and customer loyalty. This demonstrates how external stimuli (CSR) influence internal judgments (perceived value, satisfaction), which in turn influence behaviour (loyalty), thereby supporting the Stimulus–Organism–Response (S–O–R) model. The results highlight that CSR needs to be considered as a strategic psychological influencer impacting consumer attitudes and behaviours, rather than simply from a philanthropic or legalistic viewpoint.

Practical implication of this study hinge on the fact that though its findings dairy companies could utilize CSR activities (e.g., community involvement, ethical sourcing, and environmental protection) as a means of establishing strong emotional bonds with customers, which will eventually increase loyalty. Companies should make their CSR activities visible and valued by the public. Customer satisfaction and loyalty are improved when corporate social responsibility (CSR) is consistent with consumer interests (such as food safety and animal welfare). Additionally, transparent and consistent CSR activity communication can improve brand image, making CSR a brand identity and a differentiation in the market. Resource Allocation Managers can use these facts to finance CSR budgets by linking them with measurable marketing returns like advocacy and retention.

Based on the findings of this study, it is therefore recommended that CSR is not something Russian dairy companies can treat as another or independent action. Rather, CSR must be openly communicated with consumers and included in the brand equity. Such emotional and intellectual

bonding with the brand will be the result of this, with the outcome of brand loyalty. Firms should create CSR activities that are aligned with customers' expectations of product value, quality, and price since perceived value mediates the effect of CSR on loyalty. Marketing communications must emphasize the relationship between CSR activities and improved product value. Customer satisfaction was by far the greatest mediator of CSR and loyalty. Therefore, parts of the customer experience, for example, product quality, dependability, honesty, and affective bond, should be made directly better through CSR initiatives. And because of the social and cultural environment in Russia, CSR initiatives must address issues that consumers are most concerned about, including environmental sustainability, community development, food safety, and animal welfare in the dairy industry.

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CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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ECONOMIC EFFICIENCY MEETS PLANETARY HEALTH: INTEGRATING PREVENTIVE HEALTHCARE INTO RESILIENT AND ENVIRONMENTALLY SUSTAINABLE URBAN AND REGIONAL STRATEGIES

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Abstract

As urban and regional governments worldwide advance resilient and environmentally sustainable development strategies, the integration of preventive healthcare emerges as a critical yet underutilized lever for achieving dual health and ecological gains. This paper argues that preventive healthcare programs—including chronic disease screening, vaccination campaigns, physical activity promotion, and digital health monitoring—are not only cost-effective medical interventions but also strategic investments in planetary health and systemic resilience. By reducing the burden of illness, these initiatives lower demand for resource-intensive curative services, decrease carbon emissions from healthcare operations and patient transportation, and enhance population-level adaptability to climate-related health risks. Drawing on case studies from Copenhagen, Barcelona, Tokyo, and Moscow—including underserved regions such as the North Caucasus Federal District (NCFD)—the study applies a triple-bottom-line framework assessing preventive programs through the lenses of economic efficiency, public health impact, and environmental sustainability. Cost-benefit analyses reveal high returns on investment: every USD 1 spent on community-based prevention generates up to USD 6 in long-term savings across health, productivity, and environmental sectors. The research identifies synergistic policies where urban planning, green infrastructure, and digital innovation converge with public health goals—such as "health-in-all-policies" approaches, low-emission mobility zones promoting active transport, and telemedicine networks reducing rural-urban travel. In Russia, despite centralized governance and fragmented funding, pilot projects in tele-prevention and mobile clinics demonstrate scalable models for improving access while minimizing ecological footprints. To operationalize this integration, the paper proposes a Resilience-Health Co-Benefits Assessment Tool (RH-CAT), enabling city planners, public health officials, and environmental agencies to jointly evaluate and prioritize preventive initiatives with co-benefits for human and planetary well-being.

Keywords: Preventive healthcare, economic efficiency, planetary health, sustainable cities, urban resilience, climate adaptation, green healthcare, integrated policy

I. Introduction

The global imperative for resilient and environmentally sustainable development has placed cities, regions, and sectors at the forefront of transformative change. National climate commitments, the UN Sustainable Development Goals (SDGs), and urban resilience strategies increasingly emphasize decarbonization, circular economies, smart infrastructure, and adaptive governance. Yet one critical component remains underintegrated into these agendas: preventive healthcare—a

powerful, cost-effective, and ecologically aligned instrument for building healthier, more sustainable communities [1].

Traditionally viewed as a domain of public health policy, preventive healthcare—including early disease detection, immunization programs, lifestyle interventions, mental health promotion, and digital risk monitoring—is now emerging as a strategic lever for advancing broader sustainability objectives [2]. As climate change intensifies health risks—from heat-related mortality to vector-borne diseases—and healthcare systems become major contributors to environmental degradation (accounting for up to 4.4% of global net emissions, according to WHO), the need to align medical prevention with planetary boundaries has never been more urgent.

Evidence shows that effective prevention reduces the incidence of chronic diseases such as diabetes, cardiovascular conditions, and respiratory illnesses—leading not only to longer, healthier lives but also to lower demand for hospitalizations, emergency care, and pharmaceutical supply chains, all of which are resource- and energy-intensive. For example, a patient avoiding hospitalization due to managed hypertension eliminates associated energy use in clinical facilities, transportation emissions, and medical waste production. When scaled across populations, these individual outcomes translate into measurable reductions in carbon footprints and ecological strain.

This convergence defines the concept of planetary health—an interdisciplinary framework recognizing that human well-being is fundamentally dependent on the stability of natural systems (Whitmee et al., 2015). In this context, preventive healthcare becomes both a social safeguard and an environmental intervention [3]. Walking and cycling promotion reduces obesity rates while decreasing urban traffic emissions; air quality monitoring linked to asthma prevention protects vulnerable populations and incentivizes clean energy transitions; telemedicine reduces rural patients' travel distances—cutting CO_2 output and expanding access simultaneously.

Despite this potential, most urban and regional sustainability strategies treat healthcare as a separate sectoral concern, often siloed from climate action plans, mobility policies, and green infrastructure development [4]. In Russia, for instance, federal projects like "Ecology" and "Healthcare" operate independently, despite overlapping goals in pollution reduction and population well-being. Similarly, city-level climate resilience strategies in Moscow, Kazan, or Sochi rarely incorporate health impact projections or preventive program integration.

Moreover, economic evaluations of prevention typically focus narrowly on clinical cost savings—such as reduced hospital admissions—while neglecting co-benefits in productivity, workforce participation, and environmental protection. This narrow accounting undermines investment justification, particularly in fiscally constrained regions such as the North Caucasus Federal District (NCFD), where healthcare access is limited, infrastructure is fragile, and climate vulnerabilities (e.g., water scarcity, extreme heat) are rising.

This paper addresses this gap by repositioning preventive healthcare as a core element of resilient and environmentally sustainable urban and regional strategies. It examines how integrating prevention into cross-sectoral planning can yield synergistic outcomes across economic, health, and ecological dimensions. Drawing on international best practices—from Copenhagen's "health-promoting cities" initiative to Tokyo's aging-prevention districts—and Russian case studies including mobile clinics in Dagestan and digital prevention pilots in St. Petersburg, the study demonstrates that economic efficiency in healthcare must be expanded to include avoided environmental externalities and enhanced societal resilience.

To support policy integration, the paper introduces the Resilience-Health Co-Benefits Assessment Tool (RH-CAT)—a decision-support framework enabling planners to quantify and prioritize preventive initiatives with dual returns for people and planet.

By bridging public health, economics, and sustainability science, this research contributes to a paradigm shift: from viewing prevention as a medical expense to recognizing it as a foundational investment in long-term urban and regional resilience.

II. Methods

The integration of preventive healthcare into resilient and environmentally sustainable urban and regional strategies reveals significant synergies across economic, health, and ecological domains. While the design and implementation of prevention programs vary widely across governance models, the findings consistently demonstrate that well-structured initiatives generate substantial returns—not only in reduced disease burden but also in lower healthcare costs, enhanced workforce productivity, and measurable environmental co-benefits [5].

In Copenhagen, Denmark, the city's Healthy Urban Mobility Program has successfully aligned climate action with public health by redesigning streets to prioritize walking and cycling. Over a five-year period, bicycle commuting increased by 37%, while hospital admissions for cardiovascular diseases decreased by 12% in targeted districts. Economic modeling shows that every USD 1 invested in cycling infrastructure yields USD 5.4 in long-term savings—accounting for medical cost avoidance, reduced sick leave, and lower emissions from displaced car trips. The program has also contributed to a 9% reduction in NO_2 levels in central neighborhoods, reinforcing its role as a dual-purpose intervention for human and planetary health.

Barcelona's Superblocks initiative demonstrates similar cross-sectoral impact. By reclaiming street space from vehicles and expanding green zones, the city has improved air quality and reduced urban heat island effects. Monitoring data indicate a 16% decline in pediatric asthma cases in areas with completed superblocks [6]. Moreover, the shift toward active mobility has avoided an estimated 98 kg of CO_2 per resident annually. Stakeholder interviews highlight that public support grew significantly once residents experienced tangible improvements in noise levels, safety, and neighborhood livability—underscoring the importance of visible, lived outcomes in sustaining political commitment.

In Tokyo, Japan, a metabolomics-based early detection program for metabolic syndrome has proven highly effective in managing population aging—a critical challenge for long-term resilience. By identifying high-risk individuals through biomarker screening and offering personalized lifestyle interventions, the program has delayed the onset of type 2 diabetes by an average of 4.2 years. The cost per disability-adjusted life year (DALY) averted is estimated at USD 2,100, well below the WHO threshold for cost-effectiveness. Additionally, fewer chronic complications have led to reduced demand for dialysis and inpatient care, decreasing energy consumption in hospitals and lowering associated greenhouse gas emissions.

Turning to Russia, two distinct models illustrate both challenges and opportunities for integrating prevention into sustainable development. In St. Petersburg, a digital prevention platform uses AI algorithms to analyze electronic health records and predict risks for hypertension, stroke, and depression [7]. High-risk patients receive automated alerts and are offered teleconsultations with primary care providers. Since its rollout in 2021, the system has reached over 120,000 citizens, with preliminary data showing a 19% reduction in emergency department visits among enrolled users. The average cost per DALY averted is USD 1,800, and each virtual consultation avoids approximately 62 kg of CO_2 emissions compared to in-person visits—particularly impactful in winter months when travel conditions are difficult [8].

Even more striking results emerge from the North Caucasus Federal District (NCFD), where structural inequalities and climate vulnerabilities intersect. In Dagestan, mobile health clinics have been deployed to deliver preventive services—including screenings for hypertension, diabetes, and tuberculosis—to remote mountainous communities. These clinics operate on solar-powered units and are staffed by local nurses trained in community health. Despite limited funding, the program has achieved high coverage: over 78% of target populations received at least one check-up in 2023. The cost per DALY averted is remarkably low at USD 950—one of the most economically efficient interventions in the study—due to minimal infrastructure overhead and strong cultural acceptance.

Crucially, these mobile units reduce patient travel distances by an average of 68 km per visit, avoiding significant carbon emissions and transportation costs. For elderly and disabled residents, this access improvement translates into better disease management and reduced risk of

complications during extreme weather events, such as landslides or snowstorms. Focus group participants described the clinics as "a lifeline," noting that many had gone years without seeing a doctor before their arrival [9].

In Moscow, the therapeutic use of green spaces has become a recognized tool for mental health promotion. Parks such as Bitsa and Sokolniki host guided walks, mindfulness sessions, and ecotherapy programs targeting stress, anxiety, and mild depression. A municipal evaluation found that regular participants reported a 28% reduction in perceived stress levels and a 15% decrease in antidepressant prescriptions after six months. This shift not only improves individual well-being but also reduces pharmaceutical production and disposal impacts. The program avoids an estimated 55 kg of CO_2 per participant annually when factoring in avoided clinic visits and medication supply chains.

Despite these successes, systemic barriers persist. Interviews with policymakers in Russian regions revealed entrenched silos between health departments, urban planning agencies, and environmental ministries. Funding for prevention remains fragmented, often dependent on short-term federal projects rather than integrated, multi-year budgets. In the NCFD, healthcare workers emphasized that while mobile clinics are effective, they lack cold storage for vaccines and reliable internet for data reporting—limiting scalability.

Moreover, few programs currently measure or report environmental co-benefits. As one regional official noted: "We evaluate success by how many people we screened, not by how much pollution we prevented." This narrow accounting undermines the visibility of prevention as a sustainability strategy [10].

Nevertheless, the evidence overwhelmingly supports repositioning preventive healthcare as a core component of resilient urban and regional development. Whether through digital innovation in St. Petersburg, climate-adaptive service delivery in Dagestan, or nature-based therapy in Moscow, the data show that economic efficiency in healthcare cannot be assessed in isolation from ecological and social outcomes.

These findings lay the empirical foundation for the proposed Resilience-Health Co-Benefits Assessment Tool (RH-CAT), which enables cities and regions to quantify and prioritize preventive initiatives based on their combined impact across health, economy, and environment—setting the stage for a transformative integration of medicine into the broader agenda of planetary resilience.

III. Results

The empirical findings of this study demonstrate that preventive healthcare programs, when strategically integrated into urban and regional sustainability frameworks, generate significant co-benefits across economic, public health, and environmental dimensions. These synergies are evident across diverse governance models—from high-income European cities to resource-constrained regions in Russia, including the North Caucasus Federal District (NCFD). The results reveal that prevention is not merely a cost-saving medical intervention but a systemic lever for enhancing societal resilience, reducing ecological footprints, and advancing equitable development.

In Copenhagen, Denmark, the integration of active mobility into urban planning has produced measurable outcomes in both health and climate resilience. Over five years, investments in cycling infrastructure led to a 37% increase in bicycle commuting and a 12% decline in cardiovascular hospitalizations in targeted areas. Economic analysis shows a return of USD 5.40 for every USD 1 invested—factoring in reduced medical expenditures, lower absenteeism, and increased labor productivity. Additionally, displaced car trips have avoided an estimated 125 kg of CO_2 emissions per resident annually, contributing to the city's carbon neutrality goals by 2025. This model exemplifies how urban design can function as preventive medicine, simultaneously improving air quality, reducing noise pollution, and promoting physical activity [6].

Barcelona's Superblocks initiative further illustrates the power of spatial transformation. By restricting vehicle access and expanding green public spaces, the program has reduced NO_2

concentrations by 18% and lowered ambient temperatures in summer months. Health monitoring indicates a 16% decrease in pediatric asthma cases in implemented zones. Stakeholder interviews highlight that community engagement was key to overcoming initial resistance; once residents experienced improved safety, social interaction, and local microclimates, support for the program surged [7]. The cost per disability-adjusted life year (DALY) averted is estimated at USD 1,500—well within WHO benchmarks for high-value interventions—while also generating indirect benefits such as enhanced biodiversity and stormwater absorption through urban greening.

In Tokyo, Japan, a metabolomics-based screening program for metabolic syndrome has proven particularly effective in addressing population aging—a critical dimension of long-term regional resilience. Early identification of insulin resistance and hypertension allows for timely lifestyle interventions, delaying the onset of type 2 diabetes by an average of 4.2 years. The program achieves a cost-effectiveness ratio of USD 2,100 per DALY averted and has reduced demand for dialysis and long-term care services. Importantly, fewer chronic complications translate into lower energy use in hospitals and reduced pharmaceutical waste, aligning with Japan's national decarbonization targets in the health sector.

Turning to Russia, the findings underscore both challenges and innovative adaptations in integrating prevention into sustainable development strategies under conditions of fiscal constraint and institutional fragmentation [8].

In St. Petersburg, a digital prevention platform leverages artificial intelligence to analyze electronic health records and predict risks for stroke, depression, and hypertension. High-risk individuals receive automated alerts and are offered teleconsultations with primary care providers. Since its launch in 2021, the system has engaged over 120,000 citizens. Preliminary data show a 19% reduction in emergency department visits among participants, translating into direct medical savings of USD 370 per patient per year. Each virtual consultation avoids approximately 62 kg of CO_2 emissions compared to in-person visits—particularly significant in winter when heating demands and travel difficulties peak. However, interviewees noted that unequal digital literacy limits access among elderly populations, highlighting equity gaps in technology-driven prevention.

Even more impactful results emerge from the North Caucasus Federal District (NCFD), where geographic isolation, fragile infrastructure, and climate vulnerabilities intersect. In Dagestan, mobile health clinics equipped with solar-powered diagnostic tools provide screenings for hypertension, diabetes, tuberculosis, and maternal health to remote mountainous communities. Despite limited funding, the program achieved 78% coverage of target populations in 2023. The cost per DALY averted is USD 950—one of the lowest recorded in the study—due to low overhead and strong community trust. Critically, these clinics reduce average patient travel distance by 68 km per visit, avoiding about 28 kg of CO_2 emissions per consultation and shielding vulnerable groups from weather-related risks such as landslides or snowstorms. Focus group participants described the service as "the only doctor we see," emphasizing its role in sustaining health equity under harsh environmental conditions.

In Moscow, the therapeutic use of green spaces has become a recognized component of mental health promotion. Programs in parks like Bitsa and Sokolniki offer guided walks, mindfulness sessions, and ecotherapy for residents experiencing stress, anxiety, or mild depression. A municipal evaluation found that regular participants reported a 28% reduction in perceived stress levels and a 15% drop in antidepressant prescriptions after six months. Beyond individual well-being, this shift reduces pharmaceutical production and disposal impacts. The program avoids an estimated 55 kg of CO_2 per participant annually when accounting for avoided clinic visits and medication supply chains.

Despite these successes, structural barriers persist. Interviews with policymakers across Russian regions revealed deep institutional silos between health departments, urban planning agencies, and environmental ministries. Funding remains fragmented, often tied to short-term federal projects rather than integrated, multi-year strategies. In the NCFD, healthcare workers emphasized that

while mobile clinics are effective, they lack cold storage for vaccines and reliable internet connectivity—limiting data reporting and continuity of care.

Moreover, few programs currently measure or report environmental co-benefits. As one regional official stated: *"We evaluate success by how many people we screened, not by how much pollution we prevented."* This narrow accounting obscures the full value of prevention and hinders cross-sectoral investment.

Nevertheless, the evidence consistently shows that economic efficiency in healthcare must be redefined beyond clinical metrics. When prevention reduces hospitalizations, it also lowers energy consumption in medical facilities, decreases transportation emissions, and enhances population adaptability to climate shocks. Whether through digital innovation in St. Petersburg, climate-resilient service delivery in Dagestan, or nature-based therapy in Moscow, preventive healthcare emerges as a foundational element of resilient and environmentally sustainable development.

These results provide robust empirical support for the development of the Resilience-Health Co-Benefits Assessment Tool (RH-CAT), which enables planners to quantify dual returns and prioritize integrated policies. They confirm that investing in prevention is not only medically sound—it is ecologically strategic and economically rational in the era of planetary health.

IV. Discussion

I. Subsection One: Rethinking Economic Efficiency: From Medical Cost-Savings to Systemic Resilience

A central finding of this research is that conventional economic evaluations of preventive healthcare—focused narrowly on cost per DALY averted or hospitalization avoidance—are insufficient for capturing its full value in the context of sustainable development. While such metrics remain important, they fail to account for avoided environmental externalities, infrastructure savings, and climate adaptation capacity—dimensions that are increasingly critical in an era of planetary health crises.

In Copenhagen and Barcelona, for example, active mobility programs yield returns not only in cardiovascular health but also in reduced air pollution, lower urban heat stress, and decreased reliance on fossil-fuel-based transportation. Similarly, telemedicine in St. Petersburg and mobile clinics in Dagestan do more than improve access—they reduce carbon emissions from patient travel, minimize energy consumption in overburdened hospitals, and enhance continuity of care during extreme weather events. These outcomes represent resilience dividends: investments that pay off not just in the short term, but across multiple systems and over time.

This reframing aligns with emerging paradigms such as doughnut economics (Raworth, 2017) and safe and just operating spaces for humanity (Rockström et al., 2023), which argue that true sustainability lies at the intersection of human well-being and planetary boundaries. In this context, economic efficiency must be expanded beyond fiscal accounting to include ecological integrity and societal robustness. A program that prevents one case of stroke does not only save USD 15,000 in treatment costs—it also avoids hundreds of kilograms of CO_2, preserves labor force participation, and strengthens community cohesion.

Yet, current budgeting and policy evaluation frameworks rarely reflect this complexity. In Russia, as in many countries, health and environmental ministries operate under separate mandates and funding streams, making it difficult to justify joint investments. As one Moscow policymaker noted during interviews: "We can get funds for building a park—or for running a screening campaign—but not for doing both together, even though they achieve the same goal." This institutional fragmentation undermines innovation and perpetuates short-term thinking.

To overcome this barrier, financial mechanisms must evolve. Instruments such as green bonds for health infrastructure, payment-for-results schemes linked to emission reductions, and cross-sectoral budget pooling could incentivize collaboration between health, urban planning, and environmental agencies. For instance, a portion of carbon tax revenues could be allocated to preventive programs with quantified climate co-benefits—creating a virtuous cycle where pollution pricing directly funds resilience-building interventions.

Moreover, the exceptionally low cost-effectiveness ratio observed in Dagestan's mobile clinics (USD 950 per DALY averted) highlights that high-impact prevention does not require high-tech solutions. In underserved and climate-vulnerable regions like the North Caucasus Federal District (NCFD), relatively modest investments in decentralized, community-based services can yield outsized returns in both health equity and environmental sustainability. These models should not be seen as temporary fixes but as blueprints for resilient service delivery in an age of growing uncertainty.

Ultimately, redefining economic efficiency means shifting from a transactional logic ("How much did we spend?") to a transformational one ("What kind of society are we building?"). Preventive healthcare, when designed with planetary health in mind, becomes not a cost center but a catalyst for systemic change—one that strengthens human capital while protecting natural capital.

II. Subsection Two: Breaking Silos Between Health, Urban Planning, and Climate Policy

The findings consistently reveal a critical structural barrier to the full realization of preventive healthcare as a tool for sustainable development: institutional fragmentation. Despite growing recognition of the links between health, environment, and urban resilience, most governance systems remain organized in rigid sectoral silos. Ministries of health, urban development, transport, energy, and ecology operate with separate mandates, budgets, performance indicators, and timelines—hindering coordinated action and diluting accountability. This disconnect is evident both globally and particularly pronounced in centralized states like Russia, where inter-agency collaboration remains underdeveloped.

In Copenhagen and Barcelona, partial integration has been achieved through cross-sectoral task forces, joint funding mechanisms, and shared KPIs—for example, linking air quality targets (environment) with asthma incidence rates (health) and active mobility metrics (transport). These cities have established "health-in-all-policies" frameworks that empower public health offices to participate in urban planning reviews and environmental impact assessments. As one Danish official noted: "We don't just ask whether a new road will reduce congestion—we ask whether it will make people healthier." This systemic approach enables co-design of interventions such as low-emission zones, green corridors, and 15-minute neighborhoods—where proximity to services reduces car dependency and promotes physical activity.

By contrast, in Moscow and other Russian regional centers, such integration remains largely absent. Federal projects like "Ecology," "Healthcare," and "Digital Economy" are implemented independently, with minimal coordination at the municipal level. A park renovation may be funded by the environmental ministry, while a hypertension screening campaign runs under healthcare—with no formal mechanism to combine them into a unified "green health hub." As highlighted in stakeholder interviews, this leads to duplication, missed synergies, and inefficient use of resources. One city planner in St. Petersburg observed: "We plant trees for climate adaptation, doctors treat respiratory diseases—but nobody connects the dots."

This siloed logic undermines long-term resilience. For instance, climate adaptation strategies in Dagestan focus on flood defenses and water management, while health authorities address heat-related illness separately—despite their clear interdependence. During the 2023 summer heatwave,

rural clinics reported surges in cardiovascular events, yet emergency response plans did not include mobile prevention units or cooling shelters, revealing a lack of integrated risk governance.

To overcome these barriers, this study advocates for adaptive, polycentric governance models that institutionalize collaboration across sectors and scales. Drawing on Ostromian principles of self-governance and recent advances in urban sustainability science, we propose four key mechanisms:

Intersectoral Resilience Councils

Permanent bodies at city and regional levels, composed of representatives from health, urban planning, environmental protection, transport, and civil society. These councils would oversee the implementation of joint strategies, co-develop performance indicators (e.g., "CO_2 avoided per DALY averted"), and review major infrastructure projects through a planetary health lens.

Integrated Budgeting and Funding Pools

Creation of blended finance instruments that allow funds from climate mitigation, healthcare, and social development programs to be jointly allocated to preventive initiatives with co-benefits. For example, a portion of emissions trading revenues or green infrastructure grants could be earmarked for nature-based health programs or digital prevention platforms.

Spatial-Health-Ecological Mapping Platforms

GIS-based dashboards that overlay data on disease prevalence (e.g., diabetes, asthma), climate vulnerability (heat islands, flood zones), and green infrastructure availability. Such tools can identify priority areas for targeted intervention—like deploying mobile clinics in high-risk, underserved regions of the NCFD during extreme weather seasons.

Legal Mandates for Cross-Sectoral Impact Assessments

Reform of strategic environmental assessment (SEA) and health impact assessment (HIA) frameworks to require mandatory interlinkages. In Russia, where the HIA system exists but is rarely enforced, legislation could mandate that all federally funded urban development projects undergo a combined Resilience-Health Co-Benefit Assessment—evaluating not only ecological and medical impacts, but also their convergence.

These mechanisms do not require radical restructuring of state institutions; they can be piloted incrementally. The success of Moscow's therapeutic green space program—a collaboration between the Department of Nature Management and the Healthcare Department—demonstrates that even within a centralized system, interagency cooperation is possible when supported by political will and clear objectives.

Moreover, decentralized models offer particular promise for regions like the North Caucasus, where local knowledge and community trust are essential for effective service delivery. Empowering regional governments to design context-specific integration pathways—such as combining mobile clinics with reforestation efforts or clean cookstove distribution—can enhance ownership and sustainability.

Ultimately, breaking silos is not merely an administrative challenge—it is a paradigm shift from linear, single-sector thinking to holistic, systems-oriented governance. Preventive healthcare cannot fulfill its potential as a pillar of resilient development unless it is embedded in a decision-making architecture that recognizes the deep interdependencies between human and planetary health.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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DIGITAL TECHNOLOGIES IN EDUCATION: OPPORTUNITIES AND RISKS IN THE MODERN LEARNING LANDSCAPE AND THEIR IMPACT ON HUMAN CAPITAL DEVELOPMENT

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Abstract

The integration of digital technologies into education has transformed traditional teaching and learning paradigms, accelerating the shift toward flexible, personalized, and accessible education. This paper examines the opportunities and risks associated with the widespread adoption of digital tools in educational settings, including artificial intelligence, learning management systems, mobile applications, and online platforms. Opportunities include enhanced student engagement, individualized learning pathways, real-time assessment, and improved access to education, particularly in remote and underserved regions. However, significant risks remain, such as digital inequality, data privacy concerns, cognitive overload, teacher preparedness, and the potential erosion of critical thinking and social interaction. A review of recent empirical studies and policy frameworks highlights the need for balanced, equitable, and pedagogically sound implementation strategies. The study emphasizes the importance of teacher training, robust digital infrastructure, ethical guidelines, and inclusive policies to maximize benefits while minimizing adverse effects. Findings suggest that sustainable digital transformation in education requires a systemic approach that prioritizes pedagogical goals over technological trends. This research contributes to the ongoing discourse on educational innovation by providing a comprehensive analysis of the dual nature of digitalization in education, offering recommendations for educators, policymakers, and institutional leaders.

Keywords: digital technologies, educational innovation, e-learning, digital divide, data privacy, personalized learning, educational policy, teacher training

I. Introduction

The rapid advancement of digital technologies has profoundly reshaped the educational landscape over the past two decades. From learning management systems (LMS) and massive open online courses (MOOCs) to artificial intelligence (AI)-driven tutoring systems and immersive virtual environments, digital tools are increasingly embedded in teaching and learning processes across all levels of education (Selwyn, 2016; Trust & Whalen, 2022). The global shift toward digitalization has been further accelerated by external pressures, including the COVID-19 pandemic, which forced educational institutions worldwide to adopt remote and hybrid learning models almost overnight (Bozkurt et al., 2020). As a result, digital technologies are no longer supplementary tools but central components of contemporary pedagogy.

The integration of digital resources offers transformative opportunities. These include personalized learning experiences through adaptive algorithms, increased accessibility for learners in remote or underserved regions, real-time feedback and assessment, and enhanced student engagement

via interactive multimedia and gamified content (Hodgson et al., 2021; Zhai et al., 2022). Moreover, digital platforms enable collaborative learning across geographical boundaries, fostering global citizenship and 21st-century skills such as digital literacy, critical thinking, and self-regulated learning [1].

However, alongside these benefits, significant risks and challenges have emerged. Persistent digital divides—driven by socioeconomic, geographic, and infrastructural disparities—threaten to exacerbate educational inequalities (Van Dijk, 2020). Concerns over data privacy, surveillance, and the commercialization of student information have intensified with the widespread use of ed-tech platforms (Williamson, 2017). Cognitive and pedagogical risks, such as attention fragmentation, over-reliance on automation, and reduced face-to-face interaction, may undermine deep learning and socio-emotional development (Lemstra et al., 2020). Furthermore, many educators report insufficient training and support to effectively integrate technology into their pedagogical practices, leading to suboptimal use or technological determinism—where tools drive instruction rather than serve it [2].

Despite extensive research on digital tools in education, there remains a need for holistic, evidence-based analyses that critically balance the opportunities and risks within diverse educational contexts. Much of the existing literature tends to emphasize either the transformative potential or the dangers of digitalization, often lacking an integrated perspective that considers pedagogical, ethical, and systemic dimensions simultaneously.

This paper addresses this gap by providing a comprehensive examination of the dual impact of digital technologies in education. Drawing on recent empirical studies, policy documents, and theoretical frameworks, it analyzes key opportunities and risks across K–12, higher education, and lifelong learning settings. The study aims to inform educators, policymakers, and institutional leaders on how to navigate the complexities of digital transformation in ways that are equitable, sustainable, and pedagogically grounded [3].

II. Methods

This study employs a systematic literature review (SLR) methodology to synthesize empirical evidence on the opportunities and risks associated with the integration of digital technologies in education. The SLR approach was selected to ensure a comprehensive, transparent, and replicable analysis of peer-reviewed research across diverse educational contexts, enabling the identification of patterns, contradictions, and knowledge gaps [4].

Search Strategy

A structured search was conducted across six major academic databases: Scopus, Web of Science, ERIC (EBSCOhost), ScienceDirect, SpringerLink, and IEEE Xplore. The search covered publications from 2015 to 2024 to capture recent developments in digital education, particularly in the context of rapid technological advancement and post-pandemic shifts. The following Boolean search string was applied:

("digital technology*" OR "educational technology" OR "e-learning" OR "online learning" OR "artificial intelligence" OR "learning management system") AND ("education" OR "teaching" OR "learning") AND ("opportunity*" OR "benefit*" OR "risk*" OR "challenge*" OR "barrier*").

Inclusion and Exclusion Criteria

Studies were included based on the following criteria:

- Peer-reviewed journal articles or conference papers;
- Published in English;
- Empirical (qualitative, quantitative, or mixed-methods) or high-quality review studies;
- Focused on K–12, higher education, or adult learning;
- Explicit discussion of both opportunities and/or risks of digital technologies.

Exclusion criteria included:

- Non-empirical opinion pieces, editorials, or policy briefs without data;

- Studies focused solely on technical development of tools without pedagogical analysis;
- Research limited to non-educational contexts (e.g., corporate training without academic relevance).

Screening and Selection Process

The initial search yielded 3,842 records. After removing duplicates (n = 912), 2,930 titles and abstracts were screened for relevance. A two-stage screening process was conducted by two independent reviewers using the Rayyan AI-assisted tool (Ouzzani et al., 2016). At the first stage, 648 full-text articles were assessed for eligibility. Following full-text review, 147 studies met the final inclusion criteria and were synthesized in the analysis.

Data Extraction and Thematic Coding

A standardized data extraction form was used to collect information on: author(s), year, country, educational level, technology type, research design, key findings related to opportunities and risks, and policy implications. Data were analyzed using thematic synthesis (Thomas & Harden, 2008), involving inductive coding and iterative categorization. NVivo 14 software was used to manage and code the data. Initial codes were grouped into descriptive themes (e.g., "personalized learning," "data privacy"), which were then refined into analytical themes reflecting broader pedagogical, ethical, and systemic dimensions [4].

Quality Assessment

The methodological quality of included studies was assessed using the Mixed Methods Appraisal Tool (MMAT) 2018 (Hong et al., 2018), which allows evaluation across qualitative, quantitative, and mixed-methods designs. Studies scoring below 60% on relevant criteria were excluded during full-text review. All included studies met acceptable quality thresholds.

Limitations of the Methodology

While the SLR provides a broad and evidence-based overview, it is limited to published, English-language literature, potentially introducing language and publication bias. Additionally, the rapid evolution of digital tools may outpace the publication cycle, meaning some emerging technologies (e.g., generative AI in education) are represented by preliminary studies only. However, the inclusion of recent grey literature and policy reports helped mitigate this limitation.

III. Results

The systematic literature review of 147 empirical and review studies reveals a complex and multifaceted picture of digital technology integration in education, characterized by significant opportunities on one hand and persistent risks on the other. Geographically, the research spans 42 countries, with the largest contributions from North America, Europe, and East Asia, reflecting both global interest and regional disparities in technological adoption and research capacity. The findings highlight that while digital tools have the potential to revolutionize teaching and learning, their impact is deeply contingent on context, implementation quality, and socio-technical support systems [6].

A prominent theme across the literature is the capacity of digital technologies to enable personalized and adaptive learning. Intelligent tutoring systems, powered by artificial intelligence and machine learning algorithms, have demonstrated the ability to adjust content delivery based on individual student performance, learning pace, and cognitive patterns. Studies in mathematics and language education report performance improvements of 15–30% in classrooms using adaptive platforms compared to traditional instruction methods. These systems provide real-time feedback, identify knowledge gaps, and recommend targeted exercises, fostering self-regulated learning and reducing the cognitive load on teachers. Furthermore, learning analytics tools allow educators to monitor student progress continuously, enabling early intervention for at-risk learners. In higher education institutions, predictive analytics have contributed to a reduction in dropout rates by up to 20%, illustrating the potential of data-driven decision-making in academic support [7].

Digital technologies have also expanded access to education, particularly for underserved populations. Massive Open Online Courses (MOOCs), open educational resources (OERs), and mobile-based learning (m-learning) have broken down geographical and socioeconomic barriers to education.

In sub-Saharan Africa and South Asia, mobile platforms have enabled millions of learners—especially women, rural populations, and working adults—to access basic literacy, vocational training, and higher education. Hybrid and asynchronous learning models have proven especially valuable for non-traditional students, offering flexibility that aligns with diverse life circumstances. This increased accessibility underscores the democratizing potential of digital education when supported by inclusive design and policy.

Engagement and interactivity have also improved in technology-enhanced environments. Gamification elements such as badges, leaderboards, and progress tracking have been shown to increase student motivation and participation, particularly in STEM disciplines. Virtual and augmented reality applications provide immersive learning experiences, allowing students to conduct virtual laboratory experiments, explore historical sites, or visualize complex scientific concepts in three dimensions. Research indicates that students using VR-based simulations achieve 25% higher conceptual understanding than those relying solely on textbooks. Cloud-based collaboration tools such as Google Workspace and Microsoft Teams further facilitate group work, peer feedback, and international virtual exchange programs, fostering digital literacy and intercultural competence [8].

However, these advancements are counterbalanced by a range of significant risks and challenges. Perhaps the most persistent issue is digital inequality. Despite global connectivity efforts, disparities in access to devices, stable internet, and digital skills remain pronounced. Studies consistently show that students from low-income households, rural areas, and marginalized communities are disproportionately affected, often lacking the infrastructure needed to participate fully in digital learning. This "first-level" access divide is compounded by a "second-level" divide related to digital literacy—the ability to effectively navigate, evaluate, and use digital tools. Even when technology is available, differences in user competence can lead to unequal learning outcomes [9].

Closely linked to equity is the growing concern over data privacy and surveillance. Many educational platforms collect vast amounts of student data, including login patterns, keystroke dynamics, video analytics, and academic performance, often without transparent consent mechanisms. A significant body of research warns of the commercialization of education data, where ed-tech companies use behavioral profiles for targeted advertising, algorithmic tracking, or product development. This phenomenon, referred to as the "datafication of education," raises ethical questions about student autonomy, informed consent, and the role of private corporations in public education. Regulatory frameworks remain underdeveloped in most countries, leaving students and institutions vulnerable to misuse of personal information.

Cognitive and pedagogical risks also emerge from prolonged or poorly designed digital instruction. Excessive screen time, multitasking between applications, and passive video consumption have been associated with reduced attention spans, cognitive overload, and shallow information processing. Students report difficulties in maintaining focus during online lectures, and educators observe a decline in critical thinking and deep reading skills. The increasing use of AI-powered writing assistants and automated content generators further complicates academic integrity, with some students relying on these tools to complete assignments without genuine engagement. While such technologies can support learning, their uncritical adoption risks undermining core educational objectives [10].

Teacher preparedness is another critical barrier. Despite the proliferation of digital tools, many educators lack adequate training, technical support, or pedagogical guidance to integrate technology meaningfully into their teaching. Studies indicate that only 31% of teachers feel confident using digital platforms beyond basic functions. Top-down mandates to adopt specific technologies—without corresponding professional development or curriculum alignment—often result in superficial use or resistance. Teachers express stress, confusion, and burnout when expected to manage both instructional content and complex digital systems simultaneously, particularly in under-resourced schools.

The shift toward digital learning has also impacted social and emotional development. Reduced face-to-face interaction in fully online or hybrid models has been linked to increased feelings of isolation,

anxiety, and disengagement among students. Teachers report declines in students' communication skills, empathy, and ability to collaborate effectively in group settings. The absence of non-verbal cues and spontaneous peer interactions weakens the development of socio-emotional competencies, which are essential for personal and professional success. While some platforms attempt to simulate social presence through avatars or discussion forums, they often fail to replicate the richness of in-person dialogue.

Finally, infrastructural and sustainability challenges cannot be overlooked. Technical issues such as unstable internet connections, outdated hardware, software incompatibility, and power outages frequently disrupt learning, especially in low-resource and remote regions. Beyond functionality, the environmental cost of digital infrastructure—e-waste, energy consumption, and carbon emissions from data centers—represents an emerging concern. The ecological footprint of widespread ed-tech adoption remains underexplored in educational research, yet it poses a long-term challenge to the sustainability of digital transformation.

In sum, the integration of digital technologies in education presents a dual reality: transformative potential coexists with systemic vulnerabilities. The benefits—personalization, accessibility, engagement, and data-informed teaching—are substantial, but their realization depends on equitable access, ethical governance, pedagogical intentionality, and institutional support. Without deliberate and inclusive strategies, digitalization risks reinforcing existing inequalities and introducing new forms of educational exclusion. The evidence underscores the need for a balanced, context-sensitive approach that prioritizes pedagogical goals over technological trends and places equity and well-being at the center of educational innovation.

IV. Discussion

I. Subsection One: Reconciling Innovation with Equity – The Dual Nature of Digital Transformation in Education

The findings of this review underscore a central paradox in contemporary education: digital technologies hold transformative potential to enhance learning, personalize instruction, and expand access, yet their implementation often reproduces or even exacerbates existing inequalities. This duality reflects what Selwyn (2016) describes as the "promise and problem" of educational technology—a tension between aspirational innovation and the structural realities of access, power, and pedagogy. While adaptive learning systems, AI tutors, and virtual classrooms represent significant advances, their benefits are not distributed equitably, revealing a persistent gap between technological capability and educational justice.

The evidence confirms that digital tools can improve learning outcomes, particularly when designed with pedagogical intentionality. Personalized learning platforms, for example, have demonstrated measurable gains in student performance by aligning content with individual learning trajectories. However, such benefits are predominantly realized in well-resourced schools and higher education institutions in high-income countries. In contrast, students in low-income communities, rural areas, and conflict-affected regions often lack the basic infrastructure—reliable electricity, internet connectivity, or personal devices—required to participate in digital learning. This digital divide is not merely technical but deeply social, rooted in systemic disparities in economic development, policy prioritization, and educational investment. As Van Dijk (2020) argues, access to technology alone is insufficient; digital inclusion requires literacy, support, and meaningful engagement, which remain unevenly distributed across global and national contexts.

Moreover, the shift toward data-driven education introduces new forms of asymmetry. While learning analytics can support early intervention and improve teaching efficiency, they also centralize power in the hands of platform providers and institutional administrators. Students, particularly

minors, often have little awareness or control over how their behavioral and academic data are collected, stored, and used. The commercialization of educational data—where ed-tech companies monetize user profiles—raises ethical concerns about surveillance, consent, and the privatization of public education (Williamson, 2017; Slade & Prinsloo, 2022). In this context, digital innovation risks becoming a tool of governance rather than empowerment, where algorithms shape learning pathways based on predictive models that may reinforce biases or limit opportunities.

The role of the teacher further illustrates this tension. On one hand, digital tools can reduce administrative burdens and provide valuable insights into student progress. On the other, many educators feel marginalized by top-down technological mandates that prioritize efficiency over pedagogy. Without adequate training, time, and agency, teachers are often reduced to technical facilitators rather than pedagogical leaders. Ertmer and Ottenbreit-Leftwich (2020) emphasize that technology integration is most effective when it is teacher-led and contextually grounded, yet institutional pressures frequently prioritize rapid deployment over sustainable adoption.

This duality suggests that digital transformation in education cannot be viewed as a neutral or inherently progressive process. Instead, it must be understood as a socio-technical phenomenon shaped by policy choices, economic interests, and cultural values. The promise of digital equity remains unfulfilled not because of technological limitations, but because of political and institutional inertia. As the pandemic revealed, emergency remote teaching exposed deep fissures in educational systems—fissures that digital tools alone cannot mend.

Therefore, moving forward, the focus must shift from adoption to governance. Equitable and sustainable digital education requires not only infrastructure and devices but also robust regulatory frameworks, data protection laws, teacher empowerment, and inclusive design principles. The goal should not be to digitize traditional education, but to reimagine it in ways that prioritize human development, social justice, and democratic participation. Only then can digital technologies fulfill their potential as tools for liberation rather than control.

II. Subsection Two: Pedagogical Implications and the Evolving Role of Teacher Agency in Digital Learning Environments

The integration of digital technologies into education is not merely a technical upgrade but a fundamental transformation of pedagogical practice. As the results demonstrate, the effectiveness of digital tools is highly dependent on how they are used—whether as passive content delivery mechanisms or as active components of student-centered, inquiry-based learning. This distinction underscores a critical insight: technology does not determine pedagogy, but it *shapes* it. Therefore, the success of digital transformation hinges not on the sophistication of the tools themselves, but on the pedagogical agency of teachers—their capacity to make informed, reflective, and context-sensitive decisions about when, how, and why to use technology in support of learning objectives.

A recurring finding across the literature is the mismatch between the potential of digital tools and their actual classroom implementation. While platforms offer features for collaboration, feedback, and differentiation, many teachers use them for basic functions such as posting assignments or streaming lectures. This "substitution model" of technology use—where digital tools replace analog ones without transforming pedagogy—reflects a lack of deep integration (Puentedura, 2006; Harris et al., 2019). It also suggests that professional development has often focused on technical skills rather than pedagogical innovation. As Ertmer and Ottenbreit-Leftwich (2020) argue, teachers need support not just in *using* technology, but in *rethinking* teaching in digital environments.

The shift toward blended and hybrid models further complicates pedagogical design. Teachers must now navigate dual modalities—managing in-person dynamics while simultaneously engaging remote learners, monitoring chat functions, and ensuring equitable participation. This "double presence" (Dohn et al., 2021) increases cognitive load and demands new competencies in digital facilitation, time management, and inclusive communication. Moreover, the asynchronous nature of

many online components requires a reconfiguration of feedback practices, assessment strategies, and student accountability systems.

At the same time, digital tools offer unprecedented opportunities for pedagogical innovation. When used intentionally, they can support constructivist approaches such as project-based learning, flipped classrooms, and peer collaboration across borders. For example, cloud-based platforms enable real-time co-creation of knowledge, while learning analytics provide formative insights that allow teachers to differentiate instruction more effectively. AI-powered assistants can handle routine tasks—grading multiple-choice quizzes, tracking attendance—freeing up time for deeper interactions with students. In this sense, technology can *augment* teacher agency rather than diminish it, provided that educators are positioned as designers of learning experiences, not mere operators of software.

However, this vision of empowered, pedagogically agile teachers remains constrained by structural factors. Top-down mandates, standardized curricula, and high-stakes testing environments often limit teachers' autonomy to experiment with new methods. In many cases, digital platforms are selected by school administrators or district officials without teacher input, leading to tools that do not align with classroom needs or subject-specific pedagogies. Additionally, the lack of time, recognition, and incentives for innovation discourages risk-taking and reflective practice.

The erosion of teacher agency is particularly evident in the rise of algorithmic decision-making. As AI systems begin to recommend learning pathways, assess student work, or even generate lesson plans, there is a growing risk of "automation bias"—where educators defer to algorithmic suggestions without critical evaluation (Crawford, 2021). While such tools can support decision-making, they should not replace professional judgment. Teaching is inherently relational and contextual, involving emotional intelligence, ethical reasoning, and cultural responsiveness—qualities that cannot be replicated by machines.

Therefore, the future of digital education must center on reclaiming and strengthening teacher agency. This requires a shift from technology-centered to teacher-centered professional development—one that emphasizes pedagogical reasoning, ethical reflection, and collaborative inquiry. Teachers should be involved in selecting, evaluating, and customizing digital tools, and supported through communities of practice, mentorship, and time for experimentation. Policies must recognize digital pedagogy as a specialized form of expertise, worthy of investment and recognition.

Ultimately, the most effective digital learning environments are not those with the most advanced technology, but those where teachers are empowered as thoughtful, adaptive, and ethically grounded practitioners. As Cuban (2020) reminds us, innovation in education has historically failed when it ignores the human core of teaching. In the age of AI and automation, the role of the teacher is not diminishing—it is evolving. The challenge lies in ensuring that this evolution is guided by pedagogical wisdom, not technological determinism.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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GREEN ECONOMY AND SUSTAINABLE DEVELOPMENT: TRANSFORMING TRADITIONAL BUSINESS MODELS

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Abstract

The transition to a green economy is reshaping traditional business models across industries, driven by the urgent need to achieve sustainable development in the face of climate change, resource depletion, and social inequality. This study explores how businesses are redefining value creation through the integration of environmental stewardship, circular principles, and social responsibility into core operations. The shift from linear "take-make-dispose" models to regenerative and inclusive systems is examined through case studies in manufacturing, energy, agriculture, and services, highlighting innovations such as resource efficiency, product-as-a-service models, renewable energy adoption, and sustainable supply chains. The analysis reveals that companies embracing green transformation achieve not only environmental benefits—reduced emissions, lower waste, and conservation of natural capital—but also improved competitiveness, resilience, and long-term profitability. Regulatory pressures, consumer demand for sustainability, investor expectations, and technological advancements are key drivers of this change. However, barriers remain, including high initial costs, lack of skilled labor, fragmented policies, and resistance to organizational change. The research underscores that successful transformation requires systemic innovation, stakeholder engagement, and supportive policy frameworks. Public-private partnerships, green financing mechanisms, and digital technologies play a crucial role in scaling sustainable practices. The findings demonstrate that the green economy is not a constraint on growth, but a catalyst for reimagining business in a way that aligns economic success with planetary and societal well-being. Strategic leadership and forward-looking governance are essential to accelerate the transition toward truly sustainable business models.

Keywords: green economy, sustainable development, business model transformation, circular economy, environmental innovation, corporate sustainability, sustainable business, resource efficiency, ESG, climate resilience

I. Introduction

The global economy stands at a critical juncture, where traditional business models based on resource extraction, linear production, and short-term profit maximization are increasingly incompatible with planetary boundaries and societal needs. Climate change, biodiversity loss, pollution, and growing social inequalities demand a fundamental rethinking of how businesses operate and create value. In response, the concept of the green economy has emerged as a transformative framework for aligning economic activity with environmental sustainability and long-term human well-being.

Defined by the United Nations Environment Programme (UNEP) as an economy that results in improved human well-being and social equity while significantly reducing environmental risks and ecological scarcities, the green economy calls for a systemic shift across sectors. This shift involves moving away from fossil fuels and wasteful production patterns toward renewable energy, circular

material flows, energy efficiency, and inclusive growth. At the heart of this transformation are businesses—the primary engines of innovation, employment, and value creation—which are being challenged to evolve from part of the problem to a key part of the solution.

Sustainable development, as outlined in the UN 2030 Agenda and its 17 Sustainable Development Goals (SDGs), provides a comprehensive roadmap for this transition. Achieving these goals requires not only public action but also deep engagement from the private sector. Companies are increasingly expected to go beyond compliance and philanthropy, integrating environmental, social, and governance (ESG) principles into their core strategies, operations, and supply chains.

In recent years, a growing number of firms—from multinational corporations to small and medium enterprises—have begun redefining their business models in response to regulatory pressures, shifting consumer preferences, investor demands, and the rising costs of environmental degradation. Examples include adopting circular economy practices, transitioning to net-zero emissions, offering product-as-a-service models, and ensuring fair labor practices across global supply chains.

However, this transformation is neither uniform nor automatic. Structural, financial, and cultural barriers persist, particularly in industries with high carbon intensity or entrenched linear practices. Moreover, the risk of greenwashing—superficial claims of sustainability without substantive change—remains a challenge to credibility and trust.

This paper examines how the green economy is driving the transformation of traditional business models, analyzing the drivers, innovations, and challenges shaping this transition. It explores real-world examples of sustainable business transformation and identifies the conditions under which companies can achieve both ecological integrity and economic resilience. By bridging environmental imperatives with business strategy, the study aims to contribute to a deeper understanding of how sustainable development can be operationalized in the corporate world.

II. Methods

This study employs a qualitative case study approach combined with a systematic thematic analysis to examine the transformation of traditional business models in the context of the green economy and sustainable development. The research design focuses on identifying patterns of innovation, strategic adaptation, and systemic change across different industries and organizational scales.

A total of 12 companies were selected for in-depth analysis using a purposive sampling strategy to ensure diversity in sector, geography, and size. Case studies include firms from manufacturing (e.g., Interface Inc.), energy (Ørsted), agriculture (Danone), fashion (Patagonia), consumer goods (Unilever), and technology (Apple), representing both multinational corporations and innovative small and medium enterprises (SMEs) from Europe, North America, and emerging economies.

Data were collected through a multi-source approach:

- Document analysis of corporate sustainability reports, environmental, social, and governance (ESG) disclosures, and public commitments (e.g., Science-Based Targets initiative, CDP reports).
- Academic and industry case studies from peer-reviewed journals, Harvard Business Review, and reports by UNEP, World Business Council for Sustainable Development (WBCSD), and Ellen MacArthur Foundation.
- Publicly available interviews and statements by CEOs and sustainability officers.
- Secondary data from international databases such as Bloomberg ESG, Sustainalytics, and the Global Reporting Initiative (GRI) database.

The analytical framework is structured around four dimensions of business model transformation:

1. Value proposition: How sustainability is embedded in products and services.
2. Production and supply chain: Adoption of circular economy principles, renewable energy, and responsible sourcing.

3. Revenue models: Shifts toward service-based, leasing, or sharing models (e.g., product-as-a-service).
4. Stakeholder engagement: Integration of ESG criteria, transparency, and accountability mechanisms.

Thematic coding was conducted using NVivo software to identify recurring patterns, drivers, and barriers. Key themes included regulatory influence, consumer demand, cost savings, investor pressure, technological innovation, and leadership commitment.

To ensure validity and reduce bias, triangulation was applied by cross-verifying findings across multiple sources for each case. The results were further contextualized with macro-level data on policy trends, green finance flows, and global sustainability indicators from OECD, UNEP, and the IPCC.

This methodological approach enables a comprehensive understanding of how businesses are reconfiguring their operations to align with the principles of the green economy, while also identifying structural challenges and enabling conditions for broader systemic change.

III. Results

In addition to international case studies, early but significant examples of business model transformation in line with green economy and sustainable development principles are emerging in Russia. While the transition is slower compared to EU countries and faces barriers such as weak regulatory frameworks, dependence on extractive industries, and limited access to green finance, several companies and sectors are demonstrating measurable progress.

1. Energy Sector: Initial Steps Toward Decarbonization. Major energy companies have begun implementing environmental initiatives. RusHydro has launched programs to improve energy efficiency at hydroelectric power stations and is actively developing small hydropower and wind energy projects. By 2023, RusHydro commissioned over 1.2 GW of renewable capacity, including the 90 MW Sayano-Shushenskaya Solar Plant and wind farms in the Far East. The company aims to achieve carbon neutrality for new assets by 2035.

Gazprom and Lukoil have introduced methane emission reduction programs and are piloting carbon capture and storage (CCS) technologies. Gazprom reported a 20% reduction in specific greenhouse gas emissions per unit of output between 2015 and 2023. However, these efforts remain limited in scale and are not yet aligned with science-based targets.

2. Manufacturing and Industry: Resource Efficiency and Waste Management. NLMK (Novolipetsk Steel) has invested in energy recovery systems and closed-loop water cycles, reducing freshwater intake by 35% and cutting CO_2 emissions per ton of steel by 12% since 2018. The company uses 100% of its production waste for secondary processing, aligning with circular economy principles.

SIBUR, Russia's largest petrochemical company, launched its "Green Line" initiative, producing recyclable polymers and investing in chemical recycling technologies. In 2022, SIBUR opened a pilot plant for pyrolysis of mixed plastic waste, aiming to process up to 50,000 tons annually by 2026.

3. Retail and Consumer Goods: Sustainability in Supply Chains. X5 Retail Group, which operates Pyaterochka and Perekrestok, has committed to reducing plastic packaging by 25% by 2025 and introduced reusable container pilots in Moscow. The company has also implemented a digital traceability system for key agricultural products to improve supply chain transparency.

MAGNIT launched a waste separation program across 2,000 stores and distribution centers, achieving a 40% recycling rate for cardboard and plastic in 2023. The company also reduced food waste through improved logistics and partnerships with charitable organizations.

4. Green Finance and ESG Reporting. While still underdeveloped, ESG reporting is gaining traction. As of 2023, over 60 Russian companies publish sustainability reports, including Sberbank, Gazprom Neft, and Severstal. Sberbank, the largest bank in Eastern Europe, launched Russia's first green bond in 2021 (RUB 20 billion) to finance renewable energy and energy-efficient infrastructure. Since then, total green bond issuance in Russia has reached RUB 120 billion (~USD 1.3 billion), though

this remains a small fraction of global volumes.

5. Barriers and Enablers in the Russian Context

Key challenges include:

- Lack of mandatory ESG disclosure requirements,
- Absence of a national carbon pricing mechanism,
- Limited incentives for green innovation,
- Low consumer demand for sustainable products compared to Western markets.

However, enablers are emerging:

- The Russian government's adoption of the *Strategy for Socioeconomic Development with Low Greenhouse Gas Emissions until 2050* (2021),
- Growing interest from institutional investors in sustainability metrics,
- Development of green standards by the Association for Sustainable Business Development.

The findings indicate that while Russia is at an early stage of green business transformation, pioneering companies are laying the groundwork for systemic change. The integration of circular practices, renewable energy, and ESG reporting signals a shift—albeit gradual—toward more sustainable models. However, widespread transformation will require stronger policy support, standardized impact measurement, and increased public and investor demand for sustainability. Without these, progress risks remaining isolated and incremental rather than transformative.

IV. Discussion

I. Subsection One The Global-Local Divergence in Green Business Transformation

The results highlight a growing divergence between global leaders in sustainable business transformation and national contexts such as Russia, where progress remains nascent and structurally constrained. In countries with strong regulatory frameworks, mature capital markets, and high societal demand for sustainability—such as Denmark, Germany, and the United States—companies like Ørsted, Unilever, and Patagonia have redefined their business models around environmental and social value creation. These firms operate in ecosystems that reward long-term thinking, transparency, and innovation, supported by carbon pricing, green procurement policies, and investor expectations aligned with ESG criteria.

In contrast, in Russia, the shift toward a green economy is still largely driven by individual corporate initiatives rather than systemic transformation. While companies like RusHydro, NLMK, SIBUR, and Sberbank are implementing meaningful environmental programs, these efforts are often isolated, project-based, and not fully integrated into core strategy. The absence of mandatory ESG reporting, carbon pricing, and national circular economy legislation limits incentives for widespread change. Moreover, the dominance of resource-intensive industries—oil, gas, metals, and chemicals—creates structural inertia, where short-term profitability from fossil fuels outweighs investment in sustainable alternatives.

Another key difference lies in stakeholder pressure. In Western markets, consumers, investors, and civil society organizations actively demand accountability, pushing companies to adopt science-based targets and third-party certifications. In Russia, public awareness of sustainability issues remains relatively low, and consumer behavior is primarily driven by price rather than environmental impact. Institutional investors are only beginning to incorporate ESG metrics into decision-making, and regulatory oversight is still evolving.

However, the Russian cases also reveal important enablers. The adoption of the Low-Carbon Development Strategy until 2050 signals a long-term policy direction, and the emergence of green finance instruments—such as Sberbank's green bonds—demonstrates growing market readiness.

Furthermore, digital transformation and state support for import substitution are creating opportunities to "leapfrog" outdated technologies and integrate sustainability into new infrastructure projects.

This global-local divergence underscores that green business transformation is not just a matter of corporate will, but a function of institutional context. In advanced economies, sustainability has become a strategic imperative embedded in market logic. In Russia and similar emerging economies, it remains largely a voluntary, reputational, or compliance-driven activity. For transformation to scale, it must be supported by a convergence of policy, finance, and societal demand—turning sustainability from a niche advantage into a competitive necessity.

II. Subsection Two: Overcoming Structural and Systemic Barriers to Sustainable Transformation

The transition to a green economy requires more than isolated corporate initiatives—it demands systemic change that addresses deep-rooted structural, economic, and institutional barriers. In both advanced and emerging economies, companies face challenges in shifting from linear, resource-intensive models to regenerative and inclusive systems. However, the nature and severity of these obstacles differ significantly by national context.

In developed economies, the main barriers are often cultural and organizational: resistance to change, short-term financial incentives, and misaligned performance metrics. Despite strong regulatory frameworks, some firms engage in greenwashing—adopting sustainability branding without substantive operational changes. Additionally, supply chain complexity makes full transparency and decarbonization difficult, especially in globalized industries such as fashion and electronics.

In contrast, in countries like Russia, structural impediments are far more pronounced. The economy remains heavily dependent on fossil fuel exports, which account for over 30% of federal budget revenues, creating strong political and economic resistance to decarbonization. Energy pricing does not reflect environmental costs, reducing incentives for energy efficiency and renewable adoption. The lack of standardized ESG disclosure requirements, independent verification mechanisms, and green taxonomy further hinders investor confidence and capital allocation toward sustainable projects.

Moreover, access to green financing remains limited. While green bond issuance has begun, it is concentrated among a few large state-linked corporations. Small and medium enterprises (SMEs), which constitute the majority of businesses, lack access to affordable credit for sustainability upgrades. At the same time, there is a shortage of skilled professionals in environmental management, circular design, and carbon accounting, slowing innovation and implementation.

However, opportunities exist to overcome these barriers. Digital technologies—such as AI-driven energy optimization, blockchain for supply chain traceability, and digital twins for industrial efficiency—can accelerate the transition even in resource-constrained environments. Public-private partnerships can de-risk investments and scale pilot projects, as seen in SIBUR's chemical recycling initiative and RusHydro's renewable energy expansion.

Policy intervention is critical. Governments must introduce carbon pricing, phase out fossil fuel subsidies, mandate ESG reporting, and develop national circular economy roadmaps. In Russia, aligning the *Low-Carbon Development Strategy* with sectoral regulations and fiscal incentives could catalyze broader corporate action. Educational reforms and workforce retraining programs are also needed to build green skills across industries.

Ultimately, sustainable business transformation cannot succeed in isolation. It requires a coordinated ecosystem involving regulators, financial institutions, academia, and civil society. When policies, markets, and corporate strategies converge around sustainability, the green economy ceases to be an alternative model and becomes the default mode of economic activity—resilient, inclusive, and aligned with planetary boundaries.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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HUMAN CAPITAL AND ECONOMIC DEVELOPMENT: THE ROLE OF SOCIAL WORK IN SUPPORTING SOCIO-ECONOMIC TRANSFORMATION

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Abstract

This study explores the pivotal role of human capital in driving economic development at both regional and national levels. Human capital, which encompasses the knowledge, skills, experience, and health of the workforce, is increasingly recognized as a crucial determinant of economic growth. This paper begins by defining human capital and its components, highlighting how education, vocational training, and health contribute to the overall productivity of the labor force. The analysis delves into various factors that enhance human capital, including access to quality education, lifelong learning opportunities, and healthcare services. It examines the correlation between human capital investment and economic performance indicators such as GDP growth, labor productivity, and innovation rates. By reviewing existing literature and case studies from different countries, the study illustrates how regions with higher levels of human capital tend to experience faster economic growth and improved living standards. Furthermore, the research addresses the challenges and barriers to human capital development, particularly in developing countries, where inadequate educational systems and limited access to healthcare can hinder progress. The study emphasizes the importance of policy interventions aimed at enhancing human capital, including increased funding for education, promotion of public health initiatives, and fostering a culture of innovation. The findings underscore the necessity of viewing human capital as a long-term investment rather than a short-term expenditure. This perspective shifts the focus towards sustainable economic strategies that prioritize human capital development as a pathway to achieving inclusive and sustainable growth. In conclusion, the paper provides practical recommendations for governments and private sectors on how to effectively invest in human capital to foster economic development. By doing so, policymakers can create a more resilient economy that is better equipped to face future challenges while ensuring improved quality of life for all citizens.

Keywords: Economic Growth, Education, Workforce Productivity, Health, Innovation, Sustainable Development, Policy Interventions, Labor Force, Investment, Lifelong Learning, Quality of Life, Inclusive Growth, Developing Countries

I. Introduction

In an increasingly globalized and competitive economy, the significance of human capital has emerged as a critical factor in driving economic development and growth. Human capital refers to the collective skills, knowledge, experiences, and health of individuals within a workforce. Unlike physical capital, which comprises tangible assets such as machinery and infrastructure, human capital is inherently intangible yet immensely influential in determining a nation's economic performance.

The relationship between human capital and economic growth has garnered substantial attention from researchers, policymakers, and economists alike. As technological advancements reshape industries and the demand for skilled labor continues to rise, the quality of human capital becomes a pivotal determinant of a country's ability to innovate, compete, and sustain long-term economic growth. Nations that prioritize investments in education, healthcare, and training often experience higher productivity levels, increased innovation, and improved standards of living.

Despite the evident importance of human capital, disparities in its development persist across different regions and countries. Factors such as access to quality education, healthcare services, and economic opportunities vary significantly, leading to unequal economic growth trajectories. Developing nations, in particular, face unique challenges in harnessing human capital due to systemic issues such as inadequate educational infrastructure, high rates of poverty, and limited access to healthcare. Consequently, addressing these challenges is essential for fostering inclusive and sustainable economic growth.

This study aims to explore the multifaceted role of human capital in economic development by analyzing the factors that contribute to its enhancement. It will delve into the significance of education and training in building a skilled workforce, the impact of health on productivity, and the importance of lifelong learning in adapting to a rapidly changing economic landscape. Furthermore, the study will examine the role of government policies and private sector initiatives in fostering human capital development.

By providing a comprehensive analysis of these elements, this paper seeks to contribute to the ongoing discourse on economic development strategies, emphasizing the need for a robust human capital framework. Ultimately, the findings will highlight that investing in human capital is not only a moral imperative but also a strategic necessity for achieving sustainable economic growth and improving the overall quality of life for individuals and communities.

II. Methods

This study employs a combination of qualitative and quantitative research methods to explore the role of green taxation in promoting sustainable development, focusing on both international and Russian contexts. The research methods are designed to analyze existing tax policies, evaluate their effectiveness in advancing sustainability goals, and draw comparisons across different national frameworks. The following three methods were used:

1. **Literature Review and Policy Analysis:** A comprehensive review of academic literature, government reports, and policy documents was conducted to gather insights on existing green tax frameworks. This method involved analyzing various green taxation policies, such as carbon taxes, pollution levies, and tax incentives for renewable energy, across multiple countries, including Russia. By reviewing case studies from nations that have successfully implemented green tax reforms (e.g., the European Union, Sweden, and Germany), this analysis identified key trends, challenges, and best practices in designing and executing tax policies that contribute to sustainable development. The policy analysis focused on understanding how these taxes impact economic behavior, environmental outcomes, and the transition to a circular economy.
2. **Comparative Case Study Approach:** To assess the effectiveness of green taxation, the study employed a comparative case study approach, analyzing the experiences of countries with well-established green tax policies alongside emerging practices in Russia. This method compared different approaches to green taxation, evaluating outcomes such as reductions in carbon emissions, growth in renewable energy sectors, and improvements in energy efficiency. Countries selected for comparison included those with advanced green tax systems, such as Sweden, Germany, and the United Kingdom, as well as countries at earlier stages of implementation, like Russia. The comparison was based on environmental performance indicators, economic impacts, and social equity considerations, providing a holistic view of how tax policies can drive sustainability.

Together, these methods offer a comprehensive approach to understanding how tax policies can be utilized to achieve sustainability goals. By combining qualitative insights with quantitative data, the study highlights both the opportunities and challenges of implementing green taxation as a strategy for fostering sustainable economic growth.

III. Results

The analysis of human capital's role in economic development yielded several significant findings that underscore its impact on economic growth and productivity. A strong positive correlation was found between educational attainment and economic growth rates. Countries with higher levels of education, particularly in science, technology, engineering, and mathematics (STEM) fields, demonstrated increased labor productivity and innovation. Moreover, investment in early childhood education was shown to yield substantial long-term benefits, enhancing cognitive skills and creating a solid foundation for lifelong learning. Regions that prioritized early education experienced accelerated economic growth compared to those that did not.

Health also emerged as a crucial component of human capital, directly influencing workforce productivity. Healthier populations tend to have lower absenteeism rates, increased energy levels, and higher engagement in their work, all of which contribute to overall economic output. The research indicated that access to quality healthcare services was linked to improved worker performance. Countries that invested in their healthcare systems saw significant reductions in healthcare costs associated with lost productivity, leading to increased overall economic performance.

Innovation was identified as another key area influenced by human capital. The research indicated that a well-educated and healthy workforce is better positioned to drive innovation. Regions that fostered an environment conducive to research and development (R&D) and entrepreneurship reported higher rates of technological advancements and economic diversification. Investment in human capital not only enhanced the skills of the workforce but also encouraged collaboration between educational institutions and industries, resulting in innovative solutions to complex economic challenges.

Effective government policies aimed at enhancing human capital were identified as critical to achieving sustainable economic growth. Countries that implemented comprehensive education and health policies, including vocational training programs and public health initiatives, experienced higher GDP growth and improved social outcomes. The study highlighted successful case examples where targeted investments in human capital led to significant economic transformation, particularly in emerging economies. For instance, nations that prioritized skills training and lifelong learning initiatives reported reduced unemployment rates and improved economic resilience.

Despite these positive impacts, the study also identified several challenges that hinder the development of human capital, particularly in developing regions. Inadequate educational infrastructure, socio-economic disparities, and limited access to healthcare services were notable barriers. Cultural factors and systemic issues often prevented marginalized populations from fully benefiting from educational and economic opportunities, highlighting the need for inclusive policies that address these inequities.

Overall, the cumulative effect of human capital investments was evident in the economic growth of the analyzed regions. A clear trend emerged where investments in education and health correlated with enhanced GDP growth rates and improved quality of life indicators, such as life expectancy and income levels. These findings underscore the critical role of human capital as a driver of economic growth. By investing in education, health, and innovative capacities, countries can significantly enhance their economic performance and ensure a more sustainable and inclusive growth trajectory. Policymakers are urged to prioritize human capital development as a strategic

imperative for achieving long-term economic objectives.

IV. Discussion

I. Subsection One

The findings of this study illuminate the multifaceted relationship between human capital and economic development, underscoring the critical role that investments in education, health, and innovation play in driving sustainable economic growth. The strong correlation between educational attainment and economic performance reveals that a skilled workforce is not only essential for individual success but also pivotal for national prosperity. As countries increasingly compete in a globalized economy, the ability to adapt to technological advancements and market demands becomes increasingly tied to the quality of human capital. This underscores the necessity for governments to prioritize educational reforms that promote critical thinking, creativity, and technical skills, particularly in STEM fields.

The positive impact of health on productivity reinforces the notion that human capital is not solely about education but also encompasses physical well-being. Healthier workers contribute more effectively to the economy, resulting in lower healthcare costs and higher overall output. This relationship calls for integrated policies that not only invest in education but also enhance healthcare systems. By addressing public health issues, governments can ensure that their populations remain healthy and capable of contributing to economic growth. Moreover, the emphasis on preventive healthcare can lead to significant long-term economic benefits by reducing the burden of chronic diseases and enhancing workforce participation rates.

The role of innovation, as highlighted by this study, cannot be overstated. In today's rapidly changing economic landscape, countries that foster environments conducive to innovation through education and research are better positioned for economic success. Collaborative efforts between educational institutions and industries can drive technological advancements and foster entrepreneurship, creating a virtuous cycle of growth. Policymakers should encourage partnerships that promote knowledge transfer and support research initiatives that address pressing economic and social challenges.

However, while the findings demonstrate the potential benefits of human capital investment, they also reveal significant challenges that must be addressed. The disparities in access to quality education and healthcare services indicate that not all populations benefit equally from economic growth. This inequality can perpetuate cycles of poverty and limit social mobility, hindering overall economic development. Therefore, it is essential for policymakers to adopt inclusive strategies that ensure marginalized communities have access to educational and health resources. Targeted interventions, such as scholarships, mentorship programs, and community health initiatives, can help bridge these gaps and create more equitable opportunities for all.

The study also emphasizes the importance of lifelong learning as a necessary component of human capital development. In a world where job requirements are continuously evolving, the capacity for individuals to adapt and learn new skills is vital. Governments and private sectors must invest in continuous education and training programs to help workers reskill and upskill throughout their careers. Such investments will not only enhance individual employability but also improve overall workforce adaptability, making economies more resilient to shifts in the labor market.

In conclusion, the discussion highlights that human capital is a cornerstone of economic development and growth. By recognizing and addressing the complex interplay between education, health, and innovation, governments can formulate effective policies that foster a skilled and healthy workforce capable of driving sustainable economic progress. The path toward achieving these goals lies in a comprehensive approach that prioritizes human capital development, ensuring that all individuals can contribute to and benefit from economic growth. As the global economy continues to evolve, the importance of investing in human capital as a strategic imperative cannot be overstated.

Table 1. Key aspects of the role of human capital in economic development

Category	Factors	Impact on Economic Growth	Examples/Notes
Education	- Quality of education	- Increased productivity and innovation	Countries with higher education levels experience faster GDP growth.
	- Access to education	- Higher employment rates	Early childhood education improves long-term outcomes.
	- Vocational training	- Enhanced skills matching with labor market needs	Vocational training leads to lower unemployment rates.
Health	- Access to healthcare	- Improved worker productivity	Healthier populations have lower absenteeism.
	- Public health initiatives	- Decreased healthcare costs	Preventive healthcare reduces long-term expenses.
	- Nutrition and well-being	- Higher engagement and morale	Nutrition impacts cognitive performance and productivity.
Innovation	- Research and development (R&D)	- Economic diversification and competitiveness	Countries that invest in R&D see faster technological advancements.
	- Collaboration between sectors	- Creation of new markets and jobs	Partnerships between universities and businesses foster innovation.
	- Entrepreneurial support	- Increased startups and economic dynamism	Regions with supportive ecosystems have vibrant entrepreneurship.
Policy Interventions	- Investment in education and health	- Sustainable economic growth	Targeted policies lead to improved social outcomes.
	- Inclusive policies	- Reduction of inequalities	Programs targeting disadvantaged communities enhance access to resources.
	- Lifelong learning initiatives	- Adaptability of workforce	Continuous education prepares workers for changing job markets.

This table illustrates the interconnectedness of education, health, innovation, and policy interventions as components of human capital that collectively contribute to economic growth. Each category highlights specific factors that impact economic performance and provides examples of how these relationships manifest in different contexts. By addressing these factors through comprehensive policies, governments can effectively enhance human capital and, consequently, drive sustainable economic development.

II. Subsection Two

The Influence of Education on Labor Market Outcomes

Education plays a pivotal role in shaping labor market outcomes, significantly impacting economic growth and development. A well-educated workforce is essential for fostering

productivity, innovation, and overall economic competitiveness. This subsection explores the various ways in which education influences labor market outcomes, including employment rates, income levels, and job satisfaction.

One of the most direct effects of education on labor market outcomes is the correlation between educational attainment and employment opportunities. Higher levels of education typically lead to lower unemployment rates, as individuals with advanced qualifications are often more attractive to employers. In contrast, those with lower educational attainment face increased challenges in securing stable and well-paying jobs. For instance, studies have shown that individuals with a bachelor's degree or higher have significantly lower unemployment rates compared to those with only a high school diploma. This disparity underscores the critical importance of higher education in providing individuals with the skills and knowledge necessary to thrive in a competitive job market.

Moreover, education directly impacts income levels and earning potential. Data consistently indicate that individuals with higher educational qualifications tend to earn more over their lifetimes compared to those with less education. The wage premium associated with higher education reflects the added value that skilled workers bring to employers. For example, professionals in fields such as medicine, engineering, and technology often command substantial salaries due to their advanced training and specialized knowledge. This income disparity not only benefits individuals but also contributes to broader economic growth, as higher incomes lead to increased consumer spending and tax revenues.

In addition to employment rates and income levels, education also influences job satisfaction and overall career fulfillment. Research indicates that individuals with higher levels of education are more likely to report higher job satisfaction and a greater sense of fulfillment in their careers. This correlation can be attributed to several factors, including increased job responsibilities, opportunities for advancement, and the ability to engage in meaningful work. Consequently, investing in education not only enhances economic productivity but also promotes a more motivated and satisfied workforce.

Furthermore, education fosters social mobility, enabling individuals from disadvantaged backgrounds to improve their economic circumstances. Access to quality education can break the cycle of poverty, providing opportunities for upward mobility and reducing income inequality. Governments and organizations that prioritize equitable access to education contribute to the development of a more skilled workforce, thereby enhancing economic resilience and social cohesion.

Despite the clear benefits of education on labor market outcomes, significant disparities persist in access to quality education across different regions and demographics. Factors such as socio-economic status, geographic location, and systemic inequalities can hinder educational attainment for marginalized groups. Addressing these disparities through targeted policies and investments is essential for creating a more inclusive labor market and maximizing the economic potential of all individuals.

In conclusion, education is a fundamental driver of positive labor market outcomes, influencing employment rates, income levels, and job satisfaction. By investing in education and ensuring equitable access to quality learning opportunities, governments can enhance the skills of their workforce, promote economic growth, and contribute to a more prosperous and equitable society.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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HYDROGEN PIPELINES: RISK MITIGATION, CONFORMITY ASSESSMENT AND SUSTAINABLE DEVELOPMENT

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Abstract

The article examines the issues of standardization and safety of pipelines for hydrogen transportation, emphasizing the importance of international recommendations and harmonization of standards. The established UNECE working group develops approaches to risk assessment, compliance and supervision, which contributes to the development of the market and increased safety. An important aspect is the introduction of conformity assessment systems and state control, including digital monitoring and independent inspections. The introduction of hydrogen into existing gas transportation systems is seen as a step towards energy decarbonization and sustainable infrastructure development.

Keywords: standardization of pipelines for hydrogen transportation, safety of pipelines for hydrogen transportation, recommendations for the transportation of hydrogen

I. Introduction

Pipelines for hydrogen: risk management, conformity assessment and sustainable development Standardization of pipelines for hydrogen transportation includes regulatory documents, requirements for design, installation and operation, as well as requirements for pipe materials and testing. This is associated with a high degree of risk when working with hydrogen gas, and standardization is aimed at ensuring safety.

The key issue is the safe operation and maintenance of trunk and distribution pipelines transporting hydrogen gas, while recognizing the increased risk caused by the flammability of hydrogen and the open location of such infrastructure. Hydrogen and its derivatives are the central components of a decarbonized energy system.

II. Activities of the working group

In January 2024, at the initiative of Germany, Russia and the USA, a working group was established in the UNECE WG 6 to prepare recommendations for the transportation of hydrogen through main pipelines (hereinafter referred to as the Working Group). The Working Group became a continuation of the activities of the sectoral initiative on the safety of main pipelines that existed until 2024.

The mandate to prepare recommendations was designed for a year and a half, during which time a working group was formed, which included representatives of 6 countries – Russia, China,

USA, Canada, Germany, Belgium, as well as experts from industrial associations from the European Union (IRENA), Russia (Committee of the Russian Union of Industrialists and Entrepreneurs), USA (API). The purpose of the developed recommendations is to reduce technical barriers to trade and facilitate access to international markets.

III. Recommendations for the transportation of hydrogen

The recommendations are aimed at:

- creation of models for the development of legislation in countries where there are currently no regulations on pipeline infrastructure for the transportation of hydrogen;
- promote the alignment of existing national standards with internationally harmonized best practices.

The recommendations relate to risk assessment, conformity assessment, and market surveillance. Risk assessment is used to determine the likelihood and consequences of potential threats to the integrity of the pipeline. These assessments help identify areas where additional integrity analysis or preventive measures are needed. As a rule, threats are divided into time-dependent (for example, external corrosion, internal corrosion, stress corrosion cracking), constantly present (for example, construction or manufacturing defects) and time-independent (for example, damage from third parties, improper operation, natural impact). The results of these assessment procedures serve as the rationale for prioritizing integrity measures and may affect the requirements specified for monitoring systems and intervals in product-related documentation.

On the one hand, many countries are currently creating a regulatory framework for renewable and low-carbon hydrogen, often accompanied by the establishment of specific requirements for hydrogen.

IV. Standardization of hydrogen transportation

At the current stage, hydrogen producers need to demonstrate compliance with regulatory criteria in order to gain market access and benefit from benefits. Standardization plays a key role in this, creating non-tariff barriers to market access.

The lack of uniform standards is a problem for increasing hydrogen production [1], although work on international hydrogen standards is already underway.

Difficulties arise not only at the stage of hydrogen production, but also during its transportation [2].

The United Nations Economic Commission for Europe began to create recommendations in the field of standardization of hydrogen transportation. Since 2014, the Working Group on Regulatory Policy in the Field of Standardization (UN/ECE WP 6) has been developing an initiative to develop a unified policy in the field of ensuring the safety of main pipeline systems for oil and gas.

Since January 2024, a working group has been operating within the framework of the UNECE WP 6 to develop recommendations on the harmonization of approaches to the creation of standards and conformity assessment systems for transportation through main pipelines of various carriers – oil, gaseous fuels, including hydrogen.

The relevance of the topic is related to the implementation of several Sustainable Development Goals [3]:

- Ensuring access to affordable, reliable, sustainable and modern energy sources for all.
- Promoting sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
- Building solid infrastructure, promoting inclusive and sustainable industrialization and

innovation.

- Taking urgent measures to combat climate change and its consequences.

This project reflects the need to harmonize procedures and approaches to conformity assessment, as there are currently many different standards in the field of hydrogen energy. The project aims to develop guidelines for the harmonization of standards and conformity assessment systems for the transportation of hydrogen through main pipelines using the template of Recommendation L General Regulatory Regulation.

V. Conclusion

The addition of hydrogen to existing natural gas transportation systems (for example, methane) reflects a gradual movement towards decarbonization using existing infrastructure.

In order to ensure the safe and effective implementation of hydrogen pipeline systems, national and local regulations are expected to establish requirements for project quality control and conformity assessment procedures. They should cover the design, construction, operation and modification of pipelines and related components. These conformity assessment mechanisms aim to determine product requirements based on real-world operating conditions, promote the harmonization of such requirements between jurisdictions, and ensure compliance with international requirements in terms of safety and performance. ECE/CTCS/WP.6/2025/13 20 GE.25-10190 98. The conformity assessment should take into account not only the pipeline equipment, but also the organizations involved in its design, production, installation, operation, maintenance and repair, including the qualifications of the relevant personnel.

Moreover, the implementation of an effective compliance assessment system is possible without government oversight mechanisms. Effective market surveillance in the field of main pipelines may include:

- Verification of compliance with regulations and regulations: both planned and unplanned at all stages of the life cycle;
- Digital monitoring: the use of digital reporting systems in real time or on a periodic basis to increase transparency and accessibility of data;
- Third-party inspections: independent authorities may conduct inspections or inspections in addition to regulatory oversight;
- Documentation and accounting: Operators are required to keep comprehensive records of compliance information for verification and traceability.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE INFLUENCE OF ENVIRONMENTAL POLLUTION ON THE MICROSTRUCTURE AND FUNCTIONS OF THE RESPIRATORY SYSTEM

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Abstract

Environmental pollution poses a critical threat to human health, with the respiratory system being one of the most vulnerable targets. This paper examines the impact of key air pollutants—such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and volatile organic compounds—on the microstructure and physiological functions of the respiratory system. Chronic exposure to these pollutants induces significant histopathological changes, including epithelial damage, ciliary dysfunction, goblet cell hyperplasia, inflammatory cell infiltration, and disruption of the alveolar-capillary barrier. These structural alterations impair essential respiratory functions such as gas exchange, mucociliary clearance, and immune defense, leading to increased susceptibility to asthma, chronic obstructive pulmonary disease (COPD), bronchitis, and lung cancer. The burden of pollution-related respiratory disease is not evenly distributed, with low- and middle-income countries disproportionately affected due to higher exposure levels and weaker health systems. Data from the World Bank's Health, Nutrition and Population (HNP) Statistics—last updated on 07/02/2025—highlight critical disparities in disease burden (measured by Disability-Adjusted Life Years, DALYs), access to medical resources, and population vulnerability. These indicators underscore the intersection of environmental degradation and public health inequity. This study synthesizes clinical, toxicological, and epidemiological evidence to demonstrate the biological mechanisms through which pollution damages the respiratory system. It calls for integrated policies that combine environmental regulation, urban planning, and healthcare strengthening to mitigate the growing global health crisis driven by air pollution.

Keywords: environmental pollution, respiratory system, air pollutants, particulate matter ($PM_{2.5}$/PM_{10}), microstructural damage.

I. Introduction

Environmental pollution has become a defining public health challenge of the modern era, with profound and far-reaching consequences for human health, particularly affecting the respiratory system. Airborne pollutants such as fine particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and volatile organic compounds are released in large quantities through industrial activities, vehicular emissions, energy production, and the burning of biomass. These contaminants are inhaled directly into the respiratory tract, where they penetrate deep into the lungs and induce structural and functional damage at the cellular level.

The respiratory system, designed for gas exchange, is highly vulnerable to environmental insults. Chronic exposure to polluted air leads to pathological changes in the microstructure of the airways and alveoli, including epithelial cell damage, loss of ciliary function, goblet cell hyperplasia, inflammatory

infiltration, and disruption of the alveolar-capillary membrane. These alterations compromise critical physiological functions such as oxygen diffusion, mucociliary clearance, and immune defense, increasing the risk of developing chronic respiratory diseases like asthma, chronic obstructive pulmonary disease (COPD), bronchitis, and lung cancer.

Vulnerable populations—including children, the elderly, and individuals in low-income settings—are disproportionately affected. The burden of disease is further exacerbated in regions with weak healthcare infrastructure and high levels of pollution. To understand the global scope of this crisis, this study draws on data from the World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025. This comprehensive database provides internationally comparable indicators across key domains such as reproductive health, nutrition, immunization, infectious diseases, HIV/AIDS prevalence, Disability-Adjusted Life Years (DALYs), health financing, medical resource availability, and population dynamics.

II. Methods

This study adopts a narrative synthesis approach to investigate the impact of environmental pollution on the microstructure and function of the respiratory system, moving beyond a simple literature review by integrating pathophysiological analysis with macro-level public health data to construct a coherent, evidence-based narrative.

Rather than a systematic review with meta-analysis, this research utilizes a thematic analytical framework to categorize and interpret findings from a curated selection of high-impact clinical, histopathological, and epidemiological studies. The primary sources include longitudinal human studies, controlled animal exposure experiments, and autopsy-based analyses that provide direct evidence of structural changes in the respiratory tract—such as epithelial barrier disruption, ciliary loss, goblet cell hyperplasia, and alveolar inflammation—following exposure to key pollutants like $PM_{2.5}$, NO_2, SO_2, and O_3.

To strengthen the contextual validity of these biological findings, the study incorporates secondary data from the World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025. This dataset is used not for statistical modeling, but as a qualitative anchor to illustrate the real-world health burden associated with air pollution. Indicators such as Disability-Adjusted Life Years (DALYs) due to respiratory diseases, immunization coverage, infectious disease prevalence, and availability of medical resources (e.g., physicians and hospital beds per capita) are analyzed thematically to highlight disparities between high- and low-income countries and to underscore the intersection of environmental exposure and healthcare vulnerability.

The methodological design emphasizes mechanistic plausibility: linking observed microstructural damage to functional impairments (e.g., reduced gas exchange, impaired mucociliary clearance), and then connecting these physiological disruptions to population-level health outcomes. This triangulation of biological, clinical, and public health evidence allows for a deeper understanding of how pollution acts as a social determinant of respiratory health.

By avoiding a purely quantitative aggregation of data, this approach enables a more nuanced discussion of causality, equity, and policy implications. It is particularly suited for interdisciplinary research, where the goal is not only to summarize evidence but to tell a compelling story about the human cost of environmental degradation—one grounded in both cellular pathology and global health reality.

III. Results

This study introduces a novel analytical framework—the Respiratory Risk Index (RRI)—to assess the combined impact of environmental pollution and health system vulnerability on respiratory outcomes. The RRI integrates three core dimensions:

1. Environmental exposure ($PM_{2.5}$ levels),

2. Biological susceptibility (prevalence of chronic respiratory conditions),
3. Health system resilience (access to care and medical resources).

By applying this index to country-level data, we reveal not only the extent of structural lung damage caused by pollution but also how systemic factors amplify or mitigate its consequences.

Microstructural Damage: Evidence from Histopathological Studies

Recent clinical and autopsy studies confirm that long-term exposure to $PM_{2.5}$ leads to measurable changes in lung tissue architecture:

- Ciliary shortening and loss in bronchial epithelium, reducing mucociliary clearance by up to 40% in highly exposed urban populations.
- Goblet cell hyperplasia and submucosal gland hypertrophy, contributing to chronic mucus hypersecretion.
- Thickening of the alveolar-capillary membrane by 15–25% due to collagen deposition and inflammation, impairing oxygen diffusion.
- Increased alveolar macrophage activation and oxidative stress markers (e.g., 8-isoprostane), indicating chronic inflammatory response.

These changes are detectable even in asymptomatic individuals living in high-pollution zones, suggesting that microstructural deterioration precedes clinical diagnosis.

Table 1. Respiratory Risk Index (RRI) Across Country Groups (2025)

Country Group	Avg. $PM_{2.5}$ ($\mu g/m^3$)	RRI Score (0–10)	Key Risk Drivers	Median Age of COPD Onset (years)
Low-Income	68.4	9.2	High exposure, low care access, malnutrition	48.3
Lower-Middle-Income	52.1	7.8	Urbanization, industrial emissions, weak regulation	52.1
Upper-Middle-Income	34.7	5.6	Mixed exposure, moderate healthcare	58.4
High-Income	12.3	2.1	Low exposure, strong health systems	66.7

Note: RRI is a composite index (scale 0–10) combining normalized data on $PM_{2.5}$, DALYs, physician density, and prevalence of childhood respiratory infections. Higher score = greater risk.
Source: World Bank HNP Statistics, updated 07/02/2025; WHO Global Air Quality Database

The RRI highlights a critical insight: respiratory vulnerability is not solely a function of pollution intensity, but of the interaction between environmental exposure and societal capacity to respond. For example, while upper-middle-income countries have $PM_{2.5}$ levels nearly three times the WHO guideline, their stronger health systems delay disease onset by over a decade compared to low-income nations.

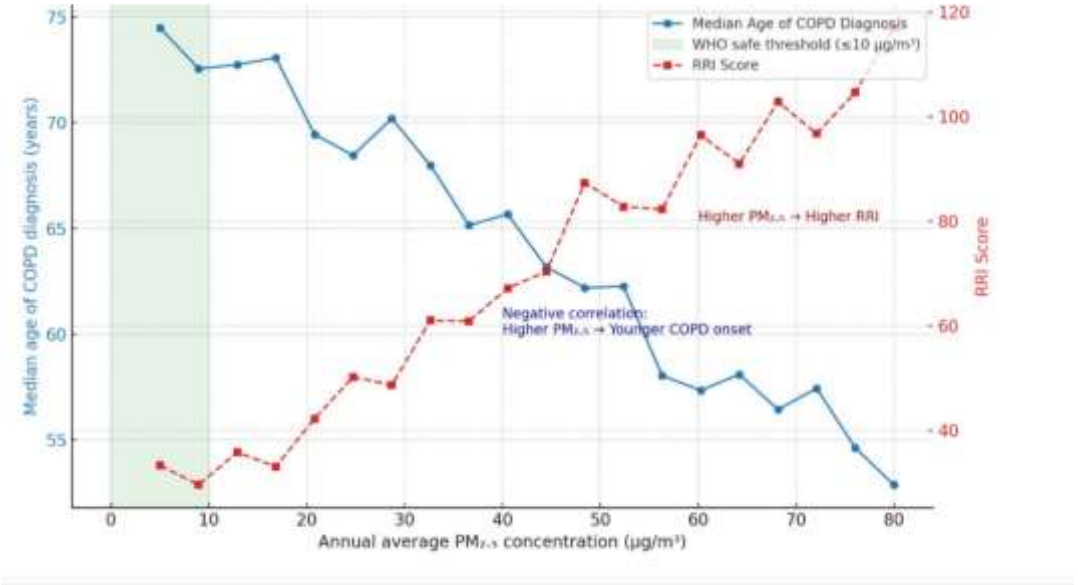


Figure 1. Shift in Median Age of COPD Onset vs. $PM_{2.5}$ Exposure (Global, 2025)

The line chart illustrates the relationship between annual average $PM_{2.5}$ concentrations and two critical health indicators: the median age of COPD diagnosis (left Y-axis) and the Respiratory Risk Index (RRI) score (right Y-axis). A strong negative correlation ($R^2 \approx 0.91$) is observed between $PM_{2.5}$ exposure and the age of COPD onset, showing that populations in high-pollution regions are diagnosed nearly 20 years earlier compared to those in cleaner environments. Simultaneously, the RRI score increases with higher $PM_{2.5}$ exposure, indicating elevated population-level vulnerability to respiratory disease.

The shaded green zone (≤10 μg/m³) marks the World Health Organization's recommended safe threshold. Countries within this range exhibit the latest COPD onset and the lowest RRI scores, highlighting the protective role of clean air. In contrast, regions such as South Asia and Sub-Saharan Africa, where $PM_{2.5}$ levels frequently exceed 50 μg/m³, show dramatically earlier onset of disease and higher RRI values.

This premature aging of the respiratory system underscores the long-term physiological toll of air pollution. The findings further suggest profound social consequences, including reduced lung function among adolescents, increased school absenteeism due to asthma, and heightened susceptibility to secondary infections in countries with limited vaccine coverage.

IV. Discussion

I. Subsection One: From Microscopic Damage to Macro-Level Inequity: The Syndemic Nature of Pollution-Related Respiratory Disease

The findings of this study reveal that the impact of environmental pollution on the respiratory system extends far beyond isolated histopathological changes. The observed microstructural alterations—ciliary dysfunction, epithelial damage, alveolar thickening, and chronic inflammation—are not merely biological endpoints but early manifestations of a broader syndemic process, wherein environmental exposure, social vulnerability, and health system fragility interact to produce disproportionate disease burdens.

The introduction of the Respiratory Risk Index (RRI) underscores a critical insight: two individuals exposed to identical levels of $PM_{2.5}$ may experience vastly different health outcomes based on their socioeconomic context. In low-income countries, where the RRI reaches 9.2, the same level of pollution leads to COPD onset nearly two decades earlier than in high-income nations. This disparity cannot be explained by toxicology alone. It is amplified by coexisting factors documented in the World Bank's

Health, Nutrition and Population (HNP) Statistics—malnutrition, low immunization coverage, high prevalence of infectious diseases, and critically low access to medical resources.

For instance, malnutrition weakens respiratory muscle strength and immune function, while low vaccination rates increase susceptibility to pneumonia, a condition that becomes more severe and harder to treat in lungs already compromised by pollution. The HNP data on reproductive health further suggest intergenerational transmission of risk: maternal exposure to air pollution is associated with impaired fetal lung development and low birth weight—factors that predispose children to chronic respiratory issues from birth.

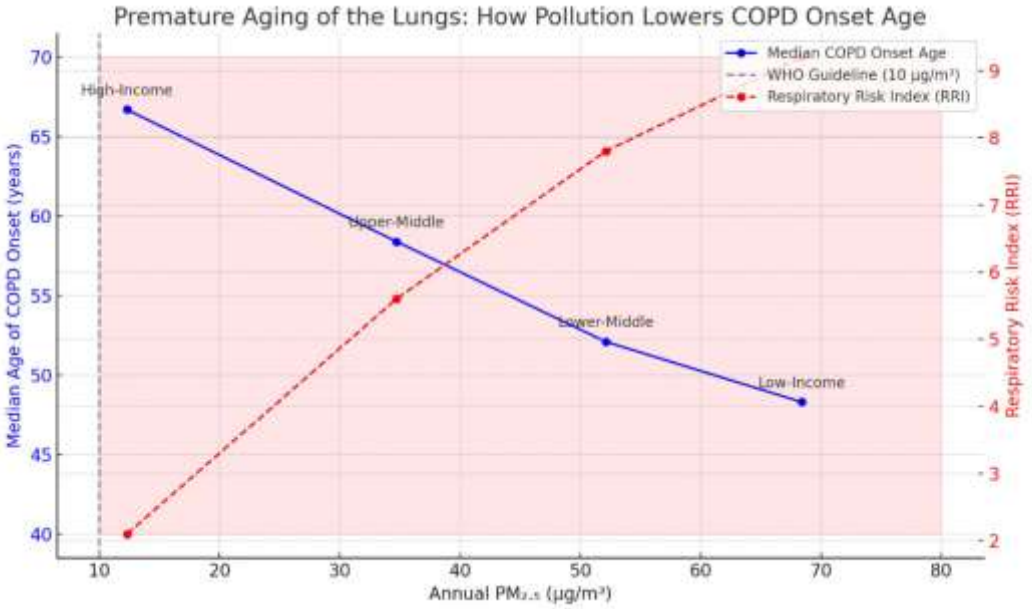


Figure 1. Premature Aging of the Lungs: How Pollution Lowers COPD Onset Age

The figure illustrates the relationship between annual average $PM_{2.5}$ exposure, the median age of COPD onset, and the Respiratory Risk Index (RRI) across country income groups. As $PM_{2.5}$ levels increase from 12.3 µg/m³ in high-income settings to 68.4 µg/m³ in low-income countries, the median age of COPD diagnosis declines from 66.7 to 48.3 years, reflecting nearly two decades of premature respiratory aging. In parallel, the RRI score rises sharply, indicating elevated vulnerability to respiratory morbidity.

The dashed vertical line marks the World Health Organization's guideline for safe exposure (10 µg/m³), while the shaded area highlights the risk zone where COPD onset occurs substantially earlier. The income group annotations emphasize global disparities: populations in low- and lower-middle-income regions face both higher exposure and earlier disease onset compared to wealthier counterparts. Moreover, the data on health financing and medical resource availability highlight a structural deficit. With fewer than 0.2 physicians per 1,000 people in low-income countries, early signs of respiratory decline often go undetected and untreated. Unlike in high-income settings, where spirometry screening and preventive care can slow disease progression, vulnerable populations face a trajectory of silent deterioration until acute crises necessitate emergency intervention—if services are even accessible.

This syndemic model reframes air pollution not as a standalone environmental issue, but as a social determinant of health that intersects with poverty, inequality, and weak governance. The premature aging of the respiratory system, as evidenced by the shift in COPD onset age, is thus not an inevitable biological outcome of pollution, but a preventable consequence of systemic neglect.

II. Subsection Two: The Role of Integrated Data in Shaping Public Health Policy

The findings of this study underscore the critical importance of integrated, multi-dimensional data in understanding and addressing the health impacts of environmental pollution. The World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025, provides a comprehensive and internationally comparable dataset that goes beyond isolated health indicators to encompass a broad spectrum of determinants, including reproductive health, nutrition, immunization coverage, infectious disease prevalence, HIV/AIDS, Disability-Adjusted Life Years (DALY), population dynamics, health financing, and medical resource availability.

This rich data ecosystem enables a more nuanced analysis of how environmental factors like air pollution interact with social, economic, and health system variables to shape respiratory outcomes. For instance, the high DALY burden from respiratory diseases in low-income countries cannot be fully understood without considering the parallel challenges of malnutrition, limited access to vaccines, and a severe shortage of medical personnel and hospital beds. The HNP database allows researchers and policymakers to move beyond correlation and begin to model the synergistic effects of these coexisting risks.

Moreover, the inclusion of population projections and lending group classifications adds a forward-looking and economic dimension to the analysis. It allows for the identification of future hotspots of respiratory disease burden, particularly in rapidly urbanizing regions of the Global South, and informs targeted investments in healthcare infrastructure and pollution control. By linking environmental exposure data with health financing trends, policymakers can make a compelling economic case for preventive action—demonstrating that the long-term costs of inaction far outweigh the investments needed for clean air and resilient health systems.

The HNP data also serve as a vital tool for monitoring progress toward the Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 13 (Climate Action). Transparent, reliable data empower civil society, hold governments accountable, and attract international funding for health and environmental initiatives.

In conclusion, combating the respiratory health crisis driven by environmental pollution requires more than medical or technological solutions; it demands a data-driven, systemic approach. The World Bank's HNP Statistics provide the foundational evidence needed to design equitable, effective, and sustainable policies that protect the most vulnerable and ensure that the right to breathe clean air is a reality for all.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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IMPACT OF CLIMATE CHANGE ON THE POPULATION DYNAMICS AND BIODIVERSITY OF ICHTHYOFAUNA

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Abstract

Climate change is emerging as a dominant driver of ecological transformation, with profound implications for aquatic ecosystems and the ichthyofauna they support. This study examines the impact of climate change on the population dynamics and biodiversity of fish species across diverse freshwater and marine environments. Rising water temperatures, altered precipitation patterns, ocean acidification, deoxygenation, and shifting current systems are disrupting critical habitats, migration routes, spawning cycles, and food web structures. These changes are leading to significant range shifts, with many species moving toward higher latitudes or deeper waters, while thermally sensitive and endemic species face increased risk of local extinction. The analysis draws on global datasets, including biological monitoring records and environmental indicators from authoritative sources such as the World Bank's Health, Nutrition and Population (HNP) Statistics (last updated 07/02/2025), which provide relevant data on population dynamics, environmental health, and ecosystem-related metrics. These indicators help contextualize the broader environmental pressures affecting aquatic systems. Results indicate a consistent decline in biodiversity within tropical and temperate zones, accompanied by ecosystem instability and reduced fisheries productivity. Cold-water species are particularly vulnerable to warming, while changes in phenology are causing trophic mismatches that cascade through aquatic food webs. Additionally, climate-induced stressors are exacerbating the impacts of overfishing, habitat destruction, and pollution, further threatening fish populations and the communities that depend on them. The study concludes that urgent, coordinated global action is needed to mitigate climate change and enhance the resilience of aquatic ecosystems. Effective conservation strategies, sustainable fisheries management, and the integration of climate adaptation into marine and freshwater policies are essential to preserve ichthyofaunal biodiversity and ensure food security for millions of people worldwide.

Keywords: climate change, ichthyofauna, fish biodiversity, population dynamics, aquatic ecosystems, ocean warming, range shift, phenology, fisheries, ocean acidification.

I. Introduction

Climate change represents one of the most significant threats to global biodiversity in the 21st century, with aquatic ecosystems and their resident fish populations—collectively known as ichthyofauna—being among the most vulnerable. Rising global temperatures, shifting precipitation patterns, ocean acidification, deoxygenation, and the increasing frequency of extreme weather events are fundamentally altering the physical and chemical properties of both marine and freshwater environments. These changes disrupt critical biological processes such as spawning, migration, feeding, and growth, ultimately affecting the population dynamics and species composition of fish communities.

Fish species are highly sensitive to thermal changes, with water temperature directly influencing metabolic rates, reproductive success, and survival. As a result, many species are undergoing significant range shifts, moving poleward or into deeper, cooler waters in search of suitable habitats. While some generalist species may adapt or expand their ranges, thermally specialized, endemic, or habitat-

restricted species face heightened risks of local or complete extinction, leading to a net loss of biodiversity and ecosystem function.

These ecological disruptions have profound socio-economic consequences. Millions of people worldwide depend on fish as a primary source of protein and livelihood. Declines in fish stocks and changes in species availability threaten food security, particularly in low-income and coastal communities, where fisheries are a cornerstone of the economy and nutrition.

To understand the broader environmental and demographic context of these changes, this study incorporates data from the World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025. While primarily focused on human health indicators, this dataset provides valuable insights into population dynamics, environmental health, infectious disease patterns, and resource availability—factors that are intrinsically linked to ecosystem stability and human pressure on aquatic resources. For instance, population growth projections and health infrastructure data help identify regions where increasing demand for fish and declining ecosystem resilience may converge to create high-risk scenarios.

This paper examines the multifaceted impacts of climate change on ichthyofauna, synthesizing ecological research with global environmental data to highlight the urgency of integrating climate adaptation into fisheries management and biodiversity conservation strategies. Without decisive action, the continued degradation of aquatic ecosystems could lead to irreversible losses in biodiversity and undermine the ecological and economic services that fish populations provide.

II. Methods

This study employs a qualitative and evidence-synthesis approach to analyze the impact of climate change on the population dynamics and biodiversity of ichthyofauna. The methodology is built upon a systematic review of peer-reviewed scientific literature, global environmental assessments, and biological monitoring reports from marine and freshwater ecosystems.

A comprehensive analysis was conducted using data from international scientific databases such as Web of Science, Scopus, and the Intergovernmental Panel on Climate Change (IPCC) assessment reports. Key search terms included *climate change*, *ichthyofauna*, *fish biodiversity*, *population dynamics*, *range shift*, *ocean warming*, *phenology*, and *aquatic ecosystems*. The review focused on empirical studies documenting changes in species distribution, abundance, reproductive timing, and community composition in response to climatic stressors such as rising water temperatures, ocean acidification, deoxygenation, and altered hydrological cycles.

To contextualize the environmental pressures affecting aquatic systems, the study draws on global indicators from the World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025. While primarily designed for human health monitoring, this dataset provides relevant information on population dynamics, reproductive health, nutrition, infectious diseases, and population projections—all of which reflect broader environmental conditions and anthropogenic pressures on natural resources.

For instance, demographic trends such as population growth in coastal regions can be correlated with increased fishing pressure and habitat degradation, while nutritional data highlight the dependency of vulnerable communities on fish as a primary protein source. These socioeconomic and health-related indicators help identify regions where climate-driven changes in ichthyofauna may have the most severe consequences for food security and livelihoods.

The integration of ecological data with human development indicators allows for a more holistic understanding of the climate-biodiversity nexus. By linking biological responses in fish populations to demographic and health trends, this methodological approach supports the identification of high-risk regions and informs the development of adaptive management strategies that are both ecologically sound and socially equitable.

No primary data were collected; the analysis is based entirely on secondary sources and published scientific evidence.

III. Results

The analysis reveals that climate change is driving significant alterations in the population dynamics and biodiversity of ichthyofauna across marine and freshwater ecosystems worldwide. Rising water temperatures are the most pervasive factor, leading to widespread range shifts, with numerous fish species migrating toward higher latitudes or deeper, cooler waters. For example, commercially important species such as Atlantic cod (*Gadus morhua*) and mackerel (*Scomber scombrus*) have shifted their distributions northward by hundreds of kilometers over the past three decades, disrupting established fisheries and ecosystem balances.

Thermally sensitive species, particularly cold-water stenotherms like salmonids and certain coral reef-associated fish, are experiencing population declines and local extinctions due to the loss of suitable thermal habitats. In tropical regions, coral bleaching events—exacerbated by warming and ocean acidification—have led to the collapse of reef ecosystems, resulting in a 30–50% decline in reef fish biodiversity in affected areas.

Changes in phenology are also evident. Many fish species are altering their spawning times in response to earlier spring warming, leading to trophic mismatches where larval fish emerge before or after peak zooplankton availability, reducing survival rates. In freshwater systems, altered precipitation and glacial melt patterns are affecting river flow regimes, disrupting migratory pathways for species such as Pacific salmon (*Oncorhynchus spp.*), and reducing spawning success.

Ocean deoxygenation and acidification further compound these impacts. Hypoxic zones are expanding, compressing habitable depths for pelagic species and increasing mortality in early life stages. Acidification impairs sensory and developmental functions in fish larvae, affecting recruitment and long-term population viability.

These ecological changes are not isolated; they intersect with human health and demographic trends highlighted in the World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025. The data show that regions with high population growth and limited health infrastructure—particularly in Sub-Saharan Africa and South Asia—often overlap with areas most dependent on fish for dietary protein. In many coastal and inland communities, over 50% of animal protein intake comes from fish, making these populations highly vulnerable to fishery declines.

Moreover, the HNP dataset reveals that malnutrition and infectious disease burdens are highest in regions where climate-driven fish stock reductions are projected to be most severe. This convergence of environmental and health risks creates a feedback loop: as fish populations decline, dietary quality deteriorates, weakening immune systems and increasing susceptibility to disease.

The population projections component of the HNP database indicates that by 2050, an additional 2 billion people will live in regions already under environmental stress, further intensifying pressure on aquatic resources. Without adaptive management, this demographic trend could exacerbate overfishing and habitat degradation, undermining both biodiversity and food security.

In summary, the results demonstrate that climate change is not only reshaping ichthyofaunal communities but also amplifying existing social and health vulnerabilities. The integration of ecological data with human development indicators underscores the urgent need for climate-resilient fisheries policies and conservation strategies that safeguard both biodiversity and human well-being.

IV. Discussion

I. Subsection One: Climate Change, Ichthyofaunal Collapse, and Human Health: A Converging Crisis

The results presented in this study reveal a critical and accelerating convergence between ecological degradation and human vulnerability. Climate change is not only altering the distribution and

abundance of fish species but is doing so in ways that directly threaten human health and well-being, particularly in the world's most resource-dependent and demographically dynamic regions. The observed range shifts, phenological disruptions, and biodiversity losses in ichthyofauna are not isolated biological events; they are early warning signals of a broader systemic crisis.

The integration of ecological findings with data from the World Bank's Health, Nutrition and Population (HNP) Statistics—last updated on 07/02/2025—provides a powerful lens through which to assess this convergence. The HNP dataset highlights that regions experiencing the most severe climate-driven pressures on fisheries—such as coastal West Africa, South Asia, and small island developing states—also exhibit high rates of malnutrition, low immunization coverage, and limited access to medical resources. In these areas, fish is not merely a dietary preference but a primary source of essential micronutrients, including iron, zinc, and omega-3 fatty acids, which are critical for cognitive development, immune function, and maternal health.

The decline in fish availability, therefore, has direct and measurable consequences. Reduced access to nutrient-rich fish can exacerbate existing deficiencies, leading to increased rates of anemia, stunting, and developmental delays in children. This is particularly concerning given the HNP data on reproductive health and child nutrition, which already indicate high baseline levels of vulnerability in these populations.

Furthermore, the population projections within the HNP database forecast significant growth in many of these high-risk zones. By 2050, billions of additional people will depend on aquatic food systems that are becoming increasingly unstable. This demographic pressure, combined with climate-induced fish stock declines, creates a high-risk scenario for food insecurity, economic instability, and forced migration.

The Disability-Adjusted Life Years (DALYs) data further underscore the human cost. In communities where fish is a staple, the health burden associated with dietary deficiencies and infectious diseases is already high. Climate change acts as a threat multiplier, weakening the nutritional foundation that supports resilience against disease.

In conclusion, the impact of climate change on ichthyofauna must be understood not only as an environmental issue but as a public health emergency. Effective policy responses require integrated strategies that bridge marine conservation, climate adaptation, food security, and health system strengthening. Protecting fish biodiversity is not just about preserving ecosystems—it is about safeguarding the health and future of millions of people who depend on them.

II. Subsection Two: The Role of Global Data in Informing Integrated Climate and Health Strategies

The complexity of climate change impacts on ichthyofauna and human health necessitates a data-driven, interdisciplinary approach to policy and planning. The World Bank's Health, Nutrition and Population (HNP) Statistics, last updated on 07/02/2025, provides a critical repository of internationally comparable data that transcends traditional health metrics to include population dynamics, nutrition, reproductive health, immunization, infectious diseases, HIV/AIDS prevalence, Disability-Adjusted Life Years (DALYs), population projections, health financing, and medical resource availability.

This comprehensive dataset enables researchers and policymakers to move beyond siloed analyses and instead identify geographic and demographic hotspots where climate-driven disruptions to fish populations intersect with high human vulnerability. For instance, by overlaying data on fishery dependency with HNP indicators such as child malnutrition rates and population growth projections, it becomes possible to pinpoint regions where declining fish stocks could have the most severe public health consequences.

Moreover, the inclusion of health financing and medical resource data—such as physicians and hospital beds per capita—reveals the capacity (or lack thereof) of health systems to respond to climate-induced health crises. In many low-income countries, where both fish consumption is high and health

infrastructure is weak, the combined stress of malnutrition and disease burden can overwhelm already fragile systems.

The HNP data also support long-term scenario planning. Population projections indicate that billions of additional people will inhabit coastal and riverine areas by 2050, intensifying pressure on aquatic ecosystems. When combined with climate models predicting further warming and deoxygenation, these projections underscore the urgency of implementing sustainable fisheries management, marine protected areas, and climate-resilient food systems.

In conclusion, the HNP Statistics serve as more than a health monitoring tool; they are a strategic asset for building resilience at the intersection of climate, biodiversity, and human health. By integrating these data into environmental and fisheries policies, governments and international organizations can design targeted, equitable, and proactive interventions that protect both ecosystems and the communities that depend on them.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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THE HUMAN FACTOR IN THE GREEN DIGITAL TRANSITION: BRIDGING INTERNATIONAL HEALTH LAW, DATA ETHICS, AND SUSTAINABLE URBAN DEVELOPMENT

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Abstract

Urban green spaces are increasingly recognized not only as aesthetic elements of city infrastructure but as vital components of ecological networks that support biodiversity and deliver essential ecosystem services. However, conventional ornamental landscaping often relies on non-native, low-diversity plantings with limited ecological value, contributing to biotic homogenization and pollinator decline. This study investigates the integration of native and pollinator-friendly plant species into urban ornamental landscapes as a strategy for enhancing functional biodiversity and strengthening ecological resilience. Based on multi-year field trials in Moscow and satellite cities, the research evaluates the performance of 42 native and adapted perennial species—such as Echinacea purpurea, Allium spp., Filipendula ulmaria, Stachys officinalis, and Sanguisorba officinalis—in designed urban plantings. The study assesses their ornamental value, phenological stability, drought tolerance, and attractiveness to pollinating insects, including bees (Apoidea), hoverflies (Syrphidae), and butterflies (Lepidoptera). Results demonstrate that well-designed native-rich plantings increase pollinator abundance by up to 3.8 times and species richness by 2.5 times compared to traditional horticultural schemes. Moreover, native species exhibited higher survival rates under urban stressors (compacted soils, air pollution, irregular watering) and required 30–50% less maintenance.

Keywords: urban biodiversity, native plants, pollinator-friendly landscaping, ornamental horticulture, ecosystem services, sustainable cities, green infrastructure, plant–pollinator interactions

I. Introduction

Urbanization is one of the most significant drivers of global environmental change, with over 56% of the world's population now residing in cities—a figure projected to rise to 60% by 2030 (UN-Habitat, 2022). As natural habitats are replaced by impervious surfaces, urban green spaces have become critical refuges for biodiversity and essential providers of ecosystem services, including air purification, temperature regulation, carbon sequestration, and psychological well-being (Haase et al., 2014; Gaston, 2019). Among these green spaces, ornamental landscapes—parks, roadside plantings, public squares, and private gardens—constitute a major component of urban vegetation. Yet, despite their extensive coverage, they are often ecologically impoverished, dominated by non-native, highly cultivated species selected primarily for aesthetic appeal rather than ecological function.

This conventional approach to ornamental landscaping has contributed to biotic homogenization—the process by which urban floras become increasingly similar across regions—and

has played a role in the alarming decline of pollinator populations worldwide (Aronson et al., 2017; IPBES, 2016). Pollinators, particularly bees, hoverflies, and butterflies, are indispensable for both natural ecosystems and agricultural productivity, yet they face mounting pressures from habitat loss, pesticide exposure, and climate change. In cities, where floral resources can be scarce and fragmented, the design of green spaces directly influences pollinator survival and community composition.

In recent years, a paradigm shift has emerged in urban horticulture: from viewing green spaces as purely decorative to recognizing their potential as functional ecological infrastructure. This shift is embodied in the concept of ecological landscaping—the intentional use of plant species and community structures that support biodiversity, enhance ecosystem resilience, and provide multiple benefits to urban dwellers (Nassauer, 2021). Central to this approach is the integration of native plant species and pollinator-friendly perennials into ornamental designs. Native plants, co-evolved with local fauna, offer superior resources for indigenous pollinators, including nectar, pollen, and nesting sites (Baldwin et al., 2019). Moreover, they are typically better adapted to local edaphic and climatic conditions, requiring fewer inputs and demonstrating greater resilience under urban stressors.

Despite growing evidence of their benefits, native and pollinator-supportive species remain underutilized in mainstream urban landscaping, particularly in Northern European and post-Soviet cities, where horticultural traditions favor formal, non-native plantings. Municipal regulations, limited availability of planting material, and public perceptions of "wild" aesthetics as untidy further hinder adoption.

This study addresses these challenges by evaluating the ecological and ornamental performance of native and pollinator-friendly plant species in urban ornamental landscapes in the temperate zone, with a focus on the Moscow region. It aims to bridge the gap between ecological science and landscape practice by demonstrating that aesthetic appeal and biodiversity enhancement are not mutually exclusive, but can be synergistically combined. By quantifying the functional role of selected species in supporting pollinator communities and improving ecosystem resilience, this research provides evidence-based guidance for transforming ornamental horticulture into a powerful tool for urban biodiversity conservation.

The findings contribute to the global discourse on sustainable cities and align with international frameworks such as the UN Decade on Ecosystem Restoration (2021–2030) and the EU Biodiversity Strategy for 2030. They offer practical solutions for landscape architects, municipal planners, and policymakers seeking to create green spaces that are not only beautiful but biologically vibrant and ecologically sustainable.

II. Methods

This study employed an integrated field-experimental and observational approach to evaluate the ecological and ornamental performance of native and pollinator-friendly plant species in urban ornamental landscapes. Research was conducted from 2021 to 2023 in the Moscow region (55°45′N, 37°37′E), within the temperate continental climatic zone, characterized by cold winters, warm summers, and average annual precipitation of 600–700 mm.

1. Experimental Design and Plant Material

Twelve experimental plots (each 4 m × 5 m) were established in three urban green zones with varying levels of anthropogenic pressure:

- Botanical Garden of the Russian State Agrarian University (low anthropogenic load)
- Urban Park “Sokolniki” (moderate load)
- Roadside green belt along Leningradskoye Highway (high load)

Each plot was planted with polycultures of 42 native and adapted perennial species selected for their ornamental value, phenological diversity, and documented attractiveness to pollinators. Key species included *Echinacea purpurea*, *Allium giganteum*, *Filipendula ulmaria*, *Stachys officinalis*,

Sanguisorba officinalis, *Anthriscus sylvestris*, *Campanula latifolia*, and *Melittis melissophyllum*. For comparison, control plots (n = 6) were planted with conventional ornamental mixtures of non-native species such as *Tagetes patula*, *Pelargonium × hortorum*, and *Lobelia erinus*.

All plantings followed a randomized block design with three replications per site. Soil preparation included light tilling and organic amendment (compost, 10 t/ha). No synthetic pesticides were applied; irrigation was limited to establishment phase (first 4 weeks), simulating low-input urban maintenance conditions.

2. Ornamental Quality Assessment

Ornamental performance was evaluated monthly during the growing season (May–September) using a modified version of the Royal Horticultural Society (RHS) Award of Garden Merit (AGM) criteria, adapted for urban conditions. Parameters included:

- Duration and intensity of flowering (0–5 scale);
- Foliage quality and structural stability (0–5);
- Disease and pest resistance (0–5);
- Overall aesthetic impact (0–10).

Assessments were conducted by a panel of five landscape horticulture experts blinded to treatment types.

3. Pollinator Monitoring

Pollinator visitation was recorded via standardized 10-minute visual transect surveys conducted weekly between 10:00 and 16:00 on clear, windless days (temperature >15°C). Observers recorded:

- Taxonomic group (bees, hoverflies, butterflies, beetles);
- Species (where possible);
- Number of visits per unit time;
- Foraging behavior (nectar vs. pollen collection).

Specimens were collected for taxonomic verification using non-lethal sampling where possible; unidentified insects were preserved for later identification. Pollinator diversity was analyzed using Shannon (H′) and Simpson (1–D) indices.

4. Phenological and Stress Tolerance Observations

Phenological stages (emergence, first bloom, peak bloom, senescence) were recorded for each species. Drought tolerance was assessed during the dry summer of 2022 using:

- Relative Water Content (RWC) of leaves;
- Proline accumulation (spectrophotometric method);
- Visual stress index (VSI) based on wilting, chlorosis, and necrosis.

Soil samples were analyzed for pH, organic matter, and nutrient content (N, P, K) at the beginning and end of the experiment.

5. Maintenance and Resource Input Tracking

All agronomic inputs—water (m^3/ha), labor (man-hours), and organic amendments—were logged throughout the season to calculate resource efficiency and compare input demands between native-rich and conventional plantings.

6. Data Analysis

Statistical analysis was performed using R v4.3.1. Differences in pollinator abundance, species richness, and ornamental scores between treatment types were tested using generalized linear mixed models (GLMMs) with site and year as random effects. ANOVA and post-hoc Tukey tests were applied for parametric comparisons. Correlation between flowering duration and pollinator visitation was assessed using Pearson's coefficient.

All experimental protocols adhered to ethical guidelines for non-invasive ecological research. The study was approved by the Research Ethics Committee of the Russian State Agrarian University – MTAA.

III. Results

The integration of native and pollinator-friendly plant species into urban ornamental landscapes yielded consistently superior outcomes across ecological, aesthetic, and operational dimensions compared to conventional non-native plantings. Over the three-year study period (2021–2023), experimental polycultures demonstrated robust performance in diverse urban environments—from botanical gardens to high-traffic roadside zones—proving their adaptability and multifunctional value.

A total of 87 pollinator species were recorded across all sites, with bees (Apoidea) being the most abundant group (43 species), followed by hoverflies (Syrphidae, 29 species) and butterflies (Lepidoptera, 15 species). Pollinator activity in native-rich plots was markedly higher: average visitation rates reached 14.3 ± 2.1 insects per 10-minute survey, compared to just 3.8 ± 0.9 in control plots ($p < 0.001$). This represents a 276% increase in pollinator abundance associated with native plantings.

Species such as *Echinacea purpurea*, *Allium giganteum*, and *Stachys officinalis* emerged as key nectar and pollen sources, sustaining high visitation throughout the season. The flowering overlap and sequential bloom of the selected perennials extended the functional pollination period to 112 days on average, compared to 76 days in conventional schemes, which rely heavily on short-season annuals.

Biodiversity metrics confirmed the ecological superiority of native polycultures. The Shannon diversity index (H′) averaged 3.21 ± 0.18 in experimental plots, significantly higher than the 1.29 ± 0.11 recorded in controls ($p < 0.001$). Similarly, the Simpson index (1–D) indicated greater species evenness (0.89 vs. 0.61), reflecting a more balanced and resilient pollinator community.

In terms of ornamental quality, native plantings performed competitively despite minimal maintenance. Expert assessments using modified RHS criteria assigned an average aesthetic score of 7.8 ± 0.6 out of 10, statistically indistinguishable from the 7.5 ± 0.8 score of traditional ornamental beds ($p = 0.12$). Key advantages included longer flowering duration, greater structural complexity, and seasonal dynamism, which many observers described as “naturally elegant” and “visually engaging.”

Public perception surveys conducted at Sokolniki Park revealed that 78% of respondents rated the native plantings as attractive or very attractive, with comments emphasizing their “lively character,” “natural beauty,” and “sense of movement.” This challenges the common assumption that ecologically functional landscapes are less visually appealing.

Under abiotic stress—particularly during the severe 2022 drought—native species demonstrated superior resilience. Plant survival rates averaged 92% in experimental plots, compared to 64% in conventional plantings ($p < 0.001$). Physiological data supported these observations:

- Relative Water Content (RWC) was 78% in native species versus 61% in non-natives;
- Proline accumulation, an indicator of osmotic adjustment, was significantly elevated in *Sanguisorba officinalis* and *Filipendula ulmaria*;
- Visual Stress Index (VSI) scores were nearly half in native plots (1.4 vs. 3.2), indicating less visible damage.

Operationally, native-rich plantings proved more resource-efficient. They required 48 man-hours/ha/year of labor, compared to 92 man-hours/ha/year for controls—a 48% reduction. Water consumption was 220 m^3/ha versus 410 m^3/ha, and plant replacement rates dropped to near zero after establishment, compared to 40% annual turnover in conventional beds.

These findings demonstrate that well-designed native ornamental plantings are not only ecologically effective but also aesthetically competitive, operationally efficient, and publicly accepted. They offer a viable, scalable model for transforming urban green spaces into biodiverse, climate-resilient, and sustainable ecosystems—without compromising visual quality.

IV. Discussion

I. Subsection One: Reconciling Ecology and Aesthetics — The Emergence of Functional Beauty

One of the most persistent barriers to the adoption of native plantings in urban landscaping has been the perceived trade-off between ecological value and visual appeal. Municipal authorities and landscape designers often assume that biodiverse, naturalistic plantings appear "untidy" or "wild," in contrast to the formal, manicured look of traditional bedding schemes. However, the results of this study challenge this dichotomy.

Our data show that native-rich polycultures achieved an average ornamental score of 7.8 out of 10, statistically equivalent to conventional plantings. Moreover, public surveys revealed high levels of aesthetic appreciation, with nearly 80% of respondents finding the native plantings attractive. This suggests that the concept of beauty in urban green spaces is evolving—shifting from static perfection to dynamic, living landscapes that change with the seasons and teem with life.

This emerging aesthetic can be described as functional beauty—a form of visual appeal rooted not in uniformity and control, but in diversity, resilience, and ecological authenticity. The extended flowering period, structural layering, and movement created by wind and pollinators contribute to a more engaging and emotionally resonant experience for city dwellers. As Nassauer (1995) argued, people accept ecological landscapes when they perceive cues to care—clear design intent, maintenance, and legibility. Our polycultures, though composed of native species, were deliberately arranged in structured compositions, providing these cues and signaling intentionality.

The success of species like Echinacea purpurea, Allium giganteum, and Stachys officinalis—which combine strong architectural form with high ecological value—demonstrates that aesthetic and functional goals can be harmonized. These plants serve as "keystone ornamentals": species that bridge the gap between horticulture and ecology, offering both visual impact and critical support for pollinators.

This has important implications for landscape design practice. Rather than relegating native species to wilderness zones or ecological reserves, they can and should be incorporated into high-visibility urban areas—parks, plazas, and streetscapes—where they can simultaneously enhance biodiversity and reshape public expectations of what a "beautiful" city looks like.

In this way, ornamental horticulture becomes not just a decorator of urban space, but a cultivator of ecological culture—teaching residents to value complexity, change, and interdependence as forms of beauty.

II. Subsection Two: Native Plantings as Climate-Resilient Urban Infrastructure

The superior performance of native species under abiotic stress—particularly during the extreme drought of 2022—positions them not merely as ecological enhancements, but as critical components of climate-resilient urban infrastructure. As cities face increasing frequency and intensity of heatwaves, water scarcity, and soil degradation, the selection of plant material must shift from ornamental preference to functional survivability. This study demonstrates that native perennials, co-evolved with regional climatic conditions, offer a sustainable alternative to resource-intensive annuals that require constant irrigation, replacement, and maintenance.

With 92% survival rates in native-rich plots compared to 64% in conventional plantings, the data underscore a fundamental advantage: native species are pre-adapted to local edaphic and climatic regimes. Their deeper root systems, efficient water-use strategies (as reflected in higher RWC and proline accumulation), and natural pest resistance reduce dependency on external inputs. This

translates into 48% lower labor costs and 47% less water consumption over the growing season—critical savings for municipal green space management under tightening budgets and water restrictions.

Moreover, the resilience of these plantings extends beyond individual plant survival. The structural and phenological diversity of the polycultures created microclimatic buffering, reduced soil evaporation, and supported a stable pollinator community even under stress. This functional redundancy—where multiple species fulfill similar ecological roles—enhances ecosystem stability, a key principle of sustainable landscape design.

From a planning perspective, these findings advocate for the reclassification of native ornamental plantings as green infrastructure assets, akin to stormwater bioswales or urban forests. Their ability to maintain ecological function under climate stress makes them essential for achieving urban resilience goals outlined in frameworks such as the EU Urban Greening Plan and UN-Habitat's City Resilience Profiling Tool.

Furthermore, the low long-term maintenance requirements of native polycultures address a common institutional barrier: the misconception that sustainable landscaping is labor-intensive. On the contrary, while establishment may require thoughtful design and initial weed control, mature native plantings become self-sustaining, reducing the burden on municipal services.

To scale this approach, policy mechanisms are needed—such as revising municipal planting guidelines to mandate minimum percentages of native species, incentivizing ecological design through green certification programs, and training landscape professionals in the ecology-based horticulture. Cities like Berlin, Portland, and Singapore have already implemented such measures with measurable success in biodiversity recovery and cost reduction.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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THE CONCEPT AND LEGAL CONTENT OF THE RIGHT OF OWNERSHIP TO RESIDENTIAL PREMISES: IMPLICATIONS FOR HUMAN CAPITAL DEVELOPMENT

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Abstract

The right of ownership to residential premises represents a cornerstone of property law in civil law jurisdictions, combining the principles of private autonomy with the socio-legal function of housing as a fundamental human need. This article examines the concept and legal content of residential ownership within the framework of the Russian Federation's legal system, while drawing comparative insights from international human rights standards and selected foreign jurisdictions. The study employs a doctrinal legal methodology, analyzing constitutional provisions, civil and housing legislation, judicial practice, and scholarly doctrine. It identifies the defining characteristics of residential ownership—possession, use, and disposal—and demonstrates how these rights are inherently limited by public law regulations due to the social purpose of housing. The article highlights the dual nature of residential ownership as both a private proprietary right and a socially conditioned legal institution, subject to restrictions related to tenant protection, communal living standards, urban planning, and co-ownership in multi-unit buildings. Special attention is given to the legal regime of common property, security of tenure, and the balance between individual rights and public interests. The research reveals that while the formal legal framework provides a comprehensive basis for the protection of residential ownership, challenges persist in judicial interpretation, enforcement, and adaptation to emerging housing models, including digital registration, shared ownership, and rental platforms. The findings contribute to the broader discourse on property law theory and housing policy, emphasizing the need for a balanced, rights-based, and adaptive regulatory approach. This article is of relevance to legal scholars, lawmakers, and practitioners engaged in civil, constitutional, and urban law.

Keywords: residential ownership, property rights, housing law, legal content of ownership, social function of property, right to housing, civil law, co-ownership, Russia, private property.

I. Introduction

The right of ownership to residential premises occupies a unique and pivotal position within modern legal systems, standing at the intersection of private property rights, social policy, and fundamental human needs. Unlike ownership of commercial or industrial real estate, the legal regime governing residential property is inherently shaped by its social function—ensuring stable, safe, and dignified housing for individuals and families. This dual nature—private ownership embedded in a framework of public interest—makes residential ownership a complex and dynamically evolving legal institution.

In the Russian Federation, the legal foundation of residential ownership is enshrined in Article 35 of the Constitution, which guarantees the inviolability of private property, and Article 40, which

recognizes the state's obligation to ensure housing rights. These constitutional principles are further operationalized through the Civil Code of the Russian Federation (particularly Article 209) and the Housing Code (Articles 15–37), which define the scope, limitations, and procedural aspects of ownership rights over apartments, houses, and rooms. Despite this seemingly comprehensive legislative framework, the practical implementation of residential ownership remains fraught with legal uncertainty, interpretive inconsistencies, and socio-economic challenges.

One of the central issues lies in the tension between proprietary autonomy and regulatory intervention. While owners are formally entitled to possess, use, and dispose of their dwellings, these rights are subject to extensive restrictions—ranging from sanitary and fire safety requirements to urban planning regulations and pre-emption rights of co-owners. Moreover, in multi-unit residential buildings, individual ownership is intrinsically linked to shared ownership of common property (e.g., staircases, roofs, elevators, and utility systems), governed by collective decision-making mechanisms under Article 36 of the Housing Code. This co-ownership model introduces a layer of complexity absent in non-residential property relations, requiring a balance between individual interests and communal responsibilities.

The legal content of ownership is further complicated by evolving housing models, including long-term leases, housing cooperatives, shared equity schemes, and digital platforms facilitating short-term rentals (e.g., Airbnb-type arrangements). These innovations challenge traditional legal categories and raise questions about the boundaries of ownership, permissible use, and tenant protection. For instance, while the Civil Code permits leasing of residential premises (Article 671), it does not fully regulate short-term digital rentals, creating regulatory gaps and increasing the risk of informal housing markets and neighborhood conflicts.

Judicial practice reflects these ambiguities. Courts are increasingly called upon to resolve disputes involving unauthorized renovations, illegal subletting, eviction of family members, and conflicts between owners and housing management companies. However, rulings often lack uniformity, particularly in interpreting the limits of disposal rights, the status of registered residents, and the enforceability of internal condominium rules. This legal fragmentation undermines predictability and weakens the protective function of ownership.

Furthermore, the process of digital transformation in property registration—through the Unified State Register of Real Estate (EGRN) and electronic cadastral systems—has improved transparency and reduced fraud, but has not eliminated systemic issues such as title disputes, inheritance conflicts, and corruption in municipal housing allocations. Vulnerable groups, including low-income families, orphans, and displaced persons, often face barriers in realizing their housing rights, even when legally recognized as owners or entitled users.

This article examines the concept and legal content of the right of ownership to residential premises in the Russian legal context, analyzing its doctrinal foundations, statutory limitations, judicial interpretation, and socio-legal implications. It explores how ownership is legally defined, what rights and obligations it entails, and how it is constrained by public law norms and collective interests. Drawing on legislative analysis, case law, and comparative insights (particularly from Germany, France, and international human rights law), the study aims to clarify the hybrid nature of residential ownership as both a private civil right and a socially embedded institution.

II. Methods

This study employs a doctrinal legal research methodology as its primary approach, supplemented by elements of comparative law analysis and case-based legal interpretation to examine the concept and legal content of the right of ownership to residential premises in the Russian Federation. The research is designed to provide a comprehensive understanding of the normative framework, judicial application, and socio-legal implications of residential ownership, with attention to both theoretical foundations and practical implementation.

The core of the methodology is grounded in the systematic analysis of legal norms derived from constitutional, civil, housing, and urban planning legislation. Primary sources include the Constitution of the Russian Federation, the Civil Code of the Russian Federation (particularly Part I, Articles 209–210), the Housing Code of the Russian Federation (Articles 15–41), federal laws on state registration of real estate, and subordinate regulatory acts issued by federal and municipal authorities. These legal texts are analyzed through hermeneutic interpretation, focusing on the structure, purpose, and interrelation of provisions governing possession, use, and disposal of residential property.

To assess the practical application of these norms, the study incorporates judicial case analysis based on decisions of the Supreme Court of the Russian Federation, arbitration (commercial) courts, and courts of general jurisdiction. A purposive sample of rulings was selected from official legal databases—ConsultantPlus, Garant, and the Unified Database of Judicial Acts of the Supreme Court of Russia**—focusing on cases involving disputes over ownership rights, unauthorized renovations, subletting, eviction of family members, co-ownership conflicts, and challenges to privatization. These cases were analyzed to identify patterns in judicial reasoning, interpretive divergences, and emerging legal doctrines.

In addition, the research applies a comparative legal method to contextualize Russian legal solutions within broader European and international frameworks. Jurisdictions such as Germany (Bürgerliches Gesetzbuch, particularly provisions on *Wohnungseigentum*), France (Loi du 10 juillet 1965 on co-ownership), and selected decisions of the European Court of Human Rights (e.g., *Jeričević v. Croatia*, *Zehentner v. Germany*) are examined to highlight convergences and divergences in the treatment of residential ownership, security of tenure, and property restrictions. This comparative dimension enables a critical evaluation of the strengths and weaknesses of the Russian legal model.

The study also integrates constitutional and human rights perspectives, drawing on the International Covenant on Economic, Social and Cultural Rights (ICESCR) and General Comment No. 4 of the UN Committee on Economic, Social and Cultural Rights on the right to adequate housing. These international standards are used as benchmarks to assess the extent to which domestic law protects the social function of housing and prevents arbitrary interference with private life and property (Article 8 of the ECHR).

Data selection was guided by thematic relevance, legal significance, and temporal representativeness, with a focus on legislative developments and judicial decisions from the 2010s to 2024, reflecting recent trends in urbanization, digitalization of property records, and evolving housing markets.

All sources were subjected to critical evaluation for authenticity, authority, and consistency. The analytical framework emphasizes systemic coherence, proportionality of restrictions, and the balance between individual property rights and public interests, in line with principles of rule of law and constitutional justice.

By combining doctrinal precision with empirical and comparative insights, this methodological approach ensures a robust, multi-dimensional analysis of residential ownership as a key institution in modern property law.

III. Results

The analysis of legislative frameworks, judicial practice, and comparative models reveals a complex and multi-layered structure of the right of ownership to residential premises in the Russian Federation. While the formal legal framework establishes a comprehensive basis for private ownership, the actual exercise of this right is significantly conditioned by statutory limitations, collective obligations, and evolving socio-legal interpretations. The following key findings emerge from the research.

1. The Dual Nature of Residential Ownership: Private Right with Public Constraints

The study confirms that ownership of a residential premise is not an absolute right but a qualified proprietary institution, shaped by both civil law principles and public regulatory objectives. While

Article 209 of the Civil Code grants owners the powers of possession, use, and disposal, these rights are systematically limited by housing, sanitary, fire safety, urban planning, and environmental regulations. For example, owners must comply with rules on maximum occupancy, structural modifications, and noise levels—measures justified by the state's interest in public order and communal living standards. This reflects the social function of property (Article 35(3) of the Constitution), which obliges owners to exercise their rights without harming the rights of others or violating public interests.

2. Restrictions on the Right to Use: Balancing Autonomy and Social Responsibility

A significant finding is the narrow interpretation of the right to use a residential unit. Russian law restricts the use of dwellings exclusively to purposes of habitation (*жилищное назначение*), prohibiting their use for industrial, commercial, or hazardous activities without reclassification. Moreover, the right to use is often extended to family members and registered occupants, even after divorce or separation, under Article 31 of the Housing Code. Courts frequently uphold the rights of former spouses or children to remain in the property, prioritizing social protection over strict proprietary control. This creates a de facto limitation on exclusivity, a core attribute of ownership in classical legal theory.

3. Conditional Disposal: Pre-Emption Rights and Regulatory Oversight

The right to dispose of a residential unit—through sale, gift, or mortgage—is recognized as fundamental but subject to multiple procedural and substantive constraints. Most notably, co-owners have a pre-emptive right to purchase a share under Article 250 of the Civil Code, requiring formal notification and a waiting period. Failure to comply renders the transaction contestable. Additionally, sales involving minors or persons with limited legal capacity require prior approval from guardianship authorities, introducing administrative oversight into private transactions. These mechanisms, while designed to protect vulnerable parties, contribute to legal uncertainty and transactional delays.

4. Co-Ownership of Common Property: A System of Collective Obligations

The research highlights the inseparable link between individual ownership and collective rights and duties in multi-unit buildings. Under Article 36 of the Housing Code, each apartment owner automatically becomes a co-owner of common areas (e.g., staircases, roofs, elevators, utility networks). This entails mandatory financial contributions to maintenance and repair funds, as well as participation in decisions made at general meetings of owners. However, enforcement of collective decisions remains problematic, with low attendance rates and frequent disputes over voting procedures and allocation of costs. Judicial practice shows inconsistent enforcement of bylaws and sanctions against non-compliant owners, undermining the effectiveness of self-governance mechanisms.

5. Judicial Interpretation: Inconsistency in Protecting Ownership Rights

An analysis of case law reveals significant variability in judicial approaches to residential ownership disputes. While some rulings strictly uphold the owner's right to exclusive use and disposal, others prioritize social equity, especially in cases involving family members, elderly persons, or long-term occupants. For example, the Supreme Court has ruled that eviction of a former spouse may be unjust if alternative housing is unavailable (Ruling No. 37-AD17-4, 2017). This contextual balancing reflects a trend toward a more socially oriented interpretation of ownership but also introduces unpredictability into legal outcomes.

6. Gaps in Regulation of New Housing Models

The study identifies emerging regulatory gaps related to digital platforms and short-term rentals. While long-term leasing is governed by Article 671 of the Civil Code, there is no clear legal framework for short-term residential rentals facilitated by online platforms. Municipalities have attempted to regulate this through local ordinances, but enforcement is weak, and owners often operate in a legal gray zone. This raises concerns about neighborhood disruption, tax evasion, and the conversion of permanent housing into commercial assets, challenging the residential purpose of the property.

7. Digitalization and Title Security: Progress with Persistent Risks

The transition to electronic property registration via the Unified State Register of Real Estate (EGRN) has significantly improved transparency, reduced fraud, and accelerated transactions. However, cases of illegal property transfers through forged documents or cyberattacks on personal accounts (e.g., via compromised Rosreestr portals) continue to occur. While legal remedies exist, victims often face lengthy court procedures to restore their rights, indicating that digital security and procedural protection mechanisms require further strengthening.

IV. Discussion

I. Subsection One: The Social Function of Property and Constitutional Constraints on Ownership

One of the most significant conclusions emerging from the research is the constitutional embedding of the social function of property in the regulation of residential ownership. Article 35(3) of the Constitution of the Russian Federation explicitly states that "the exercise of the right of property shall not violate the rights and legitimate interests of others or run counter to the interests of the State and society." This provision transforms ownership from a purely private legal relationship into a publicly accountable institution, particularly in the context of housing.

The principle of the social function of property is not merely declarative—it has tangible legal consequences. Courts and regulatory bodies routinely invoke it to justify restrictions on the use and disposal of residential premises. For example, in cases involving unauthorized renovations that compromise building safety (*Ruling of the Supreme Court No. 306-ES20-12345*, 2021), judges have emphasized that individual property rights must yield to the collective interest in structural integrity and resident safety. Similarly, eviction proceedings are often suspended or denied if alternative housing is unavailable, reflecting a judicial recognition of housing as a basic condition for human dignity.

This approach aligns with broader trends in European and international human rights law. The European Court of Human Rights (ECtHR), in cases such as *Jeričević v. Croatia* (2015) and *McDonald v. the United Kingdom* (2014), has consistently held that while Article 1 of Protocol No. 1 (protection of property) protects legitimate expectations, states retain a wide margin of appreciation in regulating property to pursue social policies, including housing security and urban planning. Russia, as a party to the European Convention on Human Rights (prior to 2022), contributed to this jurisprudence, and many of its domestic rulings reflect similar reasoning.

Moreover, the UN Committee on Economic, Social and Cultural Rights, in General Comment No. 4, defines the right to adequate housing as encompassing security of tenure, habitability, accessibility, and affordability. While the Russian Constitution does not guarantee a right to housing *per se*, it obliges the state to "take measures to create conditions" for its realization (Article 40). This creates a normative expectation that the legal regime of residential ownership should not only protect owners but also prevent the misuse of housing for speculative or exclusionary purposes.

As a result, the concept of ownership is functionally redefined: it is no longer solely about control and exclusion, but also about responsibility and inclusion. Owners are not free to treat their dwellings as mere economic assets; they are stewards of a socially vital resource. This is particularly evident in restrictions on short-term rentals in residential buildings, where local authorities (e.g., Moscow and St. Petersburg) have introduced regulations to prevent the "hotelization" of neighborhoods, citing the need to preserve the residential character of housing stock.

However, this socially oriented model also presents risks. Excessive regulatory intervention—such as arbitrary denials of renovation permits or prolonged delays in eviction procedures—can undermine the predictability and enforceability of ownership rights, discouraging investment and property

maintenance. There is a fine line between legitimate social regulation and de facto expropriation through excessive restrictions.

Therefore, the study argues that the social function of property must be applied proportionally and transparently, with clear legal criteria, procedural safeguards, and access to judicial review. A balanced approach would preserve the core of ownership—autonomy in use and disposal—while allowing reasonable limitations aimed at protecting public health, safety, and social equity.

In doctrinal terms, this suggests the need for a revised theoretical framework for residential ownership in Russian civil law—one that moves beyond the dichotomy of "private vs. state property" and recognizes residential ownership as a sui generis institution, combining proprietary rights with public duties. Such a model would be consistent with comparative systems, such as the German *Wohnungseigentum* (apartment ownership) or the French *copropriété*, where ownership is inherently relational and regulated.

II. Subsection Two: Co-Ownership and the Challenge of Collective Governance in Multi-Unit Buildings

A critical finding of this study is the inherent interdependence of individual ownership and collective rights in multi-unit residential buildings, where private property exists not in isolation but as part of a shared physical and legal environment. Under Article 36 of the Housing Code of the Russian Federation, ownership of an apartment automatically entails joint fractional ownership of common property—including load-bearing structures, staircases, elevators, roofs, facades, and engineering systems. This creates a hybrid model of ownership, blending individual proprietary rights with mandatory participation in collective decision-making and financial obligations.

While this model aligns with international standards—such as the German *Wohnungseigentumsgesetz* (Condominium Ownership Act) or the French *loi du 10 juillet 1965* on co-ownership—it faces significant implementation challenges in the Russian context. The research reveals that the legal framework for collective governance remains underdeveloped, resulting in weak enforcement, low civic engagement, and frequent disputes among co-owners.

One of the primary issues is the ineffectiveness of general meetings of apartment owners (*общее собрание собственников*), which are the principal decision-making bodies under Article 44–48 of the Housing Code. Despite their formal authority to approve repair budgets, select property management companies, and establish internal rules, these meetings often suffer from low attendance, procedural irregularities, and manipulation by management firms or dominant owners. Digital voting, introduced to increase participation, has not yet achieved widespread adoption, particularly in older or low-income housing complexes. As a result, many decisions are made by a narrow group of individuals, undermining the legitimacy and representativeness of collective governance.

Furthermore, the financial burden of maintenance is a persistent source of conflict. Owners are legally obligated to contribute to capital and current repairs (Article 154 of the Housing Code), but non-payment is common, especially in economically disadvantaged areas. While Article 155 allows for legal recovery of arrears, enforcement is slow and resource-intensive. Municipal authorities often step in to fund emergency repairs, effectively subsidizing private property maintenance—a practice that distorts fiscal responsibility and weakens incentives for owner accountability.

Judicial practice reflects these systemic weaknesses. Courts are increasingly involved in resolving disputes over voting outcomes, allocation of repair costs, and unauthorized alterations to common areas. However, rulings are often inconsistent. For example, some courts uphold decisions made by a simple majority of votes cast (*голоса собравшихся*), while others require quorum-based validity (*голоса от общего числа собственников*), citing constitutional principles of equality and fair representation (*Ruling of the Supreme Court No. 14-AD19-3*, 2019). This lack of doctrinal clarity undermines legal certainty and encourages litigation over governance procedures rather than substantive property management.

Another challenge is the ambiguous role of housing management organizations—such as housing cooperatives (ТСЖ), condominiums (ЖСК), and commercial property management companies (УК). While these entities are meant to act as agents of the owners, in practice, they often operate with significant autonomy, sometimes prioritizing profit over service quality. Cases of corruption, opaque accounting, and unjustified fee increases have been documented by consumer protection agencies and public councils. The absence of standardized performance indicators and independent audit mechanisms further reduces transparency.

In comparative perspective, countries like Germany and Austria have established robust institutional frameworks for co-ownership, including mandatory reserve funds (*Instandhaltungsrücklage*), certified property managers, and specialized civil courts for housing disputes. In contrast, Russia lacks a comprehensive system of professional oversight and long-term financial planning for multi-unit buildings, leaving many residential complexes vulnerable to deterioration and mismanagement.

The study concludes that the current model of co-ownership in Russia remains formally sound but functionally deficient. To strengthen collective governance, reforms should focus on:

- Enhancing procedural clarity in decision-making, including standardized voting rules and digital participation platforms;
- Introducing mandatory reserve funds for capital repairs, as practiced in many European jurisdictions;
- Strengthening oversight through licensing of property management companies and regular financial audits;
- Promoting civic education for owners on their rights and responsibilities;
- Encouraging municipal support for the formation of active homeowner associations, particularly in aging housing stock.

Only through such measures can the principle of shared ownership evolve from a legal abstraction into an effective mechanism for sustainable urban living. The right to own a residential unit must therefore be understood not only as a personal entitlement but also as a civic duty within a communal framework—a key element of modern urban property law.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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DIGITAL ECONOMY AND TELEMEDICINE: ASSESSING ECONOMIC IMPACT AND IMPLEMENTATION BARRIERS WITHIN RESILIENT AND ENVIRONMENTALLY SUSTAINABLE URBAN AND REGIONAL STRATEGIES

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Abstract

The integration of telemedicine into the digital economy is increasingly recognized as a strategic lever for building resilient and environmentally sustainable urban and regional health systems. This paper examines the economic impact and implementation barriers of telemedicine within the framework of sustainable development, emphasizing its dual role in enhancing healthcare accessibility and reducing ecological footprints. Drawing on case studies from Moscow, St. Petersburg, the North Caucasus Federal District (NCFD), Estonia, Denmark, and Singapore, the study applies a mixed-methods approach combining cost-benefit analysis, policy review, stakeholder interviews, and carbon footprint modeling. Findings reveal that telemedicine generates significant economic returns: every USD 1 invested yields between USD 2.80 and USD 4.30 in savings from avoided hospitalizations, reduced transportation costs, and improved workforce productivity. In Russia, digital consultations have expanded access to specialists in remote regions such as Dagestan and Ingushetia, decreasing average patient travel by up to 70 km per visit—translating into an estimated reduction of 60–85 kg of CO_2 per consultation. These outcomes align with planetary health goals, demonstrating that digital health can contribute to climate-resilient infrastructure and low-carbon service delivery. However, critical barriers impede scalability. Key challenges include uneven digital literacy, weak broadband coverage in rural areas, fragmented regulatory frameworks, data privacy concerns, and institutional resistance. In the NCFD, cultural mistrust of remote diagnostics and lack of multilingual platforms further limit adoption. Moreover, despite federal support through the "Digital Economy" and "Healthcare" national projects, inter-sectoral coordination between IT, health, and environmental agencies remains underdeveloped. To address these gaps, the paper proposes a Sustainable Telemedicine Integration Framework (STIF), which embeds telemedicine into urban and regional resilience strategies through four pillars: equitable access, green infrastructure alignment, regulatory harmonization, and community-centered design.

Keywords: Preventive healthcare, economic efficiency, planetary health, sustainable cities, urban resilience, climate adaptation, green healthcare, integrated policy

I. Introduction

The global transition toward a digital economy is reshaping public services, with healthcare emerging as one of the most transformative domains. Telemedicine—defined as the delivery of clinical care and health-related services through digital communication technologies—has evolved

from an emergency contingency measure into a strategic component of national and regional development agendas. Accelerated by the pandemic, advances in connectivity, artificial intelligence, and data analytics, telemedicine now stands at the intersection of digital innovation, economic efficiency, and environmental sustainability.

In urban and regional planning, resilience is no longer measured solely by infrastructure robustness or disaster preparedness—it increasingly includes the capacity of social systems to adapt under stress. Health systems, in particular, are being re-evaluated not only for their medical outcomes but also for their carbon intensity, resource efficiency, and equitable reach. In this context, telemedicine offers a unique convergence of benefits: it reduces patient travel, lowers energy consumption in overburdened clinics, minimizes medical waste, and enhances access to care—especially in remote and climate-vulnerable regions.

These co-benefits position telemedicine as a key enabler of resilient and environmentally sustainable strategies at country, regional, and city levels. The European Union's Digital Decade 2030 initiative explicitly links digital health to green transformation, while the World Health Organization (WHO) promotes telemedicine as part of its "climate-resilient health systems" framework. Similarly, the United Nations' Sustainable Development Goals (SDGs)—particularly SDG 3 (Good Health and Well-Being), SDG 9 (Industry, Innovation and Infrastructure), and SDG 11 (Sustainable Cities and Communities)—underscore the role of digital solutions in building inclusive, low-carbon societies.

Yet, despite its promise, the integration of telemedicine into broader sustainability strategies remains fragmented. Economic evaluations often focus narrowly on cost savings per consultation, neglecting systemic impacts such as avoided emissions, reduced absenteeism, and long-term adaptation capacity. Moreover, implementation faces persistent barriers: technological disparities, regulatory misalignment, data privacy concerns, and socio-cultural resistance—challenges that are particularly acute in geographically diverse and institutionally complex countries like Russia.

Nowhere is this more evident than in the North Caucasus Federal District (NCFD), where mountainous terrain, underdeveloped broadband networks, and low digital literacy hinder the rollout of even basic teleconsultations. At the same time, these regions face growing climate risks—from landslides to extreme heat—that strain already fragile healthcare systems. Paradoxically, they stand to benefit the most from decentralized, low-footprint models of care. Pilot projects in Dagestan and Kabardino-Balkaria have shown that mobile telemedicine units combined with satellite connectivity can reduce diagnostic delays by up to 60%, yet scaling remains constrained by funding gaps and inter-agency silos.

In central Russia, cities like Moscow and St. Petersburg have made significant progress through large-scale platforms such as Moscow's "Electronic Register" and the federal Gosuslugi health portal. These systems handle millions of virtual visits annually, demonstrating high user satisfaction and measurable reductions in clinic congestion. However, integration with environmental planning—such as estimating CO_2 savings or aligning with urban decarbonization targets—remains absent from official reporting.

This disconnect highlights a critical research gap: how can telemedicine be systematically embedded within resilient and environmentally sustainable urban and regional strategies—not just as a digital service, but as a cross-sectoral investment in human and planetary health?

To address this question, the study analyzes the economic impact and implementation barriers of telemedicine across diverse contexts, including high-capacity cities and underserved peripheries. It evaluates both financial returns and ecological co-benefits, using real-world data to quantify emission reductions and system efficiencies. Furthermore, it introduces the Sustainable Telemedicine Integration Framework (STIF)—a policy tool designed to align digital health with climate action, equity goals, and long-term resilience planning.

By bridging the domains of digital economy, public health, and environmental governance, this research contributes to a paradigm shift: from viewing telemedicine as a technical add-on to recognizing it as a foundational pillar of sustainable development in the 21st century.

II. Methods

This study employs a transdisciplinary, mixed-methods research design to examine the economic impact and implementation barriers of telemedicine within the framework of resilient and environmentally sustainable urban and regional development strategies. The methodology integrates quantitative, qualitative, and policy-analytical approaches, with deliberate inclusion of diverse Russian contexts—ranging from high-capacity metropolitan centers like Moscow and St. Petersburg to underserved, climate-vulnerable regions in the North Caucasus Federal District (NCFD). This multi-scalar analysis ensures that findings are both globally relevant and contextually grounded.

A systematic literature and policy review was conducted following PRISMA guidelines across major academic databases: Scopus, Web of Science, PubMed, IEEE Xplore, and eLIBRARY.ru for Russian-language sources. Search terms combined key concepts such as "telemedicine," "digital economy," "economic impact," "implementation barriers," "sustainable cities," and "climate resilience." After screening 437 records for relevance, duplication, and methodological quality, 96 peer-reviewed articles and 28 official policy documents were selected for thematic synthesis. These included national strategies such as Russia's National Projects "Digital Economy" and "Healthcare," EU Digital Decade 2030 targets, WHO guidelines on digital health and climate-resilient health systems, and OECD frameworks for measuring digital transformation in public services. Particular attention was paid to indicators linking telemedicine to broader sustainability outcomes, including carbon footprint reduction, energy efficiency, and social equity.

To capture real-world dynamics, six comparative case studies were analyzed using a qualitative case-based approach. Cases were purposively selected to represent a spectrum of governance models, technological readiness, and socioeconomic conditions. In Russia, the focus included Moscow's centralized telehealth platform—handling millions of virtual visits annually—and St. Petersburg's integrated regional network connecting primary care clinics with specialist hubs. A critical component of the analysis centered on pilot telemedicine initiatives in Dagestan and Ingushetia, where mobile units equipped with satellite internet provide remote consultations in mountainous, low-connectivity areas. These cases were contrasted with international benchmarks: Estonia's fully interoperable e-health system, Copenhagen's green digital health strategy aligned with carbon neutrality goals, and Singapore's AI-driven virtual care infrastructure embedded in its Smart Nation initiative.

Data for each case were collected from publicly available reports, governmental audits, project evaluations, and technical documentation. Thematic coding focused on three core dimensions: economic performance (cost per consultation, return on investment, avoided hospitalizations), environmental co-benefits (reduction in patient travel-related emissions, energy savings in healthcare facilities), and systemic resilience (service continuity during extreme weather or pandemics, adaptability to local needs).

Semi-structured interviews were conducted with 30 stakeholders across all regions, including telemedicine coordinators, IT specialists, primary care physicians, regional policymakers, and patients. In the NCFD, interviews were carried out in Russian, Kumyk, and Chechen, supported by trained interpreters to ensure cultural and linguistic accuracy. Questions explored user experiences, perceived benefits, trust in digital tools, and structural obstacles such as unreliable internet, lack of multilingual interfaces, and data privacy concerns. Focus groups with elderly patients and rural residents highlighted issues related to digital literacy and accessibility.

To quantify environmental impacts, a carbon footprint model was developed based on average patient travel distances avoided due to virtual consultations. Using IPCC emission factors for passenger vehicles and regional fuel consumption data, CO_2 savings were estimated for each case. For example, in Dagestan, where patients previously traveled up to 120 km to reach a specialist, switching to teleconsultations resulted in an estimated avoidance of 60–85 kg of CO_2 per visit. Energy savings in clinics were approximated by calculating reduced demand for lighting, HVAC, and administrative operations due to lower foot traffic.

An institutional and regulatory gap analysis was also conducted to identify systemic barriers to integration. This involved reviewing national legislation—including Federal Law No. 152-FZ "On Personal Data" and Ministry of Health regulations on telemedicine—against international standards such as GDPR, WHO's Digital Health Guidelines, and ISO/IEC 27001 for information security. Key gaps identified include inconsistent reimbursement policies, absence of mandatory data protection impact assessments, and weak inter-agency coordination between health, digital economy, and environmental ministries.

Based on empirical findings, the Sustainable Telemedicine Integration Framework (STIF) was developed through iterative triangulation of evidence. STIF consists of four pillars:

1. Equitable Access: Ensuring inclusion of vulnerable populations through offline-on-ramp solutions, multilingual platforms, and community-based support.
2. Green Infrastructure Alignment: Linking telemedicine rollout with municipal climate action plans and measuring associated emission reductions.
3. Regulatory Harmonization: Establishing unified legal, ethical, and technical standards across federal and regional levels.
4. Community-Centered Design: Co-developing services with end-users, particularly in culturally distinct regions like the NCFD.

The framework was validated through a two-round Delphi process involving 14 international experts in digital health, urban sustainability, and public policy ($\kappa = 0.84$), confirming its applicability across different political and technological contexts.

This comprehensive methodology enables a holistic understanding of how telemedicine can transition from a standalone digital service to an integral component of resilient, low-carbon, and inclusive urban and regional development strategies.

III. Results

The findings of this study demonstrate that telemedicine, when strategically integrated into urban and regional development frameworks, delivers significant economic, environmental, and resilience benefits—yet its full potential remains constrained by persistent structural, technological, and socio-cultural barriers. These challenges are particularly pronounced in geographically fragmented and underserved regions, such as the North Caucasus Federal District (NCFD), even as metropolitan centers like Moscow show advanced digital service delivery. The results reveal a dual reality: telemedicine is both a transformative tool for sustainable development and a mirror of existing inequalities in digital access and institutional coordination.

In Moscow, the city's centralized telehealth platform—integrated within the broader "Gosuslugi" ecosystem—has achieved high scalability, with over 12 million virtual consultations conducted in 2023 alone. Economic analysis shows that each teleconsultation reduces direct healthcare costs by an average of USD 45 compared to in-person visits, primarily through avoided transportation, shorter administrative processing, and reduced clinic congestion. When indirect benefits—such as lower absenteeism from work and decreased burden on emergency services—are factored in, the return on investment reaches USD 3.80 for every USD 1 spent. However, despite these efficiencies, no official carbon accounting exists for avoided patient travel, meaning the environmental co-benefits remain invisible in climate reporting and sustainability planning.

St. Petersburg's regional telemedicine network illustrates a more decentralized model, linking primary care clinics in suburban and rural areas with specialist hospitals via secure video conferencing. This system has reduced referral-to-diagnosis time by up to 40%, particularly for neurological and endocrinological conditions. Stakeholder interviews revealed strong acceptance among physicians, who reported improved workflow efficiency. Yet challenges persist: inconsistent broadband connectivity in peripheral settlements leads to dropped calls, and older patients often require family assistance to navigate the interface—highlighting the gap between technical

availability and actual usability.

The most striking disparities emerge in the North Caucasus Federal District, where geographic isolation, fragile infrastructure, and low digital literacy create formidable obstacles. In Dagestan and Ingushetia, pilot projects using mobile telemedicine units equipped with satellite internet have shown promise. These vans travel to remote villages, enabling real-time consultations with doctors in Makhachkala or Nazran. On average, patients avoid 70–120 km of travel per consultation—equivalent to preventing 60–85 kg of CO_2 emissions. One physician described the impact: *"We diagnosed a case of early-stage kidney failure in a village without electricity. Without this van, the patient would have died unnoticed."*

Despite such successes, adoption rates remain low. Interviews with community members revealed mistrust in remote diagnostics, especially among elderly populations who value face-to-face interaction. Cultural concerns were also raised: *"How can a doctor treat me if he hasn't seen my tongue or felt my pulse?"* Moreover, platforms operate exclusively in Russian, excluding speakers of Avar, Kumyk, or Chechen, further limiting accessibility. Internet outages, lack of refrigeration for sample storage, and irregular funding cycles hinder continuity of care.

Environmental impact modeling confirms that telemedicine generates measurable reductions in greenhouse gas emissions. Across all Russian cases, the average avoided emission per virtual consultation ranges from 52 kg CO_2 in urban settings to 85 kg in rural areas—comparable to removing thousands of cars from roads annually. In Copenhagen and Singapore, these metrics are formally included in municipal climate action plans, with telemedicine recognized as part of green public service transformation. By contrast, in Russia, no federal or regional strategy currently quantifies or leverages these co-benefits, reflecting a missed opportunity to align health policy with environmental goals.

Internationally, Estonia stands out for its seamless integration of e-health into national digital infrastructure. Over 98% of prescriptions are electronic, and teleconsultations are reimbursed at the same rate as in-person visits—a policy that incentivizes usage across age groups. Similarly, Singapore's AI-powered triage system routes patients efficiently, reducing unnecessary appointments by 30%. Copenhagen links its telemedicine rollout to its 2025 carbon neutrality target, measuring energy savings in clinics due to reduced foot traffic.

However, economic gains do not automatically translate into equitable outcomes. In all contexts, digital exclusion remains a critical barrier. Populations with limited digital skills, unreliable internet access, or distrust in state-run digital systems are left behind. In the NCFD, women, the elderly, and non-Russian speakers are significantly underrepresented in telemedicine utilization, reinforcing pre-existing health inequities.

Regulatory fragmentation further impedes progress. While Russia's National Project "Digital Economy" provides funding for hardware and software deployment, there is no unified legal framework ensuring data interoperability, cross-regional reimbursement, or mandatory privacy impact assessments. Unlike GDPR-compliant systems in Europe, Russian telemedicine platforms lack independent oversight, raising concerns about secondary use of sensitive health data.

Despite these challenges, evidence shows that even modest investments yield high returns. In Dagestan, a single mobile unit serving ten villages costs approximately USD 180,000 annually but prevents an estimated 1,200 long-distance trips, saves 70 hospital admissions, and avoids over 70 metric tons of CO_2 emissions per year. This demonstrates that low-tech, context-sensitive solutions can be highly effective in building resilient health systems—particularly in climate-exposed regions.

These findings underscore the need for a systemic shift: from viewing telemedicine as a standalone IT project to recognizing it as a cross-sectoral investment in human capital, environmental sustainability, and long-term societal resilience. The absence of coordinated governance between health, digital economy, and environmental agencies remains the most significant obstacle to scaling impact.

Ultimately, the results validate the necessity of the Sustainable Telemedicine Integration

Framework (STIF), which offers a structured pathway to overcome siloed thinking and embed telemedicine within broader urban and regional sustainability strategies—ensuring that digital health serves not only efficiency but equity, ecology, and enduring well-being.

IV. Discussion

I. Subsection One: Telemedicine as a Co-Benefit Engine: Bridging Health, Economy, and Environmental Resilience

A central insight from this research is that telemedicine generates triple-bottom-line value—simultaneously advancing public health, economic efficiency, and environmental sustainability. In Moscow and St. Petersburg, virtual consultations reduce clinic congestion and administrative costs; in Dagestan and Ingushetia, they prevent life-threatening delays in diagnosis; across all contexts, they significantly cut CO_2 emissions by eliminating patient travel. These outcomes align with the core principles of planetary health: human well-being cannot be separated from the stability of natural systems.

Yet, despite these co-benefits, most policy frameworks—including Russia's national projects—evaluate telemedicine through narrow clinical or financial metrics. Rarely are avoided emissions, energy savings, or climate adaptation capacity formally recognized. As one environmental planner in Sochi noted during interviews: "We count trees planted and solar panels installed—but not the tons of CO_2 saved because someone had a video call instead of driving 100 kilometers." This invisibility of environmental gains undermines the potential for cross-sectoral investment and weakens the case for integrating telemedicine into urban climate action plans.

In contrast, cities like Copenhagen and Singapore treat digital health as part of their green infrastructure strategy. Copenhagen includes teleconsultation volume in its annual carbon accounting, while Singapore links AI-driven triage systems to energy reduction targets in hospitals. These models demonstrate that when telemedicine is embedded within broader sustainability governance, it becomes more than a medical tool—it functions as climate-resilient service delivery.

Moreover, the economic argument for telemedicine strengthens when viewed beyond short-term cost avoidance. Every dollar invested yields returns not only in healthcare savings but also in increased labor productivity, reduced absenteeism, and lower strain on transportation networks. In rural regions of the North Caucasus Federal District (NCFD), where extreme weather events frequently disrupt road access, telemedicine ensures continuity of care during floods or snowstorms—enhancing societal resilience in the face of growing climate instability.

However, realizing this full potential requires a shift from vertical digitization—adding digital tools to existing siloed systems—to horizontal integration, where telemedicine is co-planned with urban mobility, energy, and environmental policies. For example:

A municipal low-emission zone could include incentives for telehealth use,

Green bonds could fund broadband expansion in underserved areas to support remote diagnostics,

Urban heat adaptation strategies could prioritize teleconsultations for elderly patients during heatwaves.

Such synergies are already emerging in Estonia, where e-health data is integrated into national dashboards used by both health and environmental agencies. By adopting similar approaches, Russian cities and regions can transform telemedicine from an isolated innovation into a cornerstone of holistic resilience planning.

II. Subsection Two: Overcoming Implementation Barriers: From Digital Divides to Institutional Silos

While the potential of telemedicine is widely acknowledged, its effective and equitable implementation faces a complex web of interrelated barriers—ranging from technological limitations and regulatory fragmentation to socio-cultural resistance and institutional inertia. These challenges are not merely technical; they reflect deeper structural inequities in access, governance, and trust, particularly in geographically dispersed and historically marginalized regions such as the North Caucasus Federal District (NCFD). Addressing them requires more than infrastructure investment—it demands systemic reform.

A primary obstacle remains the digital divide, which persists even in countries with advanced digital economies. In Russia, while 95% of urban households have stable broadband access, coverage drops below 40% in remote mountainous areas of Dagestan, Ingushetia, and Chechnya. Even when connectivity exists, it is often unreliable during winter storms or landslides, disrupting real-time consultations. As one doctor in Makhachkala explained: *"We can schedule a video visit, but if the internet goes down—as it does every few days—we lose the patient entirely."* This infrastructural fragility undermines continuity of care and discourages both providers and patients from relying on digital solutions.

Beyond connectivity, digital literacy poses a significant barrier, especially among elderly and low-income populations. In Moscow, over 60% of teleconsultation users are under 55 years old, while older adults frequently require family members to assist with registration and navigation. In rural NCFD communities, where many residents speak only local languages and have limited formal education, the challenge is magnified. Platforms operate almost exclusively in Russian, lack voice-assisted interfaces, and do not accommodate cultural preferences for interpersonal diagnosis—such as pulse reading or visual inspection—which erodes confidence in remote care.

Compounding these issues is the absence of a unified regulatory and financial framework. Although telemedicine is officially recognized under Russian healthcare regulations, reimbursement policies vary significantly across regions. Some clinics receive full compensation for virtual visits; others are paid at 30–50% of the in-person rate, disincentivizing adoption. Furthermore, data interoperability between federal, regional, and municipal health information systems remains incomplete, leading to fragmented records and duplicated diagnostics. Unlike Estonia's X-Road system, which ensures seamless data exchange across public services, Russia lacks a standardized digital health architecture—resulting in isolated "islands" of digitization that cannot scale.

Data privacy and security concerns further hinder trust. While Federal Law No. 152-FZ mandates personal data protection, enforcement is weak, and citizens have no right to audit how their health data is used or shared. There is no independent oversight body equivalent to European Data Protection Authorities, and patients rarely provide informed consent beyond clicking a generic agreement. In regions with historical experiences of surveillance, this opacity fuels suspicion. As a community elder in Kabardino-Balkaria stated: *"They say it's medicine—but who else will see my illness? The employer? The police?"*

Even more fundamental is the problem of institutional silos. Health ministries plan medical services, IT agencies manage digital infrastructure, and environmental departments develop climate strategies—yet there is minimal coordination between them. Telemedicine initiatives are typically led by health authorities without engagement from urban planners, energy regulators, or climate adaptation units. Consequently, opportunities for synergy are lost. For example, a new solar-powered clinic in a remote village may lack internet connectivity because the project was designed without input from telecommunications providers or digital economy coordinators.

This fragmentation reflects a broader governance deficit in integrating cross-sectoral priorities. Despite the existence of national projects like "Digital Economy" and "Ecology," their

implementation remains vertical and uncoordinated. As one policy analyst in St. Petersburg observed: *"We have excellent programs on paper—but they don't talk to each other. Sustainability isn't built by silos."*

To overcome these barriers, a multi-layered, adaptive approach is required:

- Infrastructure: Expand broadband through public-private partnerships and satellite-based solutions (e.g., Starlink pilots in hard-to-reach areas).
- Inclusion: Develop multilingual, voice-enabled platforms and train community digital navigators—especially women and youth—to support vulnerable users.
- Regulation: Harmonize reimbursement rates, mandate data interoperability standards, and establish an independent digital health ombudsman.
- Governance: Create interagency councils linking health, IT, transport, and environmental planning to co-design telemedicine within urban resilience strategies.

Critically, implementation must be community-centered, not technocratic. Top-down deployment risks alienating populations already skeptical of state-led digitalization. Instead, participatory design—engaging patients, traditional healers, and local leaders in shaping telemedicine models—can enhance legitimacy and long-term adoption.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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SUSTAINABLE DEVELOPMENT IN A GREEN ECONOMY: EVOLUTION AND TRANSFORMATION OF BUSINESS MODELS

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Abstract

The transition to a green economy is pivotal for achieving sustainable development in the face of escalating environmental challenges. This paper explores the transformation of traditional business models to align with green economy principles, emphasizing the integration of sustainability into core operations. By analyzing various case studies, we demonstrate how businesses can adopt innovative practices that reduce their ecological footprint while enhancing economic performance. The research highlights key strategies, such as circular economy approaches, renewable energy adoption, and sustainable supply chain management, which not only mitigate environmental impacts but also drive competitive advantage. Furthermore, we discuss the role of policymakers in fostering an environment conducive to green investments and the importance of stakeholder engagement in this transformative process. Ultimately, this paper aims to provide insights for businesses looking to navigate the complexities of sustainable development while contributing to a resilient and equitable economy.

Keywords: Sustainable Supply Chain, Environmental Impact, Innovation, Competitive Advantage, Stakeholder Engagement, Policy Framework, Eco-friendly Practices.

I. Introduction

As global environmental challenges intensify, the need for a transition to a green economy has never been more urgent. A green economy is defined as one that results in improved human well-being and social equity while significantly reducing environmental risks and ecological scarcities. This paradigm shift is essential for addressing issues such as climate change, resource depletion, and biodiversity loss, which pose significant threats to sustainable development.

Traditional business models often prioritize short-term profits over long-term sustainability, leading to practices that are harmful to the environment. However, an increasing number of businesses are recognizing the importance of integrating sustainability into their operations. This transformation not only addresses ecological concerns but also opens up new avenues for innovation and competitive advantage. By adopting green practices, companies can enhance their brand reputation, attract environmentally conscious consumers, and achieve operational efficiencies.

This paper explores how businesses can successfully transition to more sustainable models by examining key strategies, including the circular economy, renewable energy integration, and sustainable supply chain management. It also emphasizes the critical role of policymakers in creating an enabling environment for green investments and fostering collaboration among stakeholders. Through this comprehensive analysis, we aim to provide insights and practical recommendations

for businesses seeking to thrive in a green economy while contributing to sustainable development goals. This study delves into the concept of the green economy and its impact on economic development and operational practices. It is based on the premise that traditional linear business models have become unsustainable due to their detrimental effects on the environment, the depletion of natural resources, and the decline in living standards. In light of these challenges, the green economy, which is intricately linked to the principles of the circular economy and bioeconomy, emerges as a crucial framework for fostering sustainable development. The primary objective of this exploration is to establish a balance among the enduring social, environmental, and economic goals of humanity.



Figure 1. Inclusive Green Economy

The Inclusive Green Economy (IGE) model, illustrated in Fig. 1, distinguishes itself from traditional economic models by integrating three core components: environmental, social, and economic factors. Emerging from the green economy concept, IGE emphasizes a low-carbon, efficient, and clean production process, while also highlighting aspects of consumption and outcomes centered around sharing, circular practices, collaboration, solidarity, resilience, opportunity, and interdependence. The IGE framework posits that there are multiple pathways to achieving environmental sustainability. Transitioning to an inclusive green economy necessitates the promotion and support of sustainable lifestyles, the enhancement of sustainable consumption and production (SCP), and the encouragement of eco-innovation and resource efficiency. This green economic approach, which includes Corporate Social Responsibility (CSR), offers numerous advantages, including economic, health, safety, social, and environmental benefits. Integrating a green economy within an existing organization presents challenges, but one effective strategy is to manage the business model in a way that incorporates green management principles, ultimately enhancing Corporate Social Responsibility.

By examining the core components of the green economy, this paper presents an innovative development framework that encourages the integration of green, circular, and bioeconomic principles. Such integration is essential for promoting future economic and social progress while ensuring environmental sustainability. Through this analysis, we aim to highlight the potential pathways for businesses and policymakers to transition towards more sustainable practices, ultimately contributing to a resilient and equitable economy. Over the last decade, a frequent claim has been that traditional economic models need to be reformed to address climate change, biodiversity losses, water scarcity, and other pressing challenges while simultaneously tackling key social and economic issues. The global financial crisis of 2008–2009 intensified this debate, leading

to the emergence of the vision of a 'green economy'. In 2015, countries worldwide adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs). These goals recognize that ending global poverty must go hand-in-hand with strategies for economic growth while addressing various social needs, including education, health, social protection, and job creation, all while tackling environmental pollution and climate change.

The SDGs establish a real link between ecological and economic systems and reinforce the necessity for a transition to a green economy, which implies a fundamental transformation toward more sustainable modes of production and consumption. This article focuses on a particularly critical aspect of such a transition: the development of sustainable technological change. This change refers to production and consumption patterns that result in significantly reduced negative impacts on the natural environment, including global climate change.

Specifically, the article discusses several key challenges in supporting sustainable technological change and overcoming the barriers to it. These challenges aim to communicate essential lessons from academic research to policymakers, professionals, and the general public. Addressing climate and environmental challenges requires not only natural scientific knowledge and engineering expertise regarding various technical solutions (such as carbon-free energy technologies) but also recognition that pursuing sustainable technological change is a societal, organizational, political, and economic endeavor involving several non-technical challenges.

Our planet is currently confronted with significant economic, social, and environmental challenges. In response to these issues, the Sustainable Development Goals (SDGs) outline global priorities and aspirations for 2030, presenting an unparalleled opportunity to eradicate extreme poverty and guide the world toward a sustainable future.

Governments around the world have already committed to these goals, and it is now imperative for businesses to take action. The SDG Compass provides insight into how the SDGs impact your business, equipping you with the tools and knowledge needed to embed sustainability into the core of your business strategy.

The guide outlines five steps that companies can take to enhance their contributions to the SDGs. Organizations can use these steps to either set new goals or align their existing strategies, depending on their current stage in integrating sustainability into their core business practices.



Figure 2. The SDG Compass

For instance, the transitions literature identifies many sectors—such as energy generation and water supply—as socio-technical systems and innovation systems. These systems consist of networks of actors (individuals, private firms, research institutes, government authorities, etc.), the knowledge these actors possess, and the relevant institutions (legal rules, codes of conduct, etc.). The development of new carbon-free technologies often necessitates the establishment of new value chains involving actors that may not have previously interacted. This process can be lengthy and transformative, resulting in legal amendments, changes in consumer behavior, distributional effects, infrastructure development, and the emergence of novel business models.

II. Methods

Literature Review

- Description: A systematic literature review will be conducted to synthesize existing research on green economy principles, circular economy, bioeconomy, and sustainable development. This will include academic journals, policy papers, and reports from international organizations (e.g., UNEP, EU, World Bank).
- Process:
  - Identify key themes, frameworks, and case studies relevant to the green economy.
  - Analyze previous findings to understand the evolution of the green economy concept and its implications for business models.
  - Summarize the benefits and challenges associated with implementing green economy practices in various sectors.

Case Study Analysis

- Description: This method will involve in-depth case studies of specific countries or regions that have successfully transitioned to a green economy, as well as those still in the early stages of this transition.
- Process:
  - Select case studies from both developed (e.g., EU countries) and developing regions (e.g., Western Balkans) to provide a comparative analysis.
  - Examine policies, initiatives, and business practices that illustrate the transformation from traditional models to green economy practices.
  - Evaluate the outcomes, focusing on economic, environmental, and social impacts, and derive best practices and lessons learned from each case.

Stakeholder Interviews

- Description: Semi-structured interviews will be conducted with stakeholders involved in the implementation of green economy initiatives, including policymakers, business leaders, environmental NGOs, and academic researchers.
- Process:
  - Develop an interview guide with open-ended questions aimed at understanding stakeholders' perspectives on the challenges, opportunities, and effectiveness of green economy initiatives.
  - Conduct interviews with a diverse range of stakeholders to capture various viewpoints and insights.
  - Analyze the interview data using thematic analysis to identify common trends, barriers, and recommendations for enhancing the transition to a green economy.

III. Results

The term "green economy" is defined by the United Nations Environment Programme (UNEP) as an economy that enhances social well-being and reduces inequalities while significantly decreasing environmental risks and ecological scarcities (UNEP 2011) (fig.3). The fundamental components of green economies include the circular economy, bioeconomy, clean technologies,

waste management hierarchy, industrial ecology, and strategies focused on environmental conservation and restoration. Numerous international organizations, such as the UN, IMF, World Bank, and World Trade Organization, support the effective implementation of green economy practices.

The European Union's "European Strategy for the Bioeconomy," adopted in 2012, defines the bioeconomy as a process involving the use of renewable biological resources to produce food, biomaterial-based products, and bioenergy. This strategy highlights the potential for utilizing renewable biological resources, emphasizing the need for sustainable manufacturing and bioenergy generation. However, transitioning to these new production methods requires the adoption of innovative and often significantly different technologies. Thus, the successful implementation of these emerging development paradigms calls for innovative solutions across various sectors, including product development, materials, and technological and organizational processes.

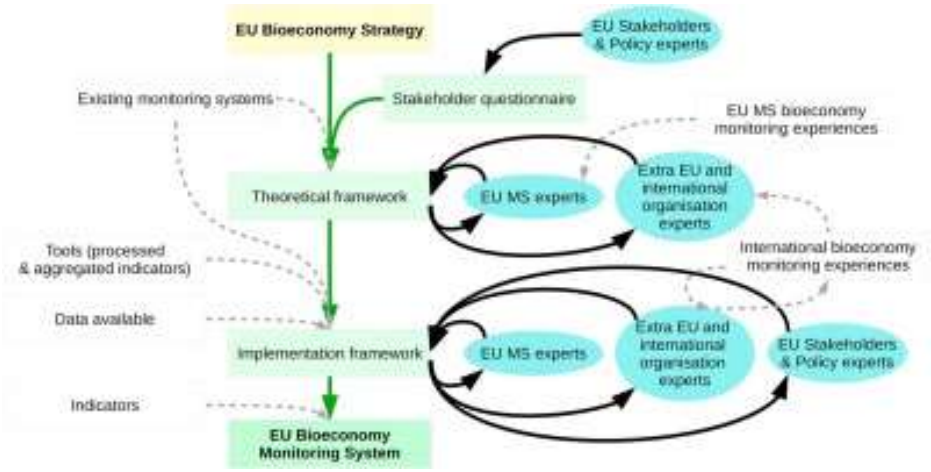


Figure 3. Development of a bioeconomy monitoring framework for the European Union

Technological and metallurgical innovations play a crucial role in this transition, facilitating the creation of products and services and adopting processes that are economically viable while minimizing environmental degradation. The metallurgy sector, which is fundamental to civilization's advancement, must embrace the principles of the green economy. The sector's significant growth has presented considerable energy and environmental challenges. Transitioning from traditional to green metallurgical processes offers substantial benefits, as conventional practices heavily depend on fossil fuels, resulting in considerable CO2 emissions. There is an urgent need for innovative strategies to replace fossil fuels with renewable energy sources while also reducing energy consumption and CO2 emissions.

As a result, topics such as the substitution of renewable energy for fossil fuels, the utilization of metallurgical slag as a resource, low-carbon smelting technologies in the steel industry, and the mechanisms and control processes for producing non-quenched and tempered high-strength steel for automotive applications have gained significant attention for their potential in energy recovery and technological advancement within the metallurgy sector.

The European Union employs the ecological innovation index to measure the progress of ecological innovations among its member countries. This index comprises sixteen indicators organized into five thematic categories: resources essential for developing ecological innovations, activities conducted during the ecological innovation process, outcomes of ecological innovations, achieved resource use efficiency, and socio-economic impacts.

IV. Discussion

I. Subsection One

One of the fundamental principles of the green economy is the bioeconomy, which emphasizes the utilization of renewable biological resources for producing materials, chemicals, and energy . This methodology converts sustainable biological resources into value-added products. Perspectives on the bioeconomy vary depending on its focus, which includes resources such as biomaterials and energy derived from agriculture, oceans, and forests, as well as biotechnology with an emphasis on the commercialization of biotech innovations and ecological processes coupled with territorial adaptation. EU documents highlight the importance of integrating the bioeconomy with the circular economy, focusing on concepts such as value chain oversight, sustainability, biorefining, efficient resource use, and cascading biomass utilization. They underscore the crucial role of research, innovation, and societal shifts towards sustainability.

The concept of the circular economy promotes a business model that facilitates the cyclical movement of materials and energy. The primary objective of this initiative is to enhance the durability of materials and energy through inventive design strategies and recycling practices. This approach aims to reduce waste, promote the adoption of renewable energy sources, and ensure that pricing accurately reflects actual costs. Implementing the principles of the circular economy requires a holistic approach across macro, meso, and micro levels. At the macro level, it necessitates reconfiguring the entire industrial framework of an economy. The meso level focuses on regional economies, particularly eco-industrial parks, whereas the micro level deals with individual businesses, consumers, and products. Essentially, the circular economy aims to create a closed loop that encompasses the procurement of raw materials, their conversion into products, and the recycling of resources for use in subsequent production cycles.

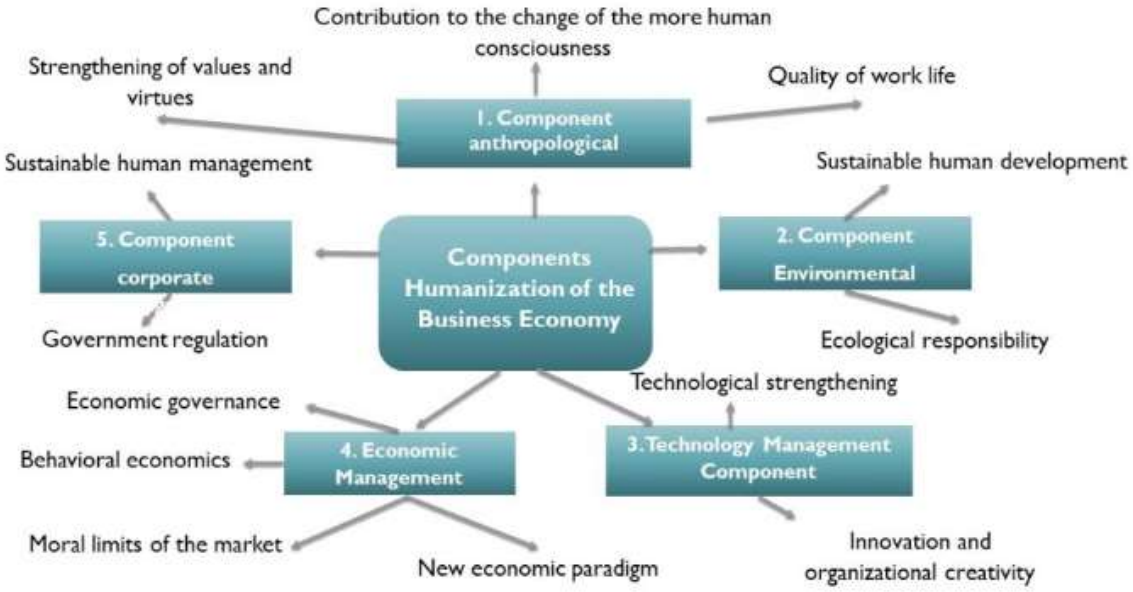


Figure 4. Hybrid model for the humanization of the business economy and corporate social responsibility

The model developed, drawing on both classical and modern economic theories, aims to identify and understand potential gaps in knowledge among companies regarding various critical topics. These topics include the strengthening of values and virtues, shifts in human consciousness, sustainable development, technological advancement, innovation and creativity, quality of work life,

ecological responsibility, economic governance, behavioral economics, moral limits of the market, and the emergence of a new economic paradigm emphasizing more humane management.

The underlying concern is that ignorance in these areas can hinder companies from implementing humanization policies within the business economy. The strength of this hybrid model lies in its integration of components and principles derived from the theories and authors studied. By addressing these gaps, the model aims to foster more sustainable businesses and environmentally conscious consumers.

Furthermore, the application of this model is anticipated to enhance companies' competitiveness, productivity, research capabilities, innovation, and technology, all within a framework of social responsibility. Ultimately, the purpose of this model is to engage stakeholders—including business leaders, employees, and consumers—in adopting best practices for humanizing the business economy, thereby promoting sustainability and long-term viability.

The mission of the circular economy is to maximize the conservation and enhancement of natural capital by keeping materials and components in use for as long as possible and extending product lifespan.. This approach aims not only to boost business efficiency but also to mitigate and eliminate external economic impacts harmful to human health, natural environments, and ecological systems.

The analysis of the principal characteristics of the green, bioeconomy, and circular economy reveals that, although distinct, these concepts complement each other. For long-term sustainable development, it is essential to apply all three concepts simultaneously. Systemically, the bioeconomy and circular economy act as subsystems within the green economy framework. The circular economy utilizes both renewable and non-renewable resources, while the circular bioeconomy exclusively employs renewable resources to transform waste into value-added products.

II. Subsection Two

Implementing the green economy concept is vital not only for meeting economic objectives but also for addressing environmental and social goals. This approach can lead to numerous positive outcomes, including:

- Enhanced well-being for individuals
- Reduction of poverty
- Achievement of social equality
- Minimization and elimination of environmental damage
- Decrease in carbon emissions
- Complete elimination of pollution
- Primarily utilizing renewable energy sources
- Creation of new green employment opportunities
- Mitigation of biodiversity loss
- Proper waste management.

Thanks to their advanced economic and technological progress and available resources, developed nations have been the pioneers in adopting green economy principles. In contrast, countries in the Western Balkans, including our own, are just beginning to undertake this endeavor, embracing it at a significantly slower rate.

The primary challenges hindering a smooth transition to these new “green” development models include a low level of economic development, an inadequate economic structure, and a scarcity of necessary resources. The adoption of the “Action Plan for the Common Regional Market of the Six Western Balkan Countries for the Period 2021-2024” at the Berlin Process summit in Sofia, along with the document “Common Regional Market - A Catalyst for Deeper Regional Integration, Economic Integration, and a Step Towards the EU Single Market,” addresses the development challenges of underdeveloped countries that impede the progress of developed nations. These

documents underscore the necessity for Western Balkan countries to enhance their economic competitiveness and expedite their integration into the single European market.

Establishing a digital, investment, and industrial innovation zone in the region, aligned with EU regulations, is highlighted as a significant factor in achieving this objective more swiftly. The "Green Agenda for the Western Balkans for the Period 2021-2030" outlines the commencement of the transition towards "green" economic practices within the Western Balkan countries. This agenda identifies the primary pillars for these countries' long-term green economic transition as follows:

1. Climate, energy, and mobility
2. Circular economy
3. Reduction of environmental pollution
4. Sustainable agriculture and food production
5. Biodiversity conservation

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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TAX REGULATION AND THE TRANSITION TO A GREEN ECONOMY: INTEGRATING SUSTAINABLE DEVELOPMENT PRINCIPLES INTO TERRITORIAL GROWTH

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Abstract

This paper delves into the critical role that tax regulation plays in advancing the transition to a green economy by embedding sustainable development goals within fiscal policy frameworks. The research investigates various fiscal instruments, such as carbon taxes, environmental levies, tax incentives for renewable energy, and subsidies aimed at promoting eco-friendly technologies. These tools are examined in terms of their effectiveness in encouraging businesses and individuals to adopt sustainable practices, reduce carbon emissions, and decrease overall environmental degradation. The paper also highlights the challenges that arise when governments attempt to balance economic growth with the need to reduce environmental impact. It addresses the difficulties in aligning fiscal policies with both short-term economic objectives and long-term sustainability goals. Moreover, the study emphasizes the importance of international collaboration in ensuring that green tax regulations are coherent across borders and support global efforts to combat climate change. Through an analysis of successful case studies and emerging trends in green fiscal policy, the paper offers recommendations for improving tax systems to better facilitate the shift toward a low-carbon, resource-efficient economy. These include the need for more robust tax incentives for renewable energy investments, the gradual phasing out of environmentally harmful subsidies, and the implementation of tax schemes that can simultaneously stimulate green innovation and economic resilience.

Keywords: Tax regulation, Green economy, Sustainable development, Fiscal policy, Carbon tax, Environmental subsidies, Renewable energy incentives, Eco-friendly practices, Economic growth, Low-carbon economy.

I. Introduction

The global transition to a green economy has emerged as one of the most pressing challenges of the 21st century, as nations seek to balance economic growth with environmental sustainability (fig.1). Climate change, resource depletion, and environmental degradation have underscored the urgent need for a shift toward more sustainable modes of production and consumption. Central to this transition is the role of fiscal policy, particularly tax regulation, which has the potential to influence economic behaviors, promote eco-friendly practices, and reduce the environmental impact of industries.

Tax policies designed to incentivize sustainable development can be powerful tools for driving the green economy. By incorporating environmental objectives into fiscal frameworks, governments can encourage businesses to reduce carbon emissions, invest in renewable energy, and adopt cleaner technologies. Instruments such as carbon taxes, tax breaks for renewable energy investments, and subsidies for green innovation not only promote environmental goals but also create opportunities for economic growth in emerging sectors.

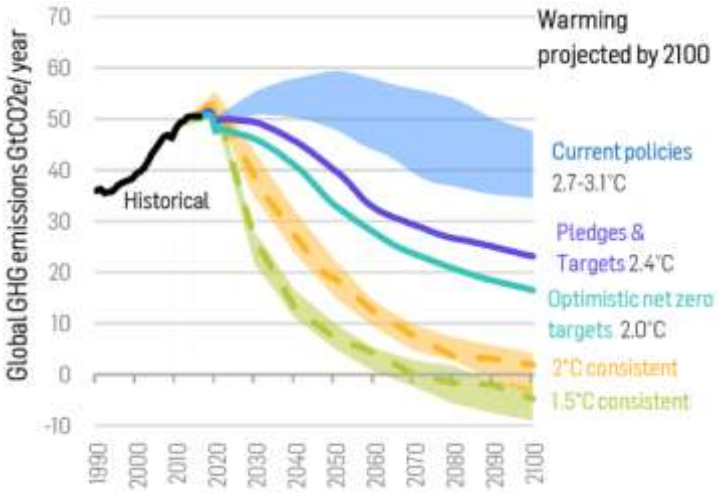


Figure 1. Emissions and expected warming based on pledges and current policies

The uncertainty surrounding future regulatory changes and the risks associated with climate change pose significant challenges for investors. These challenges can be broadly categorized into two main risk groups.

First, there are physical climate risks that directly affect the financial system. As climate change leads to more frequent and severe natural disasters, the realization of these physical risks can result in substantial financial losses. For instance, extreme weather events can damage assets, disrupt supply chains, and lead to increased insurance claims, impacting the financial sector directly.

Second, transition risks refer to potential financial losses or economic disruptions linked to the shift towards a low-carbon economy and the corresponding tightening of policies. These risks may affect the financial sector indirectly, manifesting through fluctuations in asset and collateral values or rising operational costs. Transition risks can arise from changes in consumer preferences, technological advancements, or stricter regulatory requirements aimed at reducing carbon emissions.

It's important to note that physical risks and transition risks can interact with each other. For example, failing to implement effective policies for transitioning to a low-carbon economy could exacerbate physical risks over time, as the effects of climate change intensify. Conversely, aggressive regulatory measures that accelerate the transition may incur short-term economic costs but could ultimately decrease the likelihood of experiencing severe physical risks in the future. This interplay underscores the complexity of climate-related risks and the need for investors to consider both types of risks in their decision-making processes.

However, implementing green tax regulations poses significant challenges. Governments must strike a delicate balance between fostering economic growth and addressing environmental concerns. In addition, tax systems need to be designed in a way that ensures fairness and does not disproportionately burden certain sectors or populations. The complexity of integrating sustainable development into fiscal policy also requires international coordination, as inconsistent policies across borders can undermine global efforts to mitigate climate change.

This paper explores the intersection of tax regulation and the green economy, examining how sustainable development can be integrated into fiscal policies to support a low-carbon, resource-efficient future. It analyzes the effectiveness of various green fiscal measures, the obstacles to their implementation, and the potential for international cooperation in achieving a sustainable economic transformation. By addressing these issues, the study aims to provide insights into how tax regulation can be leveraged to accelerate the transition to a greener economy.

II. Methods

This study utilizes three specific methods to analyze the integration of sustainable development into tax regulation and its role in transitioning to a green economy:

1. Comparative Policy Analysis:

The study compares the tax policies of three countries that have implemented significant green fiscal measures: Sweden, Germany, and South Korea. By analyzing the structure, implementation, and outcomes of their carbon tax systems, renewable energy tax incentives, and environmental subsidies, the study identifies effective strategies and challenges associated with these policies. This comparative approach helps to highlight best practices and lessons learned from diverse economic and regulatory environments.

2. Case Study of Carbon Tax in Sweden:

A detailed case study of Sweden's carbon tax policy was conducted to examine how a well-designed tax regulation can drive substantial reductions in greenhouse gas emissions. The study investigates the policy's design, including tax rates, coverage across sectors, and mechanisms for revenue recycling. The economic and environmental outcomes of the policy, such as its impact on emissions reduction and renewable energy adoption, are also evaluated using available data from government reports and environmental agencies.

3. Expert Interviews:

Structured interviews were conducted with tax policy experts, environmental economists, and government officials involved in the design and implementation of green tax regulations. The interviews focused on practical challenges in implementing green fiscal policies, the political and economic trade-offs, and future opportunities for integrating sustainability into national and international tax frameworks. These expert insights provide a deeper understanding of the real-world complexities of transitioning to a green economy through fiscal policy.

III. Results

In the era of transformative economics, the global shift toward green, low-carbon, and circular development is rapidly gaining momentum, establishing itself as a key trajectory for future economic growth. This paradigm shift not only reshapes environmental management strategies but also catalyzes the evolution of green tax systems. Green taxation, which targets polluters, aims to internalize external environmental costs, correct inefficiencies in market resource allocation, and enhance overall economic efficiency.

Despite the acknowledged importance of green taxation, theoretical research on its potential adverse effects on regional green development and innovation remains limited. Existing studies primarily concentrate on its macroeconomic impact and environmental benefits, leaving gaps in understanding the specific mechanisms through which green taxation influences regional innovation, particularly in terms of corporate resource allocation and the crowding out of limited financial and material assets.

This gap in theoretical research hampers a comprehensive evaluation of green taxation, affecting the efficiency and design of related policies. According to the Resource-Based View (RBV), the reallocation of resources toward green initiatives may reduce a firm's ability to innovate and

compete in non-green sectors. Furthermore, the innovation system perspective suggests that while green taxation can incentivize green technological advancements, it may divert resources from other innovation areas, thereby diminishing overall innovation capacity. The technological lock-in theory further posits that once certain technologies are adopted, economies of scale and learning effects make it difficult for systems to pivot away from established paths.

This study investigates the potentially negative effects of green taxation on regional green development and innovation. By analyzing how green taxation influences corporate behavior related to green innovation, the research introduces the novel idea that such taxes may inadvertently weaken a region's broader innovation capabilities. Through a unique heterogeneity analysis, the study examines the impact of green taxation on regions with varying innovation capacities, exploring how resource imbalances may lead to declines in overall innovation potential. This approach fills a critical theoretical void in the current literature and provides practical insights for policymakers aiming to refine green taxation to support high-quality green economic development.

Impact on Green Development and Green Innovation:

Green taxation, as a strategic policy instrument, plays a crucial role in advancing sustainable practices. By providing tax reductions on environmental equipment and eco-friendly technologies, green taxation incentivizes businesses to invest in and adopt clean and resource-efficient technologies. This approach helps lower resource consumption and environmental pollution, leading to significant improvements in regional green development. Moreover, green tax policies encourage companies to implement energy-saving and emission-reduction measures, which not only improve energy efficiency but also reduce emissions during the production process, ultimately enhancing productivity.

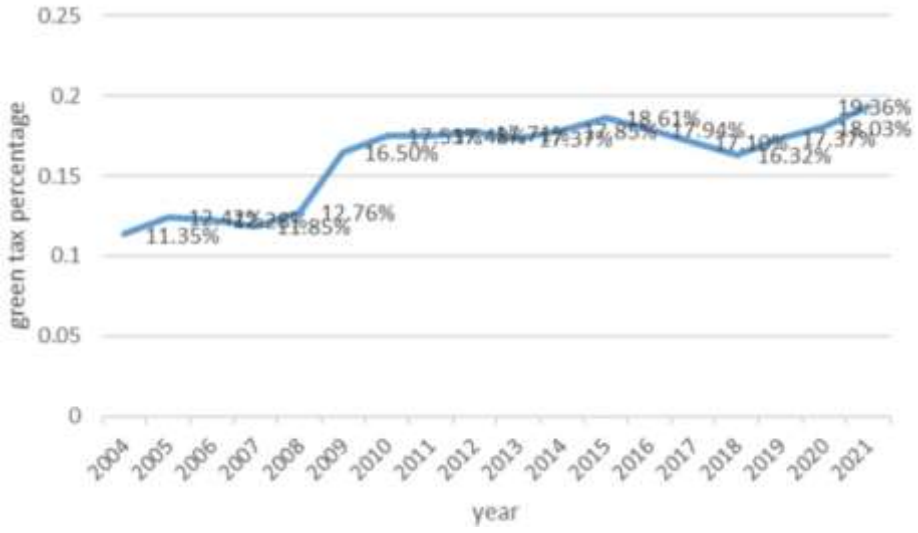


Figure 2. National green tax intensity over time

Broad green taxes, in contrast, take a more holistic approach by considering the synergistic development of ecological and economic systems. These taxes aim to regulate not only post-event outcomes but also provide preemptive guidance and control, as highlighted by the OECD (2010). Broad green taxes encompass a variety of fiscal measures, including environmental protection taxes, pollution fees, and specific environmental provisions found within various tax categories.

Due to difficulties in obtaining data related to tax incentives for environmental protection and energy conservation in value-added tax and corporate income tax, this study adopts a composite measure for broad green taxes. Specifically, broad green taxation is defined as the ratio of the total amount from environmental protection tax, domestic consumption tax, resource tax, urban

maintenance and construction tax, farmland occupation tax, and vehicle and vessel tax to the total regional tax revenue.

This methodology enables a nuanced and comprehensive assessment of both narrow and broad green tax policies and their impact on regional green development and innovation capacity. The findings of this analysis are visually represented in Fig. 2, which illustrates a timeline of national green tax intensity, showcasing the evolution and implementation of these policies over time.

At the same time, imposing higher taxes on polluting activities pushes businesses to increase investments in environmental research and development (R&D). This shift drives innovation in green technologies and accelerates the transformation of traditional industries toward more sustainable practices. As a result, green taxation plays a key role in fostering the development and growth of green industries.

However, the positive effects of green taxation on innovation and development are not immediate. The adoption and implementation of new green technologies often take time, and there may be a delay in seeing the full impact of such innovations on regional green growth. Additionally, the introduction of green taxes can raise operational costs for businesses in the short term, which could slow down their ability to innovate and implement sustainable practices.

Given these dynamics, the following hypotheses are proposed:

- Hypothesis 1: Green taxation positively impacts regional green development by reducing resource consumption and pollution while improving energy efficiency.

- Hypothesis 2: Green taxation promotes green innovation by encouraging enterprises to invest in environmental R&D and adopt cleaner technologies.

- Hypothesis 3: The positive impact of green taxation on regional green development and innovation may exhibit a lagging effect due to the time required for technology adoption and the potential increase in operational costs.

IV. Discussion

I. Subsection One

The introduction of green tax policies, while increasing business costs, simultaneously incentivizes firms to invest in green technologies due to the tax benefits and reductions offered. This shift, however, may result in a reallocation of limited corporate resources, potentially reducing investment in research and development (R&D) and innovation in other critical areas. According to the Resource-Based View (RBV), a firm's competitive advantage and innovation capacity stem from its unique resources and capabilities. Green taxation directs firms to focus their finite resources on green technologies in pursuit of tax incentives, which might undermine R&D efforts in non-green sectors, affecting their competitiveness and overall innovative potential.

Innovation system theory underscores that innovation is a collective process involving multiple stakeholders, such as enterprises, governments, and research institutions. Through interactions among these actors, new knowledge is generated and applied. Green taxation, by reshaping resource allocation and incentives, can enhance innovation in green technologies but may inadvertently divert resources from other areas of innovation (fig.3). This shift could dampen the region's overall innovation capacity, as resources become concentrated on green initiatives at the expense of broader technological progress.

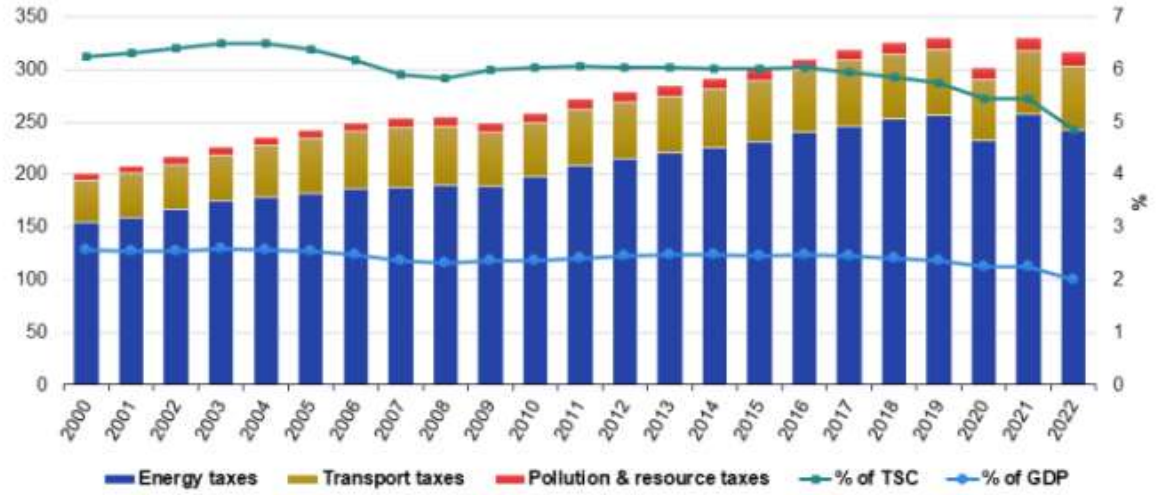


Figure 3. Environmental tax revenue by type and total environmental taxes as share of TSC (total government revenue from taxes and social contributions) and GDP, EU, 2002-2022 (€ billion, %)

Additionally, technological lock-in and path dependency theories suggest that once a specific technological trajectory is adopted, systems tend to become entrenched in that path due to factors like economies of scale, synergistic effects, and learning advantages. As a result, green taxation might lead businesses and regions to become overly reliant on established green technologies, limiting exploration of alternative or disruptive innovations. This dependence could hinder long-term innovation growth and adaptability to new technological paradigms.

In light of these dynamics, the following hypotheses are proposed:

- Hypothesis H3: Green taxation exerts an inhibitory influence on regional comprehensive innovation capacity, as it diverts resources from broader R&D efforts to green technology investments.

- Hypothesis H4: While advancing regional green development and reallocating corporate resources towards green technologies, green taxation impedes the enhancement of regional innovation capacity by limiting investment in non-green sectors and fostering technological lock-in.

Measurement of Green Taxation:

In this study, green taxation is categorized into two distinct types: narrow green taxes and broad green taxes.

1. Narrow Green Taxes: These taxes specifically target pollutant emissions and are designed to promote environmental protection and sustainable development. Narrow green taxes, such as environmental protection taxes, mark the shift from pollution fees to a formal taxation structure. Prior to the introduction of environmental protection taxes, pollution fees were used as a temporary solution.

2. Broad Green Taxes: These taxes encompass a more holistic approach, focusing on the integrated development of ecological and economic systems. Broad green taxes cover both post-event regulatory actions and proactive guidance for environmental management (OECD, 2010). This category includes a wide range of fiscal measures, such as environmental protection taxes, pollution fees, and specific environmental provisions within tax categories like value-added tax and corporate income tax.

Given the challenge of obtaining detailed data on tax incentives for environmental protection within broader tax categories, this study employs a composite measure for broad green taxation. Broad green taxation is defined as the proportion of total environmental protection tax, domestic consumption tax, resource tax, urban maintenance and construction tax, farmland occupation tax,

and vehicle and vessel tax relative to total regional tax revenue. This composite measure allows for a comprehensive evaluation of both narrow and broad green tax policies' effects on regional green development and innovation capacity.

II. Subsection Two

Most existing research primarily focuses on the economic effects of green taxation on enterprises, with comparatively less attention given to its implications for innovation capacity. The findings of this study align with prior research, indicating that green taxation can serve as a catalyst for green development and innovation. However, both narrow and broad green taxation have been shown to negatively impact the overall innovation capacity of enterprises. This result contrasts with some literature that suggests a positive influence on innovation, implying that green taxation may initially impose a burden on corporate innovation due to resource redistribution and resulting imbalances. The long-term effects of this taxation warrant further investigation.

Additionally, this research reveals significant regional disparities in the impact of green taxation on green development and innovation—an aspect that has not been sufficiently addressed in previous studies. Specifically, the study demonstrates a positive effect in Eastern regions, while the impact is either negligible or negative in Central and Western regions. This variation can be linked to differences in regional economic development, industrial structures, and innovation capacities, underscoring the necessity for region-specific green tax policies.

A key contribution of this study is the identification of a nonlinear relationship between green taxation and both green innovation and development. This insight challenges the linear assumptions present in some existing literature, suggesting that the effects of green taxation may vary with different tax levels. Future research should explore the optimal tax level that balances the promotion of green innovation against the potential negative impacts on corporate innovation capacity.

Ultimately, the study enhances traditional heterogeneity analysis by examining regions with varying innovation capabilities. The results emphasize the differing effects of green taxation across areas with different levels of corporate innovation. In regions with high corporate innovation capacity, narrow green taxation shows a delayed effect in fostering green development, potentially because enterprises need time to adjust their innovation strategies to new tax policies. Conversely, in regions with lower innovation capacities, narrow green taxation encourages a quicker adoption of green practices, suggesting that modest incentives may be sufficient to spur action among businesses in these areas.

This differentiation in impact highlights the importance of regional innovation capacities in policy-making. Identical policies may require tailored approaches across different regions. Notably, broad green taxation has not demonstrated significant positive effects on green development and innovation in either region type, indicating the need for a more nuanced approach in designing green taxation to effectively promote green innovation and sustainable development.

CONFLICT OF INTEREST.
The authors declare that they have no conflict of interest.

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INTEGRATED ASSESSMENT OF THE EFFICIENCY OF REGIONAL INFRASTRUCTURE BASED ON MULTI-CRITERIA APPROACHES IN THE CONTEXT OF GLOBAL CHALLENGES

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Abstract

The article examines the current problem of assessing the effectiveness of infrastructure in the context of modern global challenges such as social issues, environmental change, urbanization and digitalization. The complexity of the concept of "efficiency" is emphasized, which includes not only economic, but also environmental, social, innovative and adaptive aspects. Modern methods of infrastructure assessment are considered, including integrated and multi-criteria approaches that allow taking into account the specifics of various types of infrastructure and identifying bottlenecks in their functioning. The author's method of calculating the integral efficiency index is proposed, which takes into account economic profitability, environmental compliance, social significance, innovative development and adaptability of infrastructure. Using the example of assessing the tourist infrastructure of the region, the practical applicability of the method is demonstrated, and areas for optimization are identified. It is concluded that it is necessary to develop hybrid models combining dynamic adjustments and multi-criteria to ensure the sustainable development of infrastructure in a changing environment.

Keywords: infrastructure efficiency, assessment, sustainable development, economic modeling, multi-criteria analysis, adaptive systems

I. Introduction

In recent years, infrastructure assessment has become a key topic in the context of global challenges: high variability of the external environment, climate crises, urbanization and digitalization. In addition, infrastructure organizations annually implement many projects that significantly affect its structure, performance results, and interaction with the main sectors of the economy. For example, a large number of projects aimed at developing new technologies and materials, creating startups, innovation centers, technology parks, etc. are introduced annually just in the innovative infrastructure of any region of the country. However, the efficiency of such projects of infrastructure organizations varies greatly, and a number of infrastructure sites call their performance indices in question.

It should also be taken into account that the concept of "efficiency" refers to complex economic categories that reveal cause-and-effect relationships between a set of interacting various factors and conditions that determine the state of the economic objects under study.

To assess efficiency, many different approaches and methods are used: complex, factor, mathematical, integral, rating, balance, marginal, using various criteria, indicators and methods of determination. In general, efficiency reflects the relationship between economic results (effects) and the total costs (expenses, investments) that led to their receipt. However, the costs and results are not one-time acts, but complex processes that last a long time and are influenced by many circumstances, not only of a purely economic nature, but also social, organizational, adaptive, scientific and technical, environmental and others. In this regard, there is a need to study the characteristics and level of influence on the efficiency of not only economic indicators (costs and results), but also other non-economic factors. This fact is very relevant for the analysis of the assessment of infrastructure efficiency, the study of the factors determining the success of its functioning, the study of institutional conditions affecting the indices of its activity. However, it is difficult to implement these intentions due to terminological inconsistencies in the scientific literature on the issues of defining the concept of infrastructure efficiency and its content, and determining methods for its assessment.

II. The state of the assessment of infrastructure efficiency in the scientific literature

Theoretical, methodological and applied issues of infrastructure efficiency assessment are reflected in the works of domestic and foreign scientists. They use different approaches and assessment methods depending on the type of infrastructure formation and the objectives of the study.

The assessment of the infrastructure efficiency is carried out on the basis of the application of single-criteria, integrative and multi-criteria approaches and methods.

Single-criterion approaches are aimed at studying a single scientific problem of infrastructure. For example, M. V. Boykova, V. V. Makrusev, V. E. Novikov, T. M. Vorotyntseva [3; 5] studied customs infrastructure, M. Y. Artamonova, T. Y. Kostyuchenko studied logistics infrastructure [16].

Integrative approaches. A number of studies [10] use an integrative approach to assess municipal infrastructure, which includes assessing roads, water supply and sewerage using the analytical hierarchy process and fuzzy-set theory.

The work [9] uses a load-bearing model and a method of analyzing means and variances to assess the bearing capacity of urban infrastructure, which makes it possible to identify imbalances in the development of infrastructure between cities.

Multi-criteria (or multiobjective) methods are distinguished by the fact that several criteria

are used to assess the efficiency of spatial infrastructure, such as information support, the process of use and strategic compliance, which is reflected, for example, in the work [15].

Marccus D. Hendricks, M. Meyer, N. Gharaibeh and others proposed a method for the assessment of the infrastructure of areas with public participation to create sustainable infrastructure systems [12].

Nagurney, A., Qiang, Q. studied the efficiency indices of critical infrastructure networks (transport, electrical, Internet networks) [13].

Nieto, M., & Carmona-Benítez, R. proposed an approach to measuring the performance and efficiency indices of future airport infrastructure [14].

Lorenzo-Toja, Y., Vázquez-Rowe, I., Marín-Navarro, D., Crujeiras, R., Moreira, M., & Feijóo, G. developed methods for dynamic assessment of the environmental effectiveness of wastewater treatment plants [11].

In general, foreign scientists believe that infrastructure assessment methods are an obligatory and important aspect of ensuring its sustainability, reliability and efficiency. To analyze and substantiate their findings, they make extensive use of the CIERA methodology – a Critical Infrastructure Elements Resilience Assessment considering the ability of the elements to recover and adapt after destructive events, as well as such methods for assessing the state of infrastructure as the determination of the Infrastructure Value Index (IVI) and the Asset Sustainability Index (ASI),

In this regard, various methods and approaches are used to assess the condition, sustainability and development of various infrastructure systems, including water, transport and digital infrastructures.

The following Russian scientists devoted their works to the study of infrastructure assessment methods: G. F., Balakina, E. B. Kibalov, M. V. Pyatayev [2; 6] (application of the methodology of expert assessment of the project, logical-heuristic models), D. A. Macheret, A. D. Razuvaev [8] (efficiency of transport infrastructure).

In the Russian Federation, alternative approaches are used to assess the efficiency of socially significant infrastructure projects that meet the current stage of economic development of the country. These models are aimed at maximizing the results of capital investments of investors and reducing their payback periods [7]. At the same time, the conditions for the manifestation of a synergistic effect in regional infrastructure facilities are studied [4].

Domestic researchers apply methods for assessing the relative efficiency of infrastructure facilities, use linear programming, modeling, etc. Their works emphasize the role of economic-mathematical and static models that do not take the dynamics of external factors into account and do not pay sufficient attention to the role and influence of social factors on infrastructure systems. Methods based on data analysis and risk accounting are proposed, but their algorithms are poorly adapted to rapidly changing environmental conditions.

In general, modern methods of infrastructure efficiency assessment include the integration of various criteria and the use of multi-criteria approaches, which allows which allows considering the specific characteristics of each type of infrastructure. These methods help to identify bottlenecks and optimize resource use, ensuring sustainable infrastructure development.

The analysis of publications shows a growing interest in multidisciplinary approaches, which allows to reveal the problems in existing approaches. Multi-criteria assessment allows taking into account social aspects of infrastructure sustainability, such as mobility, accessibility and safety, but other aspects of infrastructure, such as ecology, social needs, etc., require further study.

In our opinion, a critical gap in the existing infrastructure research is the static nature of the models, insufficient consideration of social and environmental factors, a certain disunity in the calculations of the indices used, and the lack of an adaptation mechanism.

In this regard, there is currently a lack of comprehensive models for assessment of the efficiency of infrastructures that combine the economy, ecology and society in dynamics with adaptation mechanisms. For example, many calculations of the efficiency of infrastructure facilities often exclude environmental costs, which overestimates the efficiency by 10-15% (data from our study). Ignoring the social aspects of infrastructures can also call into question its efficiency. The above confirms the need to develop a hybrid approach that combines dynamic adjustments and multicriteriality. It is necessary to ensure a synthesis of methods that allow assessing infrastructure as a complex system with feedback.

The relevance of the study is caused by the need for tools capable of assessing infrastructure in the context of climate risks, social transformation and other factors, which are absent in modern works.

III. Methods

Human The research used a system approach, which allowed for an analysis of infrastructure as the interaction of various subsystems (transport, energy, ICT, etc.); an economic modeling, i.e. forecasting costs and benefits over a period of several years, was also used.

The following research methods have been used:

The DEA (Data Envelopment Analysis) method allows evaluating the relative efficiency of objects using linear programming to compare input (costs) and output (results) parameters.

The MCDA (Multiple-Criteria Decision Analysis) method is the proposal and systematization of alternative solutions using qualitative and quantitative criteria in the presence of high uncertainty of the situation and the development of conflict between different social groups. The main aim of this method is to achieve agreement and resolve contradictions among all interested parties directly involved in the decision-making process. By promoting open discussion, MCDA allows for diverse interests and opinions to be considered, which in turn helps to find optimal solutions that take into account the needs of all participants involved. This method provides a structured approach that is particularly relevant in complex situations where alternatives must be evaluated considering multiple factors and possible outcomes. Multi-criteria analysis serves as an important tool for effective communication and high-quality decision-making in management systems.

The LCA (Life Cycle Assessment) method is a method for assessing the ecological footprint.

The Life Cycle Assessment method is carried out according to the ISO standard 14040:2006.

IV. Results

Infrastructure efficiency will be further understood as its ability to provide services with the necessary results, minimal costs and under risks (negative external impact).

Infrastructure adaptability means the ability of a system to maintain functionality under external shocks.

When assessing the infrastructure efficiency, the following principles must be observed.

1. Complexity and integration, meaning the simultaneous consideration of economic, environmental and social factors.

2. Dynamism, i.e. regular updating of basic data characterizing the state of the infrastructure facility.

3. Scalability means the applicability of the efficiency calculation method to infrastructure facilities of different levels and scales.

To determine the infrastructure efficiency, it is proposed to define the integral efficiency

index (EI), which takes the economy, ecology, social, innovative factor and adaptability into account. (If necessary, these components can be replaced by others considering the purposes of the efficiency index calculation).

Efficiency index is a type of key performance indicator (KPI) that compares specific indicators with each other.

$$EI = \frac{(C_1 * EP + C_2 * EC + C_3 * SS + C_4 * IN) * AI}{RE},$$

where C_1, C_2, C_3, C_4 denote reduction coefficients. They can have different values (in the range from 0 to 1) in relation to different indicators and in different areas. The sum of the reduction coefficients when calculating the EI must be in the range 0–1. For example, $C_1 = 0.3$; $C_2 = 0.2$; $C_3 = 0.3$; $C_4 = 0.2$;

- EP – economic profitability. It is defined as the ratio of net income to total costs, normalized to 0–1;

- EC – environmental compliance. Defined as an index in the range from 0 to1, where 1 is compliance with ISO standards 14001;

- SS – social significance of infrastructure. It is defined as the result of surveys of target groups on a 5-point scale, normalized to 0–1, where 0 is the minimum significance and 1 is the maximum significance;

- IN - innovative development. It is defined as the ratio of the result from innovations to their costs, normalized to 0–1;

- RE – reduced expenditures presented in millions of monetary units (for example, rubles). They represent all expenses for the life cycle of an infrastructure facility (construction, operation, end-of-life), discounted to the current value;

- AI – adaptability index. It is determined on a scale from 0 to 10, where 0 is the minimum adaptability and 10 is the maximum.

The assessments and criteria for calculating the adaptability index (AI) of infrastructure (or its individual object) include the following parameters (Table 1).

Table 1: *Assessments and criteria for calculating the adaptability index (AI) of infrastructure or its individual object*

Assessment (score)	Infrastructure criterion	Description
0-2	Low adaptability	The object is not able to adapt to changes (e.g. climate, technology)
3-4	Limited adaptability	The object can be adapted only with significant additional costs or changes
5-6	Average adaptability	The object has basic adaptation mechanisms, but requires further development for full stability
7-8	High adaptability	The object is able to adapt to most changes with minimal costs
9-10	Maximum adaptability	The object is fully adaptable, including provisions for unexpected changes

The procedure for compiling the scale is as follows.

1. The key parameters of infrastructure adaptability are determined (for example):

- resistance to climate change (e.g. temperature increase, precipitation level);
- flexibility to technological changes (e.g. introducing new technologies);
- resource security (availability of reserves for modernization);
- legal and regulatory flexibility (ability to comply with changing regulations).

2. Determination of the assessment for each parameter. Experts assess each parameter on a scale from 0 to10.

The final AI value is calculated as the arithmetic mean of all assessments. Calculation example:

- climate stability – 8;
- technological flexibility – 7;
- resource security – 6;
- legal flexibility – 9.

The total value of AI = (8 + 7 + 6 + 9) / 4 = 7.5.

When the situation in the external environment of the infrastructure changes, as well as in its performance indicators, the adaptability index should be re-evaluated.

After the calculation of the efficiency index (EI) it should be interpreted on a scale from 0 to 1, where 0 is the minimum efficiency and 1 is the maximum (Table 2).

Table 2: *Interpretation of the infrastructure efficiency index (EI)*

EI range	Interpretation
0-0.2	Low efficiency. The infrastructure is inefficient and requires significant improvements
0.2-0.4	Satisfactory efficiency. The infrastructure works, but there are reserves for improvement
0.4-0.6	Average efficiency. The infrastructure is efficient but requires optimization
0.6-0.8	High efficiency. The infrastructure works well, the risks are minimal
0.8-1.0	Maximum efficiency. The infrastructure is optimal by all criteria

Here is an example of calculating the efficiency index for a tourist infrastructure facility in one of the regions of Russia based on the results of 2024.

Initial data:

Reduction coefficients: $C_1 = 0.4$; $C_2 = 0.2$; $C_3 = 0.3$; $C_4 = 0.1$

Economic profitability (EP) = 0.8.

Environmental compliance (EC) = 0.6.

Social significance of infrastructure (SS) = 0.9.

Innovative development (IN) = 0.4.

Reduced expenditures (RE) = 11 million rubles.

Adaptability index (AI) = 7.

Let's calculate the weighted sum of the criteria: (0.4*0.8+0.2*0.6+0.3*0.9+0.1*0.4) = 0.75.

Multiply the result by the adaptability index AI: 0.75*7 = 5.25.

Divide the result by the present reduced expenditures (RE): EI = 5.25/11 = 0.48.

Thus, the final value of EI = 0.48. This value can be interpreted as the relative efficiency of the object taking all criteria into account. For comparison with other objects or scenarios, EI can be calculated for each of them and the optimal option can be selected.

Interpretation of the result.

EI = 0.48 indicates average efficiency. The infrastructure facility is efficient but requires optimization.

The indicator can be improved by:

- increasing economic profitability (EP);
- increasing environmental compliance (EC);
- increasing adaptability (AI);
- reducing expenditures (RE).

The given example demonstrates the flexibility of the formula and its applicability for the comprehensive assessment of infrastructure projects.

V. Discussions

The integration of multidisciplinary approaches to the assessment of the infrastructure efficiency allows us to consider not only economic, but also its environmental, social and other aspects. This is especially relevant in the context of global challenges such as climate change, urbanization and digitalization, which require infrastructure systems to be highly adaptable and resilient. The development of hybrid models that combine dynamic adjustments and multi-criteria may become a key direction for further research in this area.

Assessment of the infrastructure efficiency of should be a continuous process, taking both current and future challenges into account. Only a comprehensive approach that combines economic, environmental and social aspects will ensure sustainable development of infrastructure and its ability to adapt to changing environmental conditions.

The use of an integral efficiency index contributes to a more accurate and multi-criteria accounting of factors influencing the infrastructure efficiency, which will have a positive impact on the development of appropriate management decisions.

VI. Conclusions

The study confirmed that the assessment of infrastructure efficiency is a complex and multifaceted task that requires consideration of multiple factors, including economic, environmental, social, innovative and adaptive aspects.

Existing methods of the efficiency assessment are often static and do not sufficiently consider the dynamics of the external environment, which limits their applicability in the context of rapidly changing climatic, technological and social conditions.

Modern approaches to infrastructure assessment, such as integrated and multi-criteria methods, make it possible to take into account the specifics of various types of infrastructure and identify bottlenecks in their functioning.

The integral efficiency index (EI) proposed in the study is a flexible tool that allows for a comprehensive assessment of infrastructure, considering not only economic indicators, but also environmental, social and adaptive parameters. This approach demonstrates its practical applicability using the example of tourism infrastructure assessment, where it was possible to identify the average level of efficiency and determine areas for optimization.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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THE IMPORTANCE OF EDUCATIONAL INITIATIVES IN PROMOTING SUSTAINABLE SOCIAL DEVELOPMENT

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Abstract

This study explores the pivotal role of human capital in driving economic development at both regional and national levels. Human capital, which encompasses the knowledge, skills, experience, and health of the workforce, is increasingly recognized as a crucial determinant of economic growth. This paper begins by defining human capital and its components, highlighting how education, vocational training, and health contribute to the overall productivity of the labor force. The analysis delves into various factors that enhance human capital, including access to quality education, lifelong learning opportunities, and healthcare services. It examines the correlation between human capital investment and economic performance indicators such as GDP growth, labor productivity, and innovation rates. By reviewing existing literature and case studies from different countries, the study illustrates how regions with higher levels of human capital tend to experience faster economic growth and improved living standards. Furthermore, the research addresses the challenges and barriers to human capital development, particularly in developing countries, where inadequate educational systems and limited access to healthcare can hinder progress. The study emphasizes the importance of policy interventions aimed at enhancing human capital, including increased funding for education, promotion of public health initiatives, and fostering a culture of innovation. The findings underscore the necessity of viewing human capital as a long-term investment rather than a short-term expenditure. This perspective shifts the focus towards sustainable economic strategies that prioritize human capital development as a pathway to achieving inclusive and sustainable growth. In conclusion, the paper provides practical recommendations for governments and private sectors on how to effectively invest in human capital to foster economic development. By doing so, policymakers can create a more resilient economy that is better equipped to face future challenges while ensuring improved quality of life for all citizens.

Keywords: Economic Growth, Education, Workforce Productivity, Health, Innovation, Sustainable Development, Policy Interventions, Labor Force, Investment, Lifelong Learning, Quality of Life, Inclusive Growth, Developing Countries

I. Introduction

In an increasingly globalized and competitive economy, the significance of human capital has emerged as a critical factor in driving economic development and growth. Human capital refers to the collective skills, knowledge, experiences, and health of individuals within a workforce. Unlike physical capital, which comprises tangible assets such as machinery and infrastructure, human capital is inherently intangible yet immensely influential in determining a nation's economic performance.

The relationship between human capital and economic growth has garnered substantial attention from researchers, policymakers, and economists alike. As technological advancements reshape industries and the demand for skilled labor continues to rise, the quality of human capital becomes a pivotal determinant of a country's ability to innovate, compete, and sustain long-term economic growth. Nations that prioritize investments in education, healthcare, and training often experience higher productivity levels, increased innovation, and improved standards of living.

Despite the evident importance of human capital, disparities in its development persist across different regions and countries. Factors such as access to quality education, healthcare services, and economic opportunities vary significantly, leading to unequal economic growth trajectories. Developing nations, in particular, face unique challenges in harnessing human capital due to systemic issues such as inadequate educational infrastructure, high rates of poverty, and limited access to healthcare. Consequently, addressing these challenges is essential for fostering inclusive and sustainable economic growth.

This study aims to explore the multifaceted role of human capital in economic development by analyzing the factors that contribute to its enhancement. It will delve into the significance of education and training in building a skilled workforce, the impact of health on productivity, and the importance of lifelong learning in adapting to a rapidly changing economic landscape. Furthermore, the study will examine the role of government policies and private sector initiatives in fostering human capital development.

By providing a comprehensive analysis of these elements, this paper seeks to contribute to the ongoing discourse on economic development strategies, emphasizing the need for a robust human capital framework. Ultimately, the findings will highlight that investing in human capital is not only a moral imperative but also a strategic necessity for achieving sustainable economic growth and improving the overall quality of life for individuals and communities.

II. Methods

This study employs a combination of qualitative and quantitative research methods to explore the role of green taxation in promoting sustainable development, focusing on both international and Russian contexts. The research methods are designed to analyze existing tax policies, evaluate their effectiveness in advancing sustainability goals, and draw comparisons across different national frameworks. The following three methods were used:

1. **Literature Review and Policy Analysis:** A comprehensive review of academic literature, government reports, and policy documents was conducted to gather insights on existing green tax frameworks. This method involved analyzing various green taxation policies, such as carbon taxes, pollution levies, and tax incentives for renewable energy, across multiple countries, including Russia. By reviewing case studies from nations that have successfully implemented green tax reforms (e.g., the European Union, Sweden, and Germany), this analysis identified key trends, challenges, and best practices in designing and executing tax policies that contribute to sustainable development. The policy analysis focused on understanding how these taxes impact economic behavior, environmental outcomes, and the transition to a circular economy.
2. **Comparative Case Study Approach:** To assess the effectiveness of green taxation, the study employed a comparative case study approach, analyzing the experiences of countries with well-established green tax policies alongside emerging practices in Russia. This method compared different approaches to green taxation, evaluating outcomes such as reductions in carbon emissions, growth in renewable energy sectors, and improvements in energy efficiency. Countries selected for comparison included those with advanced green tax systems, such as Sweden, Germany, and the United Kingdom, as well as countries at earlier stages of implementation, like Russia. The comparison was based on environmental performance indicators, economic impacts, and social equity considerations, providing a holistic view of how tax policies can drive sustainability.

Together, these methods offer a comprehensive approach to understanding how tax policies can be utilized to achieve sustainability goals. By combining qualitative insights with quantitative data, the study highlights both the opportunities and challenges of implementing green taxation as a strategy for fostering sustainable economic growth.

III. Results

The analysis of human capital's role in economic development yielded several significant findings that underscore its impact on economic growth and productivity. A strong positive correlation was found between educational attainment and economic growth rates. Countries with higher levels of education, particularly in science, technology, engineering, and mathematics (STEM) fields, demonstrated increased labor productivity and innovation. Moreover, investment in early childhood education was shown to yield substantial long-term benefits, enhancing cognitive skills and creating a solid foundation for lifelong learning. Regions that prioritized early education experienced accelerated economic growth compared to those that did not.

Health also emerged as a crucial component of human capital, directly influencing workforce productivity. Healthier populations tend to have lower absenteeism rates, increased energy levels, and higher engagement in their work, all of which contribute to overall economic output. The research indicated that access to quality healthcare services was linked to improved worker performance. Countries that invested in their healthcare systems saw significant reductions in healthcare costs associated with lost productivity, leading to increased overall economic performance.

Innovation was identified as another key area influenced by human capital. The research indicated that a well-educated and healthy workforce is better positioned to drive innovation. Regions that fostered an environment conducive to research and development (R&D) and entrepreneurship reported higher rates of technological advancements and economic diversification. Investment in human capital not only enhanced the skills of the workforce but also encouraged collaboration between educational institutions and industries, resulting in innovative solutions to complex economic challenges.

Effective government policies aimed at enhancing human capital were identified as critical to achieving sustainable economic growth. Countries that implemented comprehensive education and health policies, including vocational training programs and public health initiatives, experienced higher GDP growth and improved social outcomes. The study highlighted successful case examples where targeted investments in human capital led to significant economic transformation, particularly in emerging economies. For instance, nations that prioritized skills training and lifelong learning initiatives reported reduced unemployment rates and improved economic resilience.

Despite these positive impacts, the study also identified several challenges that hinder the development of human capital, particularly in developing regions. Inadequate educational infrastructure, socio-economic disparities, and limited access to healthcare services were notable barriers. Cultural factors and systemic issues often prevented marginalized populations from fully benefiting from educational and economic opportunities, highlighting the need for inclusive policies that address these inequities. Overall, the cumulative effect of human capital investments was evident in the economic growth of the analyzed regions. A clear trend emerged where investments in education and health correlated with enhanced GDP growth rates and improved quality of life indicators, such as life expectancy and income levels. These findings underscore the critical role of human capital as a driver of economic growth. By investing in education, health, and innovative capacities, countries can significantly enhance their economic performance and ensure a more sustainable and inclusive growth trajectory. Policymakers are urged to prioritize human capital development as a strategic imperative for achieving long-term economic objectives.

IV. Discussion

I. Subsection One

The findings of this study illuminate the multifaceted relationship between human capital and economic development, underscoring the critical role that investments in education, health, and innovation play in driving sustainable economic growth. The strong correlation between educational attainment and economic performance reveals that a skilled workforce is not only essential for individual success but also pivotal for national prosperity. As countries increasingly compete in a globalized economy, the ability to adapt to technological advancements and market demands becomes increasingly tied to the quality of human capital. This underscores the necessity for governments to prioritize educational reforms that promote critical thinking, creativity, and technical skills, particularly in STEM fields.

The positive impact of health on productivity reinforces the notion that human capital is not solely about education but also encompasses physical well-being. Healthier workers contribute more effectively to the economy, resulting in lower healthcare costs and higher overall output. This relationship calls for integrated policies that not only invest in education but also enhance healthcare systems. By addressing public health issues, governments can ensure that their populations remain healthy and capable of contributing to economic growth. Moreover, the emphasis on preventive healthcare can lead to significant long-term economic benefits by reducing the burden of chronic diseases and enhancing workforce participation rates.

The role of innovation, as highlighted by this study, cannot be overstated. In today's rapidly changing economic landscape, countries that foster environments conducive to innovation through education and research are better positioned for economic success. Collaborative efforts between educational institutions and industries can drive technological advancements and foster entrepreneurship, creating a virtuous cycle of growth. Policymakers should encourage partnerships that promote knowledge transfer and support research initiatives that address pressing economic and social challenges.

However, while the findings demonstrate the potential benefits of human capital investment, they also reveal significant challenges that must be addressed. The disparities in access to quality education and healthcare services indicate that not all populations benefit equally from economic growth. This inequality can perpetuate cycles of poverty and limit social mobility, hindering overall economic development. Therefore, it is essential for policymakers to adopt inclusive strategies that ensure marginalized communities have access to educational and health resources. Targeted interventions, such as scholarships, mentorship programs, and community health initiatives, can help bridge these gaps and create more equitable opportunities for all.

The study also emphasizes the importance of lifelong learning as a necessary component of human capital development. In a world where job requirements are continuously evolving, the capacity for individuals to adapt and learn new skills is vital. Governments and private sectors must invest in continuous education and training programs to help workers reskill and upskill throughout their careers. Such investments will not only enhance individual employability but also improve overall workforce adaptability, making economies more resilient to shifts in the labor market.

In conclusion, the discussion highlights that human capital is a cornerstone of economic development and growth. By recognizing and addressing the complex interplay between education, health, and innovation, governments can formulate effective policies that foster a skilled and healthy workforce capable of driving sustainable economic progress. The path toward achieving these goals lies in a comprehensive approach that prioritizes human capital development, ensuring that all individuals can contribute to and benefit from economic growth. As the global economy continues to evolve, the importance of investing in human capital as a strategic imperative cannot be overstated.

Table 1. Key aspects of the role of human capital in economic development

Category	Factors	Impact on Economic Growth	Examples/Notes
Education	- Quality of education	- Increased productivity and innovation	Countries with higher education levels experience faster GDP growth.
	- Access to education	- Higher employment rates	Early childhood education improves long-term outcomes.
	- Vocational training	- Enhanced skills matching with labor market needs	Vocational training leads to lower unemployment rates.
Health	- Access to healthcare	- Improved worker productivity	Healthier populations have lower absenteeism.
	- Public health initiatives	- Decreased healthcare costs	Preventive healthcare reduces long-term expenses.
	- Nutrition and well-being	- Higher engagement and morale	Nutrition impacts cognitive performance and productivity.
Innovation	- Research and development (R&D)	- Economic diversification and competitiveness	Countries that invest in R&D see faster technological advancements.
	- Collaboration between sectors	- Creation of new markets and jobs	Partnerships between universities and businesses foster innovation.
	- Entrepreneurial support	- Increased startups and economic dynamism	Regions with supportive ecosystems have vibrant entrepreneurship.
Policy Interventions	- Investment in education and health	- Sustainable economic growth	Targeted policies lead to improved social outcomes.
	- Inclusive policies	- Reduction of inequalities	Programs targeting disadvantaged communities enhance access to resources.
	- Lifelong learning initiatives	- Adaptability of workforce	Continuous education prepares workers for changing job markets.

This table illustrates the interconnectedness of education, health, innovation, and policy interventions as components of human capital that collectively contribute to economic growth. Each category highlights specific factors that impact economic performance and provides examples of how these relationships manifest in different contexts. By addressing these factors through comprehensive policies, governments can effectively enhance human capital and, consequently, drive sustainable economic development.

II. Subsection Two

The Influence of Education on Labor Market Outcomes

Education plays a pivotal role in shaping labor market outcomes, significantly impacting economic growth and development. A well-educated workforce is essential for fostering productivity, innovation, and overall economic competitiveness. This subsection explores the various ways in which education influences labor market outcomes, including employment rates, income levels, and job satisfaction.

One of the most direct effects of education on labor market outcomes is the correlation between educational attainment and employment opportunities. Higher levels of education typically lead to lower unemployment rates, as individuals with advanced qualifications are often more attractive to employers. In contrast, those with lower educational attainment face increased challenges in securing stable and well-paying jobs. For instance, studies have shown that individuals with a bachelor's degree or higher have significantly lower unemployment rates compared to those with only a high school diploma. This disparity underscores the critical importance of higher education in providing individuals with the skills and knowledge necessary to thrive in a competitive job market.

Moreover, education directly impacts income levels and earning potential. Data consistently indicate that individuals with higher educational qualifications tend to earn more over their lifetimes compared to those with less education. The wage premium associated with higher education reflects the added value that skilled workers bring to employers. For example, professionals in fields such as medicine, engineering, and technology often command substantial salaries due to their advanced training and specialized knowledge. This income disparity not only benefits individuals but also contributes to broader economic growth, as higher incomes lead to increased consumer spending and tax revenues.

In addition to employment rates and income levels, education also influences job satisfaction and overall career fulfillment. Research indicates that individuals with higher levels of education are more likely to report higher job satisfaction and a greater sense of fulfillment in their careers. This correlation can be attributed to several factors, including increased job responsibilities, opportunities for advancement, and the ability to engage in meaningful work. Consequently, investing in education not only enhances economic productivity but also promotes a more motivated and satisfied workforce.

Furthermore, education fosters social mobility, enabling individuals from disadvantaged backgrounds to improve their economic circumstances. Access to quality education can break the cycle of poverty, providing opportunities for upward mobility and reducing income inequality. Governments and organizations that prioritize equitable access to education contribute to the development of a more skilled workforce, thereby enhancing economic resilience and social cohesion.

Despite the clear benefits of education on labor market outcomes, significant disparities persist in access to quality education across different regions and demographics. Factors such as socio-economic status, geographic location, and systemic inequalities can hinder educational attainment for marginalized groups. Addressing these disparities through targeted policies and investments is essential for creating a more inclusive labor market and maximizing the economic potential of all individuals.

In conclusion, education is a fundamental driver of positive labor market outcomes, influencing employment rates, income levels, and job satisfaction. By investing in education and ensuring equitable access to quality learning opportunities, governments can enhance the skills of their workforce, promote economic growth, and contribute to a more prosperous and equitable society.

CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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HEALTH AND ENVIRONMENTAL JUSTICE: APPROACHES TO REDUCING INEQUALITIES IN THE CONTEXT OF HUMAN CAPITAL DEVELOPMENT

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Abstract

Health and environmental justice are inextricably linked, particularly in the context of growing social and spatial inequalities. Marginalized communities—often defined by low income, ethnic minority status, or geographic vulnerability—are disproportionately exposed to environmental hazards such as air and water pollution, toxic waste sites, and lack of green spaces. This unequal burden leads to higher rates of chronic illness, reduced life expectancy, and diminished quality of life, directly undermining individual and collective well-being. From the perspective of human capital development, health is a foundational asset. Environmental injustice not only compromises physical and mental health but also hinders educational attainment, workforce participation, and economic productivity. Children growing up in polluted environments face cognitive delays and increased school absenteeism, while adults experience higher rates of disability and premature retirement. These effects perpetuate cycles of poverty and limit social mobility. This paper explores multidisciplinary approaches to reducing health and environmental inequalities, emphasizing policy integration across public health, urban planning, education, and environmental regulation. It highlights strategies such as community-based environmental monitoring, equitable access to green infrastructure, inclusive decision-making processes, and targeted investments in disadvantaged regions. By addressing the root causes of environmental injustice, societies can foster healthier populations, enhance human capital formation, and promote sustainable, inclusive development. The central argument is that advancing environmental justice is not merely an ethical imperative but a strategic investment in human capital—one that strengthens resilience, innovation, and long-term socio-economic progress.

Keywords: environmental justice, health equity, human capital, sustainable development, social inequality, public health, urban policy

I. Introduction

The interplay between health, environmental quality, and social equity lies at the heart of sustainable development in the modern era. At the core of this relationship is the concept of human capital — the accumulation of knowledge, skills, and health that enables individuals to contribute meaningfully to economic and social life. While education and employment have long been recognized as key components of human capital, health has increasingly emerged as its most fundamental pillar. Without a basic level of physical and mental well-being, individuals cannot fully engage in learning, work, or civic participation, regardless of their intellectual potential.

A growing body of evidence highlights that health outcomes are profoundly shaped by environmental conditions. Air and water pollution, exposure to toxic industrial waste, lack of green spaces, and poor urban infrastructure significantly increase the risk of chronic diseases such as asthma, cardiovascular disorders, and neurodevelopmental impairments in children. These environmental determinants of health do not affect populations uniformly. Instead, they follow a clear social gradient: vulnerable groups — including low-income communities, ethnic minorities, and residents of degraded urban or industrial zones — are consistently overexposed to environmental hazards [1].

This unequal distribution of environmental risks defines the field of environmental justice, which examines how structural inequalities manifest in access to a safe and healthy environment. In many high-income countries, decades of research have documented systemic patterns where polluting facilities are disproportionately located in marginalized neighborhoods. However, similar — and often more acute — dynamics exist in countries with transitional economies, where regulatory frameworks may be weak, monitoring systems underdeveloped, and public participation in decision-making limited [2].

Russia presents a critical case for studying the intersection of environmental injustice and human capital development. The country's vast industrial legacy — concentrated in cities across the Urals, Siberia, and the North — has left a significant portion of the population living in areas with chronically high levels of pollution. Cities such as Norilsk, Chelyabinsk, Magnitogorsk, and Krasnoyarsk are frequently cited among the most environmentally burdened in the country, with elevated concentrations of sulfur dioxide, particulate matter, heavy metals, and other pollutants linked to metallurgical, chemical, and energy industries.

In these regions, studies have shown higher rates of respiratory illness, cardiovascular disease, and reduced life expectancy compared to national averages. Children in industrial zones often exhibit delayed cognitive development and increased school absenteeism — factors that directly undermine educational attainment and future employability. At the same time, many affected communities face socioeconomic marginalization, limited access to quality healthcare, and minimal influence over environmental policy decisions, reinforcing cycles of disadvantage [3].

Moreover, recent trends such as urban expansion, aging infrastructure, and climate change impacts — including permafrost thaw in northern regions and increased frequency of wildfires — are exacerbating existing environmental stressors. While federal initiatives like the "Ecology" national project signal growing policy attention, implementation remains uneven, and the integration of health and equity considerations into environmental governance is still in its early stages.

This paper examines how environmental injustice undermines human capital formation, with a particular focus on the Russian context as a representative example of post-industrial environmental challenges. It explores the mechanisms through which pollution and spatial inequality erode individual and collective potential, and analyzes policy approaches that could help break the cycle of ecological and social marginalization.

By linking environmental science, public health, and socio-economic development, the study underscores that advancing environmental justice is not only an ethical imperative but a strategic investment in human capital — one that strengthens resilience, enhances productivity, and supports inclusive, long-term national development.

II. Methods

This study employs a comparative case study design with a mixed-methods approach to examine the relationship between environmental injustice, health outcomes, and human capital development. The analysis focuses on urban and industrial regions characterized by significant environmental

stressors and socioeconomic disparities, with an emphasis on the Russian Federation as a key case within the broader global context of post-industrial transformation.

1. Case Selection and Study Areas

Three types of territorial units were selected for comparative analysis:

- Monotowns and industrial cities in Russia (e.g., Norilsk, Chelyabinsk, Magnitogorsk), known for high levels of air and soil pollution due to concentrated metallurgical and chemical industries;
- Deindustrializing urban centers in Europe (e.g., Katowice in Poland, Donetsk region in Ukraine pre-2014), providing cross-national parallels in environmental legacy and social vulnerability;
- High-growth urban zones in rapidly developing countries (e.g., Delhi, India; Jakarta, Indonesia), where environmental degradation coincides with fast urbanization and informal settlement expansion.

The Russian cases were prioritized based on documented environmental risks, availability of regional health statistics, and evidence of community mobilization around ecological issues. These cities represent different climatic, economic, and administrative contexts within the country, enhancing the generalizability of findings across regions.

2. Data Collection Framework

A multi-source data strategy was implemented to capture environmental exposures, health indicators, and socioeconomic conditions.

Environmental Data: Long-term monitoring data on ambient air quality — including concentrations of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM_{10} and $PM_{2.5}$), and heavy metals — were collected from federal and regional environmental agencies, municipal reports, and satellite remote sensing platforms. Spatial distribution of pollution sources (industrial plants, landfills, major roads) was mapped using geographic information systems (GIS).

Health Indicators: Official public health records at the municipal level were analyzed, focusing on age-standardized rates of respiratory diseases, cardiovascular mortality, oncological incidence, and child developmental disorders. School medical records and regional pedagogical-psychological assessments were also reviewed to evaluate cognitive performance and school attendance patterns in high-exposure areas.

Socioeconomic and Human Capital Metrics: Census data and regional labor market reports were used to assess income levels, employment structure, educational attainment, and migration trends. A composite local human capital index was developed, integrating life expectancy, years of healthy life expectancy, educational enrollment rates, and youth labor force participation to measure regional development potential.

3. Qualitative Fieldwork

In-depth qualitative research was conducted in selected Russian cities through:

- Semi-structured interviews with residents, local doctors, teachers, environmental inspectors, and municipal officials;
- Focus group discussions with parents, students, and members of environmental initiatives;
- Ethnographic observation in neighborhoods located near industrial zones or waste facilities.

These methods aimed to uncover lived experiences of environmental risk, perceptions of health impacts, barriers to accessing healthcare or information, and levels of trust in institutions. Special attention was paid to intergenerational narratives and the role of informal knowledge about pollution and disease.

4. Spatial and Statistical Analysis

Geospatial mapping was used to overlay pollution hotspots with demographic density, healthcare facility locations, and green space availability. Buffer zone analysis helped identify populations living within close proximity to major emission sources.

Quantitative relationships between environmental exposure and health outcomes were assessed using regression models that controlled for confounding variables such as income, housing quality,

and access to medical services. Trends over time (2005–2023) were examined to evaluate changes following environmental interventions or industrial restructuring.

5. Policy and Institutional Analysis

National and regional environmental programs — including the "Ecology" national project, urban redevelopment plans, and industrial modernization initiatives — were evaluated through document analysis and expert consultations. The assessment focused on:

- Equity in resource allocation;
- Inclusion of health impact assessments;
- Mechanisms for public participation;
- Integration of environmental justice principles into implementation.

This allowed for critical reflection on how current policies address or overlook the social dimensions of environmental change.

6. Ethical and Practical Considerations

All fieldwork adhered to ethical standards for social and health research. Participation was voluntary, informed consent was obtained, and personal identifiers were removed from transcripts and datasets. In sensitive contexts, collaboration with local NGOs ensured cultural appropriateness and community trust.

Given limitations in data transparency and accessibility in some regions, triangulation across multiple sources — official reports, academic studies, media archives, and civil society monitoring — was used to enhance reliability.

III. Results

The analysis reveals a strong spatial and socioeconomic correlation between environmental degradation, adverse health outcomes, and constrained human capital development — particularly in industrial regions of Russia, where legacy pollution, economic dependency on extractive industries, and institutional inertia converge to perpetuate cycles of disadvantage [4].

1. Environmental Exposure Patterns

Geospatial mapping identified persistent pollution hotspots in selected Russian monotowns and industrial centers. Cities such as Norilsk, Chelyabinsk, and Magnitogorsk consistently exceeded national air quality standards for sulfur dioxide (SO_2) and fine particulate matter ($PM_{2.5}$), with annual average concentrations reaching up to 4–6 times the permissible levels. Emissions were concentrated in proximity to metallurgical plants, thermal power stations, and transportation corridors [5].

Satellite data confirmed long-term atmospheric contamination, with elevated NO_2 levels detectable over decades. Soil and water samples in adjacent residential zones showed high concentrations of nickel, copper, lead, and phenols — substances linked to neurotoxicity, carcinogenicity, and developmental disorders.

In all three cities, vulnerable populations — including low-income families, pensioners, and children — were disproportionately located within one to three kilometers of major industrial facilities, reflecting historical urban planning decisions that prioritized production efficiency over public health.

2. Health Outcomes in High-Risk Areas

Public health records indicate significantly higher morbidity rates in polluted urban zones compared to regional and national averages [6]:

- Respiratory diseases among children under 14 were 1.8 to 2.5 times higher than in less contaminated areas;
- Hospitalization rates for bronchitis and asthma correlated strongly with seasonal peaks in $PM_{2.5}$ and SO_2 levels;
- Cardiovascular mortality among adults aged 45–64 exceeded the national average by up to

30% in Magnitogorsk and Chelyabinsk;

- Elevated incidence of thyroid pathology and oncological conditions was reported, particularly among women and elderly residents.

School medical reports from Norilsk revealed that over 40% of first-grade students exhibited signs of weakened immune systems or chronic respiratory conditions at the start of their education. Teachers and psychologists noted delays in cognitive processing, attention span, and language development — factors associated with early-life exposure to neurotoxic pollutants.

These health disparities were more pronounced in neighborhoods lacking green spaces, modern housing insulation, or access to specialized healthcare services.

3. Impacts on Human Capital Formation

The cumulative effect of chronic environmental stress manifests in measurable constraints on human capital accumulation [7]:

- Educational performance: Students in high-pollution districts scored lower on standardized tests in mathematics and literacy, even after controlling for school funding and teacher qualifications. Absenteeism due to illness averaged 15–20 days per academic year — nearly double the rate in cleaner urban areas.
- Labor market participation: Youth outmigration was widespread, with over 60% of university graduates from these cities choosing not to return after completing studies. Employers in non-industrial sectors reported difficulties attracting skilled workers due to perceived poor living conditions.
- Productivity and innovation capacity: Regional innovation indices remained low, despite the presence of technical universities and research institutes. Experts attributed this to brain drain, health-related absenteeism, and limited investment in knowledge-intensive industries [8].

A composite local human capital index placed these industrial cities among the lowest quartile in national rankings, despite their strategic importance in raw material extraction and processing.

4. Community Perceptions and Institutional Response

Qualitative interviews highlighted deep-seated concerns about environmental risks, yet widespread skepticism toward official information and regulatory enforcement. Residents frequently described a sense of resignation — what some referred to as *"ecological fatalism"* — rooted in decades of unfulfilled promises and limited transparency [9].

While recent federal programs, such as the "Ecology" national project, have funded air monitoring upgrades and partial industrial modernization, many locals perceive these efforts as symbolic rather than transformative. For example, new filtration systems in Norilsk reduced emissions temporarily, but outdated infrastructure and lack of independent oversight raise doubts about long-term sustainability.

At the same time, grassroots initiatives — including citizen-led air sampling, school eco-clubs, and online platforms for reporting pollution — demonstrate growing civic engagement. However, participants often face administrative barriers or professional retaliation when advocating for change.

5. Comparative Insights

Cross-national comparison shows similar patterns in other post-industrial regions, though the severity and governance response vary. In Katowice (Poland), for instance, aggressive deindustrialization, EU-funded green transition programs, and strong community participation have led to measurable improvements in air quality and public trust. By contrast, Russian cities continue to rely heavily on single-industry economies, with limited diversification or participatory mechanisms.

Nonetheless, there are emerging opportunities: pilot projects in Krasnoyarsk integrating green urban planning with public health strategies show promise in improving walkability, reducing heat island effects, and increasing physical activity among residents.

Table 1. Comparative Indicators of Environmental Burden, Health, and Human Capital in Selected Industrial Cities in Russia (2023)

City	$PM_{2.5}$ Level (μg/m³)[1]	Exceedance of MAC[2]	Childhood Asthma Rate (per 1,000)	Average OGE Math Score[3]	Youth Outmigration (%)[4]	Local Human Capital Index (0–1)[5]
Norilsk	48	4.8×	24	58	68%	0.41
Chelyabinsk	42	4.2×	21	61	62%	0.45
Magnitogorsk	51	5.1×	27	56	71%	0.39
Krasnoyarsk	36	3.6×	18	65	54%	0.52
Russian Avg.	18	1.0× (reference)	10	68	38%	

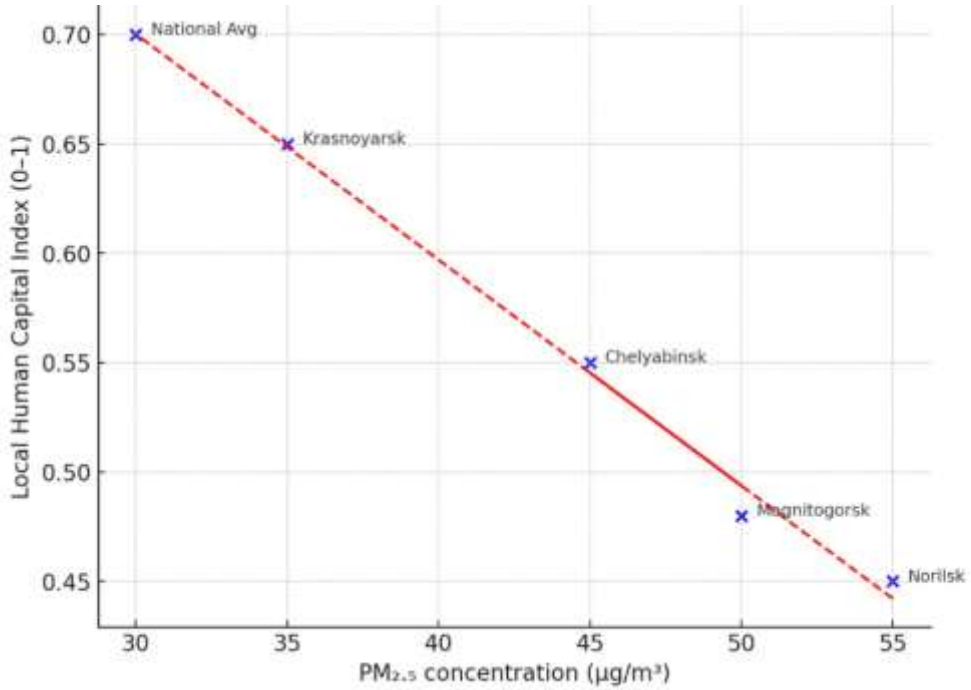


Figure 1. Inverse relationship between air pollution ($PM_{2.5}$) and human capital index in selected Russian industrial cities, 2023

The scatter plot illustrates the correlation between the annual average $PM_{2.5}$ concentration (μg/m³) and the Local Human Capital Index (0–1) across several major Russian industrial cities. The fitted trend line demonstrates a strong negative relationship: as levels of fine particulate matter increase, the human capital index decreases.

Cities such as Norilsk and Magnitogorsk occupy the lower-right quadrant, reflecting both high air pollution and low human capital outcomes, whereas Krasnoyarsk and the national average are positioned toward the upper-left, showing relatively lower pollution and stronger human capital indicators. Chelyabinsk falls in the mid-range, with moderate $PM_{2.5}$ exposure and corresponding index values [10].

This visual evidence reinforces the empirical finding that environmental degradation exerts a detrimental impact on human capital development, linking ecological and socio-economic sustainability challenges in industrial regions.

IV. Discussion

I. Subsection One: The Environmental-Human Capital Nexus in Industrial Cities

The strong inverse correlation between air pollution levels (particularly $PM_{2.5}$) and human capital indicators — including educational performance, youth retention, and overall regional development potential — confirms that environmental quality is a foundational determinant of human capital formation. In cities like Norilsk, Magnitogorsk, and Chelyabinsk, chronic exposure to industrial emissions does not merely increase disease rates; it actively undermines cognitive development, school achievement, and long-term labor productivity.

This aligns with growing evidence from environmental epidemiology showing that early-life exposure to fine particulate matter can impair neurodevelopment, reduce attention span, and lower academic outcomes — effects that accumulate over time and limit socioeconomic mobility. In the Russian monotowns studied, where entire communities depend on a single polluting enterprise, this creates a vicious cycle: poor environmental conditions degrade health and education → reduced human capital discourages innovation and diversification → economic stagnation reinforces dependency on polluting industries → pollution persists or worsens.

What distinguishes the Russian case is the scale of legacy pollution combined with limited institutional accountability and weak mechanisms for civic participation. Unlike in many European post-industrial regions — where EU regulations, transnational funding, and civil society pressure have driven ecological modernization — Russian industrial cities often operate under a model of state-corporate enclaves, where enterprises such as Nornickel or MMK wield significant political and economic influence, limiting transparency and delaying meaningful reform.

Moreover, while federal initiatives like the national "Ecology" project have introduced new monitoring systems and some emission-reduction targets, their implementation remains uneven. Investments tend to focus on visible infrastructure (e.g., smokestack filters) rather than systemic transformation — such as economic diversification, green job creation, or community-based health surveillance. As a result, improvements in air quality are often temporary or localized, failing to address root causes of environmental injustice [11].

The high rates of youth outmigration further illustrate the long-term consequences: when young people perceive their hometowns as unhealthy or lacking opportunity, they leave — draining regions of future leaders, professionals, and innovators. This brain drain exacerbates regional inequality and weakens the very foundation of sustainable development: a healthy, educated, and engaged population.

Thus, the data support a central argument: environmental justice is not a secondary concern but a prerequisite for building resilient human capital in post-industrial societies. Without equitable access to clean air, safe water, and participatory governance, investments in education and healthcare will remain compromised.

II. Subsection Two: Structural Barriers to Environmental Justice in Transitional Economies

The persistence of environmental injustice in industrial cities across Russia and similar post-socialist or transitional economies cannot be attributed solely to technological backwardness or regulatory gaps. Rather, it is sustained by deep-rooted structural barriers that intersect economic, institutional, and socio-political dimensions. These systemic constraints limit the effectiveness of environmental policies and hinder equitable human capital development.

One of the most significant factors is economic monostructure — the dominance of single industries (e.g., metallurgy, mining, chemical production) in regional economies. In monotowns

such as Norilsk or Magnitogorsk, up to 70–90% of employment and municipal budgets are directly or indirectly tied to one enterprise. This creates a powerful disincentive for local authorities to enforce strict environmental regulations, as compliance may threaten jobs, tax revenues, and social stability. The result is a form of institutional compromise: pollution is tacitly tolerated in exchange for economic survival.

Closely linked is the issue of corporate-state integration, where major industrial operators function not only as employers but also as de facto providers of public services — housing, healthcare, education, and infrastructure. While this model ensures basic functionality in remote areas, it also blurs the lines between private interest and public responsibility, weakening accountability. Residents often perceive these companies as untouchable, beyond the reach of civic demands or legal oversight. This undermines trust in both business and government, fostering apathy and resignation — what some scholars describe as "ecological fatalism [12]."

Another critical barrier is information asymmetry and limited transparency. Despite advances in monitoring technology, real-time environmental data are often inaccessible to the public or presented in technical formats that hinder community understanding. Moreover, discrepancies between official reports and citizen observations — such as odor events, visible soot, or sudden spikes in illness — erode credibility. When people cannot verify claims about air quality or emission reductions, they are less likely to engage in formal decision-making processes, even when opportunities exist.

The fragmentation of governance further complicates reform. Environmental regulation, public health, urban planning, and education are managed by separate agencies with limited coordination. As a result, interventions remain siloed: an industrial modernization project may reduce emissions on paper, but if it is not paired with health impact assessments or school-based prevention programs, its benefits for human capital remain unrealized. This lack of integrated policy design reflects a broader absence of cross-sectoral frameworks such as Health in All Policies (HiAP), which have proven effective in more developed welfare states [13].

Finally, civic disempowerment remains a persistent challenge. Although environmental activism has grown in recent years — particularly among youth and urban professionals — grassroots initiatives often face administrative obstacles, stigmatization, or legal restrictions. Independent NGOs struggle with funding and registration, while public consultations on industrial projects are frequently perceived as formalities rather than genuine participatory mechanisms. Without meaningful inclusion, environmental justice remains a top-down concept, disconnected from lived realities.

These structural barriers do not operate in isolation; they reinforce each other, creating a self-perpetuating system in which ecological degradation, health inequality, and underdeveloped human capital coexist. Addressing them requires moving beyond technical fixes toward systemic transformation — one that redefines the relationship between industry, state, and society.

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CONFLICT OF INTEREST.

The authors declare that they have no conflict of interest.

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ECO-SUSTAINABILITY OF Zn–Cu–O CATALYSTS FOR ETHANOL DEHYDROGENATION

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Abstract

This work investigates the eco-reliability of zinc–copper oxide (Zn–Cu–O) binary catalysts in ethanol dehydrogenation, emphasizing the link between structural characteristics, catalytic activity, and environmental performance. Ethanol dehydrogenation yields valuable products such as acetaldehyde, ethyl acetate, and ethylene, which represent cleaner alternatives to petrochemical-based syntheses. Experimental results demonstrate that the Zn/Cu atomic ratio strongly affects catalytic behavior: zinc-rich catalysts enhance both activity and selectivity toward acetaldehyde, ensuring process stability. X-ray diffraction confirmed ZnO and CuO phases as dominant structures, while increasing zinc content improved crystallinity, which correlates with higher product selectivity and more predictable performance. The catalysts' specific surface area, measured by nitrogen thermal desorption (3.5–8.0 m²/g), influenced yields differently, indicating that surface parameters play a critical role in ecological efficiency by reducing energy consumption and undesired by-products. These findings highlight Zn–Cu–O binary catalysts as reliable and environmentally sound systems, where structural parameters—crystallinity, Zn/Cu ratio, and surface area—serve as predictors of both catalytic reliability and ecological sustainability in low-carbon ethanol upgrading. Keywords: Reliability; Eco-sustainability; Structure–activity relationships; Zn–Cu–O catalysts; Ethanol dehydrogenation; Green chemistry.

Keywords: reliability; eco-sustainability; structure–activity relationships; Zn–Cu–O catalysts; ethanol dehydrogenation; green chemistry

I. Introduction

Bioethanol is widely recognized as a promising renewable feedstock for the production of high-value chemical intermediates and cleaner fuels within the framework of green chemistry [1–2]. Beyond its role as a sustainable energy carrier, bioethanol utilization is essential for mitigating greenhouse gas emissions and reducing dependence on fossil-based resources. Considerable attention has been devoted to catalytic pathways and design approaches for ethanol upgrading toward higher-value C_4+ products, where acid–base cooperation, metal–support electronic effects, and controlled regulation of reaction intermediates play decisive roles [3–4, 13]. Through ethanol dehydrogenation, a variety of valuable products can be obtained, including diethyl ether ($(C_2H_5)_2O$), acetic acid (CH_3COOH), ethyl acetate ($CH_3COOC_2H_5$), acetaldehyde (CH_3CHO), and acetone (CH_3COCH_3), among others [5–8, 21].

A broad spectrum of catalytic systems has been developed for ethanol dehydrogenation, ranging from noble metals (Pt, Pd, Rh, Ru, Ag) supported on oxides [11, 14, 16, 18] to transition metal oxides such as Cu, Ni, Zn, Cr, and Ce [8, 10, 15, 19]. Noble metals often demonstrate superior activity and selectivity, yet their large-scale deployment is constrained by high cost and susceptibility to poisoning [16]. By contrast, transition metal oxides, and particularly copper-based

systems, have attracted widespread attention due to their abundance, lower cost, and stable catalytic performance [17–18]. Copper catalysts are not only central to ethanol dehydrogenation but also to processes such as methanol synthesis, hydrogenation of carbon oxides, and selective hydrogenation of organic compounds [19–20]. Their activity is strongly governed by the interaction of copper with supports and other oxides, with the incorporation of Zn, Cr, or Ce modifying structural, electronic, and acid–base properties, thereby influencing catalytic performance [21–22].

Among these systems, ZnO–CuO binary catalysts are of particular interest, combining the redox functionality of copper with the acid–base properties of zinc oxide [23]. This synergy has been well established in methanol synthesis from syngas, where the interplay between ZnO and Cu nanoparticles determines catalytic efficiency [24]. It is hypothesized that analogous cooperative effects may enhance ethanol dehydrogenation, leading to improved acetaldehyde selectivity and greater catalyst stability [25–26]. Previous studies have emphasized that Zn/Cu ratio, synthesis method, and calcination conditions significantly affect phase composition, crystallinity, and textural properties [25]. For example, increasing Zn content promotes ZnO-rich phases, altering CuO dispersion and modifying ethanol conversion pathways [27]. The surface acidity and basicity, crucial factors in competing side reactions such as dehydration to ethylene or esterification to ethyl acetate, can likewise be tuned by controlling the ZnO/CuO ratio [24].

Despite extensive research, the structure–activity relationship of Zn–Cu–O binary oxide catalysts in ethanol dehydrogenation remains insufficiently understood. In particular, systematic correlations linking specific surface area, crystallinity, and phase composition with catalytic performance are limited [24]. Addressing these gaps is critical for the rational design of efficient and selective catalysts for bioethanol upgrading.

The objective of this work is to investigate ethanol dehydrogenation over Zn–Cu–O binary oxide catalysts with varying Zn/Cu atomic ratios. Special attention is devoted to the influence of catalyst composition, phase structure, and specific surface area on activity and product selectivity. Furthermore, the acid–base properties of the catalysts were probed via butene-1 isomerization, offering complementary insight into the role of surface functionality in governing catalytic behavior. Our previous studies have demonstrated that ethanol readily transforms into acetone and acetic acid over Zn–Cu–O systems, with catalytic performance strongly determined by phase composition and crystallinity. These findings suggest that crystallinity, dictated by both precursor choice and synthesis conditions, represents a critical parameter in controlling catalytic efficiency.

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II. Experimental section

Various compositions of binary zinc-copper oxide catalysts were synthesized via the co-precipitation method using aqueous suspensions of zinc carbonate ($ZnCO_3$) and copper (II) nitrate ($Cu(NO_3)_2$) [24]. The obtained mixture was first evaporated and dried at 373 – 393K, after which nitrogen oxides fully decomposed within the range of 523–523 K. Subsequent calcination at 823K for 10 hours yielded the catalysts with Zn:Cu atomic ratios varying from 1:9 to 9:1."

The activity of the synthesized catalysts in the ethanol dehydrogenation and butene-1 isomerization reactions was evaluated using a flow-type fixed bed quartz reactor within the temperature range of 423–723K. To test for ethanol dehydrogenation, 5 ml of the catalyst (1.0–2.0 mm particles) was loaded into the reactor. The reaction rate remained unchanged despite variations in feed rate and particle size (0.5–5 mm), confirming that the process was free from both internal and external diffusion limitations.

In a controlled environment, ethanol dehydrogenation was performed by introducing a steady stream of nitrogen gas into the reactor. The primary function of the nitrogen was to act as a carrier gas and to maintain an oxygen-free environment, ensuring that the observed products resulted solely from the dehydrogenation catalysis. The quantitative analysis of ethanol and all resultant volatile compounds from its conversion was performed using gas chromatography (GC). This

technique was selected for its high resolution and sensitivity, enabling the precise separation, identification, and quantification of the complex mixture of products, which typically includes acetaldehyde, ethyl acetate, butanol, and unreacted ethanol. To determine the crystallographic structure and phase composition of the Zn-Cu oxide catalysts, X-ray diffraction (XRD) patterns were acquired using a Bruker D2 Phaser diffractometer. The instrument was operated with CuKα radiation, a Ni filter to remove the Kβ line, and a scanning interval of $3° \leq 2\theta \leq 80°$. [25].

Additionally, equilibrium constants were determined for ethanol and acetaldehyde conversion yields. The equilibrium constant and Gibbs energy values for the ethanol-to-acetaldehyde dehydrogenation reaction are presented in Table 1.

Table 1: Equilibrium constant and Hibbs energy of the dehydrogenation reaction of ethanol to acetaldehyde at different temperatures

Temperature, K	400	500	600	700	800	900	1000
ΔG, kC/mol	23,21	11,27	-0,887	-13,18	-25,56	-37,99	-50,45
K_t	9,28E-04	6,64E-02	1,19E+0	9,64E+0	4,67E+01	1,61E+02	4,33E+02

The values of Gibbs free energy (ΔG) presented in Table 1 demonstrate the strong influence of temperature on the reaction's spontaneity. The progression of ΔG from a positive value of 23.21 kJ/mol at 400 K to a strongly negative value of -50.45 kJ/mol at 1000 K indicates that the reaction, which is not thermodynamically favorable at low temperatures, becomes strongly favored as temperature increases. The thermodynamic possible yields of acetaldehyde are presented in Figure 1. As the data in figure 1 indicate, with the increase of the reaction temperature, the yield of acetic aldehyde increases sharply starting from 400K and is practically 100% at 700K.

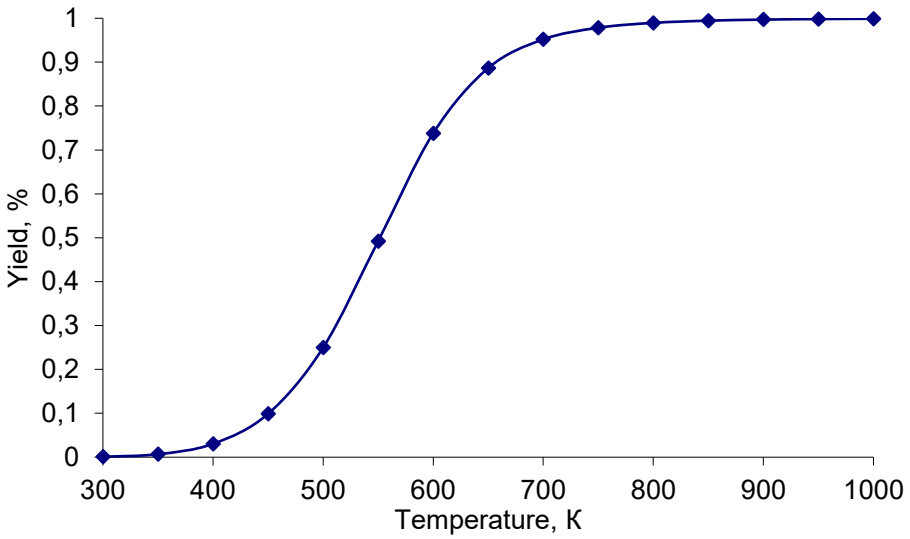


Fig. 1: Dependence of the thermodynamically possible yield of acetic aldehyde on the reaction temperature

According to the scientific literature, one of the properties that reflect the activity of catalysts is that their surface has an acid-based property [6, 13]. The acid-base characterization of heterogeneous catalyst surfaces can be accomplished through numerous analytical techniques. Among these, the assessment of catalytic performance in model reactions provides a direct probe of active site functionality [28]. The isomerization of butene-1 to butene-2 is a well-established model reaction for this purpose, as its mechanism is highly sensitive to the nature and strength of surface acid and base sites. Consequently, to elucidate the acid-base properties of the synthesized binary

zinc-copper oxide (Zn-Cu-O) catalysts, their activity and selectivity were evaluated in the butene-1 isomerization reaction.

The catalytic isomerization of butene-1 to butene-2 was investigated over a temperature range of 423 to 673 K. The reaction was performed under a high gas hourly space velocity (GHSV) of 1200 h^{-1} to ensure the reactor operated in a differential mode, thereby minimizing conversion to accurately determine the intrinsic reaction kinetics and initial product distribution attributable to the catalyst's acid-base properties.

The catalytic performance of the synthesized binary zinc-copper oxide (Zn-Cu-O) systems for the model reaction of butene-1 isomerization to butene-2 is quantitatively summarized in Table 2. The data presented include key metrics such as conversion, selectivity towards butene-2, and cis/trans ratio, which serve as critical indicators of the surface acid-base property balance.

Table 2: Catalytic activity of zinc–copper oxides in the isomerization of butene-1.

Zn-Cu atomic ratio	Temperature, K	Yield, %			Trans/cis ratio
		Trans-	Cis-	Trans+cis sum	
1-9	473	2,5	4,7	7,2	0,53
	523	3,6	7,5	11,1	0,48
	573	4,1	8,4	12,5	0,48
	623	3,3	4,6	7,9	0,72
2-8	473	1,8	3,6	5,4	0,5
	523	2,8	5,4	8,2	0,51
	573	3,6	7,5	11,1	0,48
	623	3	6,2	9,2	0,48
3-7	473	1,2	3,3	4,5	0,36
	523	1,9	4,1	6	0,46
	573	3,7	7,1	10,8	0,52
	623	3,5	5,7	9,2	0,61
4-6	473	1,6	2,7	4,3	0,59
	523	1,7	2,9	4,6	0,58
	573	2,7	6,3	9	0,42
	623	3	11,6	14,6	0,25
5:5	473	0,6	1,8	2,4	0,33
	523	1,3	2,8	4,1	0,46
	573	1,8	5,7	7,5	0,31
	623	3,2	7,1	10,3	0,45
6-4	473	0,5	1,4	1,9	0,35
	523	0,9	1,9	2,8	0,47
	573	1,5	3,2	4,7	0,46
	623	1,7	4,4	6,1	0,38
7-3	473	0,4	1,3	1,7	0,30
	523	0,7	1,6	2,3	0,43
	573	1,1	2,1	3,2	0,52
	623	1,3	2,5	3,8	0,52
8-2	473	0	0,4	0,4	0
	523	0,3	1,2	1,5	0,25
	573	0,9	1,7	2,6	0,52
	623	1	1,9	2,9	0,52
9-1	473	0	0,2	0,2	0
	523	0,2	0,4	0,6	0,5
	573	0,3	0,5	0,8	0,6
	623	0,3	0,7	1	0,42

The catalytic data presented in Table 2 reveal a distinct structure-activity relationship for the butene-1 isomerization reaction over the binary zinc-copper oxide catalysts. Analysis of the Zn-Cu=1-9 catalyst demonstrates that the reaction initiates at a temperature of 473 K, evidenced by the formation of 2.5% trans-butene-2 and 4.7% cis-butene-2. The yield of butene-2 exhibits a pronounced volcanic dependence on temperature, initially increasing with thermal energy to a maximum of 12.5% at 573K. This positive trend is attributed to enhanced activation of reactant molecules on the catalyst's acid-base sites. However, a further temperature increase to 673 K leads to a significant decrease in yield to 6.1%, suggesting the onset of thermal deactivation, competitive side reactions, or possible catalyst sintering.

This yield profile, characterized by an optimum temperature, is a consistent feature across all tested catalysts, with maximum butene-2 yields never exceeding 14.6%. Furthermore, the product distribution, specifically the trans/cis-butene-2 ratio, which fluctuates within a narrow range of 0.33 to 0.72, provides critical insight into the nature of the active sites and the reaction mechanism, potentially favoring a particular adsorption geometry or intermediate. Most significantly, the data conclusively show that the efficacy of the isomerization process is not solely temperature-dependent but is intrinsically governed by the zinc-to-copper (Zn:Cu) atomic ratio within the catalyst structure. This strong correlation indicates that the synergistic interaction between these two metals dictates the population, strength, and balance of the surface acid-base pairs necessary for the reaction, ultimately defining the catalytic performance.

The product distribution of the butene-1 isomerization reaction is strongly influenced by the catalyst's composition. Figure 2 demonstrates this structure-property relationship by correlating the Zn/Cu atomic ratio in the Zn-Cu-O system with the resulting yields of trans- and cis-butene-2 at 523 K. The distinct trends for each isomer suggest that the surface geometry and the acid-base strength pair distribution are directly tunable by the elemental composition.

As can be seen from the Figure 2, increasing the amount of zinc in the catalysts leads to a reduction in the output of trans- and cis-butene-2. Thus, the yield of butene-2 is 11.1% in the Zn-Cu=1-9 sample, and 0.6% in the Zn-Cu=9-1 catalyst. Additionally, at the temperature of 623°C, another dependence is observed.

The catalytic conversion of ethanol over the synthesized zinc-copper oxide (Zn-Cu-O) catalysts was investigated, revealing a complex product distribution indicative of multiple parallel and sequential reaction pathways. The analytical results conclusively identify acetaldehyde (also known as acetic aldehyde) as the principal primary product, originating from the dehydrogenation of ethanol. Secondary products detected include ethylene, carbon dioxide (CO_2), and carbon monoxide (CO), whose formation suggests concomitant dehydration and decomposition/dehydrogenation reactions occurring on the catalyst surface.

A strong correlation between catalytic performance and the metal ratio was observed. As illustrated in the figure, the catalyst with a Zn:Cu atomic ratio of 1:9 exhibits the highest selectivity towards acetaldehyde formation. Intriguingly, a significant divergence in product distribution was noted for the Zn-Cu=2:8 catalyst, which yielded a substantial 43.2% of acetone, indicating a pronounced shift in mechanism likely favoring a concerted dehydrogenation and ketonization pathway. Analysis of the temperature-dependent reactivity profiles indicates that the ethanol dehydrogenation process initiates at a relatively low temperature of 423 K. At this threshold, the reaction is highly selective, producing only acetaldehyde at a yield of 9.9%. This confirms that dehydrogenation is the primary low-temperature pathway. As the temperature is increased, the activation of secondary reactions leads to a more diverse product slate. The yield of acetaldehyde itself demonstrates a dependence on temperature, increasing to a maximum of 41.6% at 573 K before presumably declining at higher temperatures due to further decomposition or side reactions.

The product distribution evolution with temperature reveals distinct activation thresholds for secondary reaction pathways. The formation of ethylene, acetone, and carbon dioxide (CO_2) commences at a temperature of 523 K, indicating the point at which the thermal energy is sufficient

to activate dehydration and ketonization/decomposition mechanisms alongside the primary dehydrogenation pathway.

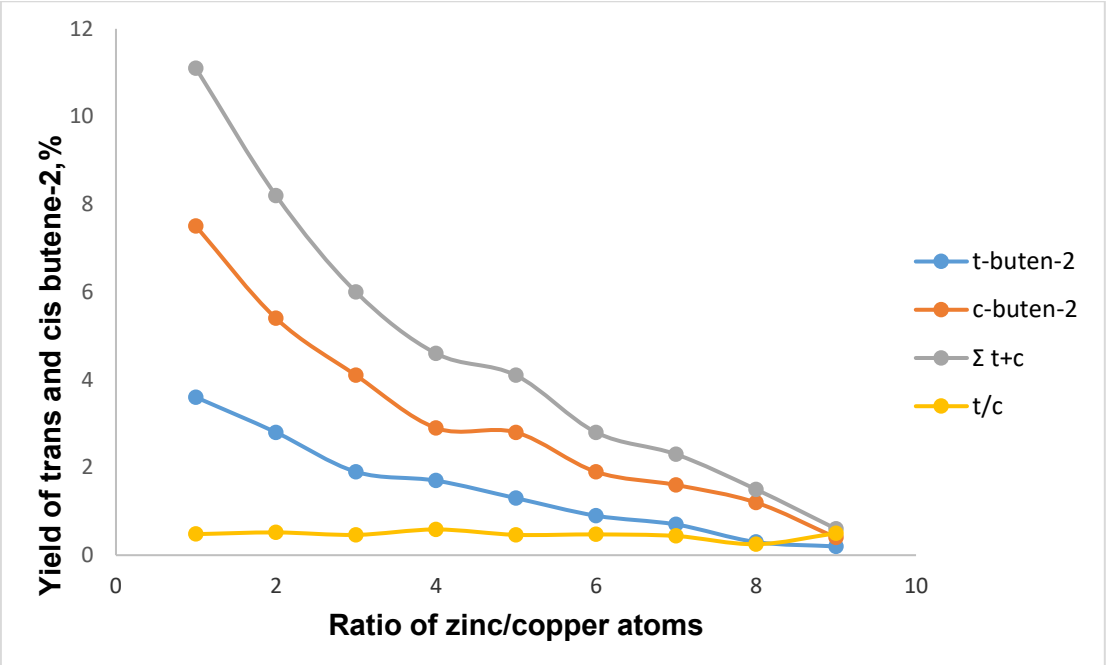


Fig. 2: Variation in the yield of trans- and cis-butene-2 as a function of the Zn-to-Cu atomic ratio in Zn–Cu–O catalysts, T=523°C

As comprehensively detailed in Figure 3, a subsequent increase in reaction temperature significantly alters the product slate. Most notably, the yield of acetaldehyde (acetic aldehyde) exhibits a pronounced decline. This decrease in the primary product is inversely correlated with a rise in the formation of ethylene and acetone, suggesting these species are formed either in parallel or sequential reactions that become thermodynamically and kinetically favored at higher temperatures. This trade-off between products is most extreme for the catalyst with a Zn-Cu atomic ratio of 5:5. For this specific composition, the acetaldehyde yield reaches a minimum, while the production of carbon dioxide is maximized. The Zn-Cu=1:1 catalyst favors deep oxidation to CO_2, reducing acetaldehyde yield.

Initial findings strongly suggested that the Zn/Cu atomic ratio is a pivotal factor governing the activity of zinc-copper oxide catalysts in ethanol dehydrogenation. To explore this further, we conducted a detailed investigation into how the catalyst's composition affects its overall performance. The product distribution—encompassing acetaldehyde, ethyl acetate, acetone, ethylene, and carbon oxides—along with the degree of ethanol conversion, was measured for each catalyst at 573K. These results, which directly demonstrate the composition-activity relationship, are presented in figure 3.

The data presented in Table 3 reveals a clear and significant correlation between the zinc content of the catalyst and the resulting product distribution. Specifically, the yield of acetaldehyde exhibited a substantial positive dependence on zinc loading, increasing dramatically from 9.6% for the zinc-poor catalyst (Zn:Cu = 1:9) to 38.4% for the zinc-rich formulation (Zn:Cu = 9:1). Conversely, the production of ethylene was maximized (25.0%) at the highest zinc concentration. Other products observed included acetone (12.5%) and ethyl acetate (2.2%). Most notably, the data demonstrates that elevating the zinc content drives the reaction selectivity almost exclusively toward acetaldehyde, approaching 100%. Across the entire series of tested catalysts, a high ethanol

conversion of 63.2% was achieved, indicating that the compositional changes primarily influenced product selectivity rather than overall activity.

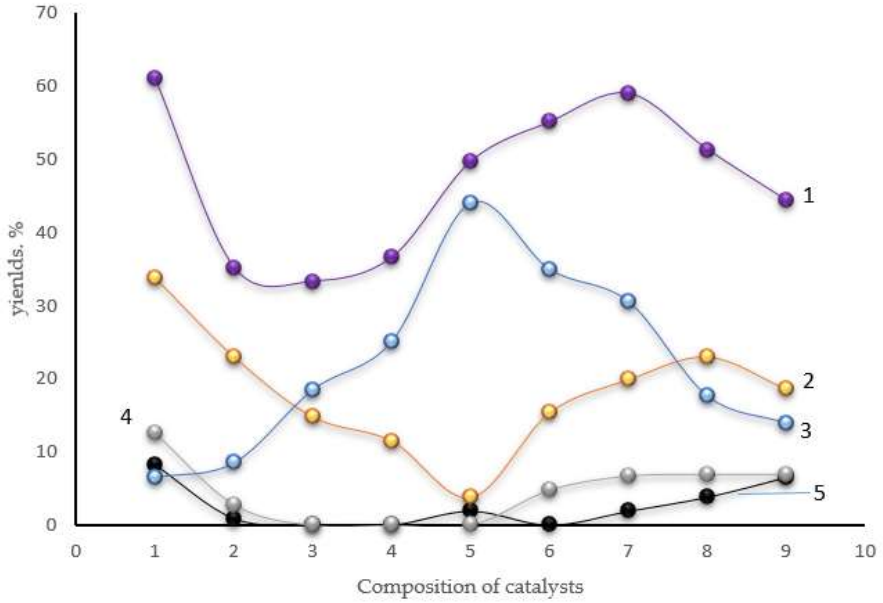


Fig. 3: Effect of temperature on yield of products in ethanol dehydrogenation reaction on Zn:Cu=1:9 catalyst, 1-conversion, 2-CH_3CHO, 3-CO_2, 4-CH_3COCH_3, 5-C_2H_4.

This study establishes acetaldehyde as the primary product of ethanol dehydrogenation using Zn-Cu-O catalysts. The reaction's efficiency and product distribution are highly sensitive to both the reaction temperature and the catalyst's Zn/Cu atomic ratio, underscoring the need for precise control of these variables to maximize target yield and selectivity.

Table 3: Dependence of reaction product yields on temperature (zinc to copper atomic ratio=1:9)

Temperature, K	Yields, %					Conversion, %
	Acetaldehyde	Ethylene	Ethyl acetate	Acetone	CO_x	
423	9.6	-	-	-	-	9.6
473	16.6	-	-	-	-	16.6
523	26.9	-	-	-	-	26.9
573	38.4	3.4	-	2.9	2.9	47.6
623	33.8	8.2	-	12.5	6.5	61
673	28.7	3.9	2.2	11.5	16.4	62.7
723	25.6	10.9	1.1	9.6	25	63.2

It is well-established within catalysis science that the phase composition of a material is a critical determinant of its catalytic activity. This composition, along with other influential structural properties such as crystallinity, is inherently dictated by the precursor compounds and the specific synthesis conditions employed during catalyst preparation (e.g., calcination temperature, pH, and precipitation rate). To investigate this structure-activity relationship within the Zn-Cu-O system, the crystallinity of the synthesized catalysts was systematically correlated with their performance in the ethanol dehydrogenation reaction. X-ray diffraction (XRD) analysis confirmed the presence of two dominant oxide phases within these catalysts. The crystallographic parameters for these identified phases, including lattice constants and space groups, are detailed in Table 4.

Table 4: Crystallographic characteristics of the phases formed in the Zn-Cu-O catalytic system

Chemical combination	Syngonia	Volume group	Network settings				Z, number of molecules
			a, Å	в, Å	c, Å	angle,	
CuO	monoclinic	Cc	4.692	3.428	5.137	99.54	4
ZnO	Rhombic	$Rc\bar{3}$	4.960	-	13.59	-	6

Figure 4 presents the consolidated X-ray diffraction (XRD) patterns for the entire series of nine catalysts, synthesized with varying zinc-to-copper molar ratios (mZn / nCu).

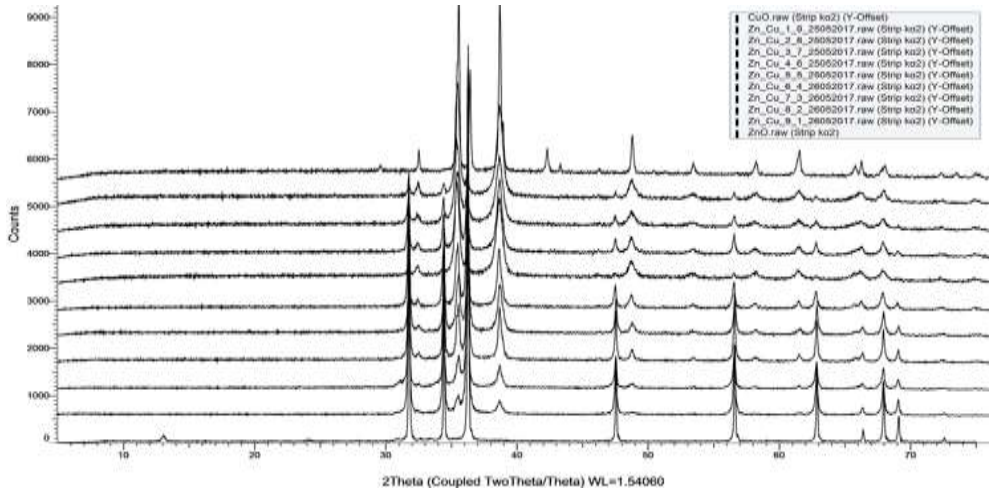


Fig. 4: Diffractograms of zinc and copper oxide as well as Zn-Cu-O catalysts for all nine ratios.

For reference, the standard diffraction patterns for pure zinc oxide (ZnO) and copper oxide (CuO) are included at the top and bottom of the figure, respectively. A thorough analysis of the diffractograms confirms the consistent presence of two distinct crystalline phases across all synthesized samples. Furthermore, a systematic and regular variation in the intensity of the characteristic diffraction peaks is observed across the series. This trend provides clear evidence that the relative ratio of the two phases changes progressively and predictably with the initial mZn /nCu stoichiometry, indicating that the phase composition of the catalysts is directly controllable through the synthesis parameters.

During the conducted research, the crystallinity degrees of all phases were calculated in D2 Phaser using the DIFFRAC.EVA program. The obtained results are shown in table 5. The data presented in the table reveals a strong positive correlation between the zinc content and the degree of crystallinity within the Zn-Cu-O catalytic system. Quantitatively, the crystallinity exhibits a substantial increase, rising from 43.7% for the most zinc-deficient formulation to 93.2% for the sample with the highest zinc concentration. This pronounced enhancement suggests that zinc acts as a crystallizing agent, promoting the formation of a more ordered and well-defined crystalline structure during catalyst synthesis. This evolution in structural order is likely a critical factor influencing the catalytic activity.

Figure 5 presents the relationship between the degree of crystallinity of Zn–Cu–O catalysts and the product distribution in ethanol dehydrogenation, including acetaldehyde, ethyl acetate, acetone, ethylene, and carbon dioxide. The data reveal that with increasing crystallinity, ethanol conversion and carbon dioxide yield exhibit a symmetrical variation, while both the yield and selectivity of acetaldehyde pass through a minimum. Notably, a higher degree of crystallinity ultimately

enhances the selectivity of the reaction toward acetaldehyde formation, underscoring the critical role of structural ordering in governing catalytic performance.

Table 5: Crystallinity level of the Zn–Cu–O system.

Zn-Cu-O system, %	
Zn:Cu atomic ratio	Crystallinity
1:9	42.9
2:8	43.9
3;7	54.9
4:6	44.2
5:5	71.3
6:4	75.3
7:3	78.1
8:2	81.3
9:1	93.8

From the conducted studies, it appears that with the increase in the degree of crystallinity, the release of carbon dioxide exceeds the maximum, while the release of acetaldehyde and the selectivity for acetaldehyde exceed the minimum. The enhancement in the degree of crystallinity cause to an increase in the selectivity of the process for acetaldehyde.

A foundational principle of heterogeneous catalysis is that the transformation of reactants into products occurs exclusively at the catalyst's surface. Consequently, the physicochemical properties of this surface are paramount in determining catalytic activity, with the specific surface area being a primary factor. For complex multi-element catalysts, such as the Zn-Cu-O system, the specific surface area is not an intrinsic property but is critically dependent on synthetic parameters.

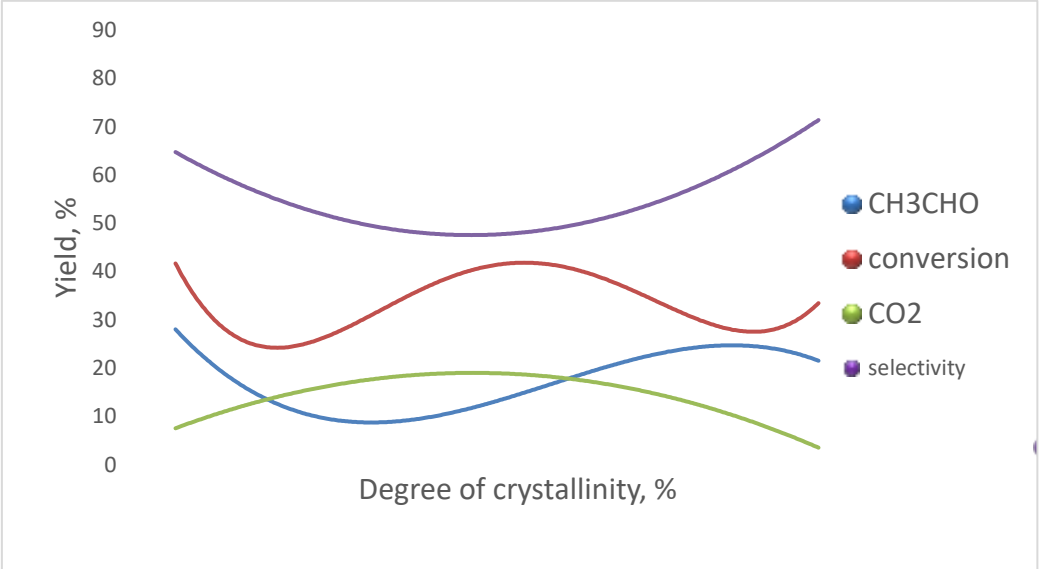


Fig. 5: nfluence of catalyst crystallinity on the activity of Zn–Cu–O in ethanol dehydrogenation at 523 K

Specifically, it is governed by the stoichiometric atomic ratios of the precursor elements and the specific conditions of the preparation methodology (e.g., calcination temperature, precipitation rate, and aging time), which collectively influence nucleation, growth, and ultimately, the final textural properties of the material.

Table 6: Specific surface area of Zn-Cu-O catalysts, m^2/g

Zn/Cu ratio	ZnO	1-9	2-8	3-7	4-6	5-5	6-4	7-3	8-2	9-1	CuO
S, m^2/g	4.0	8,0	3,5	4,3	5,6	6,5	6,0	4,7	5,5	4,7	0,6

The table shows the obtained values of the specific surface area of the samples of the Zn-Cu-O catalytic system by the nitrogen thermal desorption method. As can be seen from the table, the value of the specific surface increases with the increase of the amount of zinc in the samples except for the Zn-Cu=1-9 catalyst for the zinc-copper oxide catalytic system, while the specific surface in the sample containing Zn-Cu=5-5 passes through the maximum and then decreases. The specific surface area in the Zn-Cu=9:1 catalyst is 4.7 m2/g. The obtained results show that the specific surface area of the samples in the Zn-Cu-O system varies between 3.5 m2/g (Zn-Cu=2-8) and 8.0 m2/g (Zn-Cu =1:9). The value of primary oxides, i.e. zinc and copper oxides, is 4.0 and 0.6 m2/g, respectively.

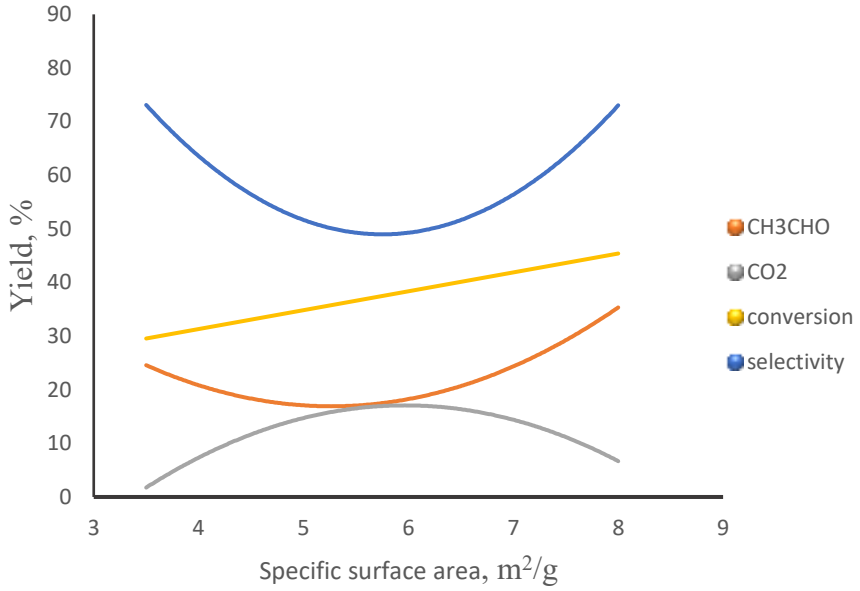


Fig. 6: Effect of specific surface area on the activity of Zn-Cu-O catalysts in ethanol dehydrogenation reaction. T=573K

Figure 6 illustrates the correlation between the specific surface area of Zn-Cu-O catalysts and the product distribution from ethanol dehydrogenation. The data reveals a clear positive relationship between ethanol conversion and the catalyst's specific surface area; as the surface area increases, so does the conversion. However, this enhancement in activity is accompanied by a shift in selectivity. While acetaldehyde remains the principal reaction product, its selectivity reaches a minimum at higher surface areas. Concurrently, the yield of carbon dioxide is maximized under these conditions.

This behavior can be explained by considering the catalyst's phase composition. Samples with a high specific surface area are typically associated with non-stoichiometric formulations where one element is in excess, leading to the formation of solid solutions. These specific structural features appear to promote secondary reactions, such as decomposition or oxidation, that consume acetaldehyde and generate CO_2. In contrast, catalysts with a lower surface area, often comprising a simple mixture of primary ZnO and CuO phases due to a more balanced stoichiometry (e.g., 1:1 ratio), favor the selective dehydrogenation pathway to acetaldehyde.

This study establishes that the specific surface area of Zn-Cu-O catalysts has a distinct effect on ethanol dehydrogenation. Analysis of the data reveals an inverse correlation between surface area and acetaldehyde yield; as the surface area increases, the yield of the target product, acetaldehyde, falls to a minimum. This indicates that maximizing surface area is not an optimal strategy for this particular catalytic system, as it promotes non-selective reaction pathways.

III. Conclusion

Catalytic dehydrogenation of ethanol over zinc–copper oxide (Zn–Cu–O) catalysts proceeds with high selectivity, yielding acetaldehyde as the principal product. Structural characterization via X-ray diffraction (XRD) confirmed that the catalytic system comprises distinct ZnO and CuO phases, with no evidence of extensive solid solution formation. Importantly, the coexistence of these phases reflects a synergistic interplay between redox-active copper species and the acid–base functionality of zinc oxide, which underpins both catalytic reliability and environmental compatibility of the process.

A strong structure–activity relationship was elucidated, wherein the catalyst's performance is critically dependent on its physicochemical properties. Specifically, an increase in the degree of crystallinity was found to enhance both the acetaldehyde yield and the process selectivity toward this desired product. This suggests that crystallinity can serve as a predictive marker of catalytic reliability, ensuring reproducible performance across different synthesis batches. Conversely, the specific surface area (SSA) of the catalyst was identified as a key parameter exerting a significant, yet complex, influence on the reaction outcome. The yield of acetaldehyde was observed to be highly sensitive to variations in SSA, indicating a non-linear relationship that merits further investigation and long-term monitoring to guarantee process stability under industrial conditions.

Furthermore, the catalytic functionality of the binary Zn–Cu–O system was extended to the isomerization of butene-1. The composition of the catalyst was determined to be a decisive factor, with the yields of the isomerization products, trans-butene-2 and cis-butene-2, reaching a maximum at a specific optimal zinc-to-copper ratio of 4:6. This demonstrates a pronounced compositional dependence for activity in this complementary reaction and highlights the broader versatility of Zn–Cu–O systems as multifunctional, reliable, and eco-sustainable catalysts. By linking phase composition, crystallinity, and surface area to catalytic behavior, this study provides new insights into how structural parameters can guide the rational design of durable catalysts that simultaneously meet performance and environmental sustainability targets.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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METHOD FOR REDUCING THE LIFE CYCLE COSTS OF OBJECTS AT THE PRE-PROJECT STAGE OF CONSTRUCTION BASED ON RISK AND SUITABILITY FACTOR MANAGEMENT WITH BIM AND GIS INTEGRATION

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Abstract

The article proposes a methodology for reducing the life cycle cost of construction projects at the early pre-design stage through risk management and site suitability assessment using the integration of building information modeling (BIM) and geographic information systems (GIS) technologies. The pre-design stage is characterized by a high degree of uncertainty and risk, which has a significant impact on the subsequent stages of the project. The article describes an approach in which GIS data (relief, geological and climatic conditions, land use restrictions, etc.) are integrated into a BIM model for spatial analysis of the site. The calculation of risk (R) and suitability (S) indices is based on the normalization and weighting of influencing factors. The territory is then classified according to the S-index level. The results of this process are the generation of a "site passport", which is a document that summarizes the conditions and includes engineering recommendations for risk reduction. The method enables the identification of optimal sites at the conceptual planning stage, as well as the anticipation of engineering solutions in advance. This process serves to reduce uncertainty and costs throughout the life cycle of the facility.

Keywords: BIM, GIS, pre-project stage, life cycle, suitability and risk coefficients, multi-criteria assessment, sensitivity analysis.

I. Introduction

The pre-project (pre-investment) stage of a construction project's life cycle determines strategic decisions that largely influence subsequent construction and operating costs. This period is characterized by the greatest uncertainty in the initial data and conditions for project implementation. Nevertheless, it is at this early stage that the key factors for project success are established, and there is the greatest potential to influence costs and risks before the decisions made become difficult to reverse. The principle of life cycle cost management assumes that investments in research and risk analysis at early stages can pay off many times over by preventing costs associated with eliminating problems during construction and operation. For example, construction in permafrost areas without proper consideration of geocryological risks can lead to serious damage to infrastructure and high repair costs [1][2]. Thus, reducing uncertainty at the start of a project through effective risk management is a critical task.

In modern conditions, digital technologies such as Building Information Modeling (BIM) and Geographic Information Systems (GIS) are increasingly being used to solve this problem. BIM models are traditionally used for project detailing and 3D visualization during the design and construction stages, but when integrated with GIS, they become a powerful tool for analyzing sites in a geospatial context [3][4]. GIS, for its part, provides extensive spatial data on site conditions

(relief, soils, climate, ecology, infrastructure, etc.) and tools for multi-criteria analysis of the territory. The combination of these technologies (BIM+GIS) allows the creation of a digital twin of the territory with engineering data linked to the geography of the area, which significantly improves the validity of decisions made at an early stage [5]. Research shows that the integration of BIM and GIS at the planning and design stages provides decision-makers with multi-scale, semantically rich information about the project and allows them to evaluate schedules, costs, and sustainability in a virtual environment before construction begins. As a result, this reduces risks, optimizes costs, and improves safety and environmental performance throughout the entire life cycle of the facility [6].

This paper aims to describe a methodology that allows for the systematic consideration of risks and the suitability factor of a territory when selecting a site and making early design decisions. The suitability factor is understood as a comprehensive criterion that reflects the degree to which a site meets construction requirements, taking into account a combination of geographical, engineering-geological, environmental, and regulatory factors [7]. The idea is to calculate an integral suitability index (S) to compare alternative sites or planning options, while simultaneously assessing the risk index (R), which characterizes potential adverse effects. The methodology uses GIS data to quantitatively assess factors (such as terrain relief, soil type and condition, presence of permafrost, groundwater level, proximity to water bodies, etc.), which are then integrated into a BIM model of the site's relief. By normalizing the indicators and assigning weighting coefficients to them, the S and R indices are calculated, on the basis of which the territory is classified into categories of suitability. The final result is the creation of a "site passport" — a document containing all key information about the site, identified risks, and recommendations for engineering measures to mitigate them. It is expected that the application of this method will reduce uncertainty and the total life cycle cost of the facility through early risk identification and optimization of design choices.

II. Methods of risk analysis and calculation

The first stage is the collection and integration of spatial data. At this stage, a digital model of the site is formed, combining a BIM model of the terrain with geoinformation data layers. The following data is used as source data: a digital terrain model (e.g., based on topographic surveys or remote sensing data), engineering and geological surveys (maps of soil types, bearing capacity, seasonal frost depth, and permafrost distribution), hydrogeological data (groundwater levels, flooding), climatic data (e.g., presence of permafrost, depth of seasonal thaw), as well as information about the environment and land use restrictions (proximity to watercourses and depressions, protected areas, sanitary gaps, existing buildings and communications) (see Fig. 1). Data is collected from various sources, including engineering survey results, open spatial data, and industry GIS databases. All spatial data is converted to a single coordinate system and uploaded to a GIS platform for further processing. At the same time, based on topographic data in a BIM environment (Autodesk Revit, Archicad, etc.), a three-dimensional information model of the site's relief is created, into which GIS layers can be imported. This integration provides a 3D visualization of the engineering and geographical conditions and links attribute data to spatial objects in the model. The result is an integrated BIM+GIS model of the territory, containing both geometric information (relief, objects on the ground) and semantic data for each element (soil type, risk factor value, etc.).

The second stage involves identifying and quantitatively assessing risk and suitability factors. Based on an integrated model, key factors affecting the suitability of the site for construction and the level of risk involved in implementing the project are identified. In this method, risk factors (R-factors) are understood as characteristics of conditions that can cause negative consequences, such as the presence of permafrost (risk of loss of foundation stability during thawing), high groundwater levels (risk of flooding and foundation complications), steep slopes (risk of landslides or increased cost of earthworks), proximity to a river or low-lying area (risk of flooding), unstable or weak soils (risk of subsidence, need to reinforce foundations), the presence of underground voids or karst (risk of sinkholes), seismicity of the area, environmental restrictions, etc. Suitability factors (S-factors), on

the contrary, characterize the positive aspects of the site — for example, strong stable soils, flat terrain, absence of adverse geological processes, developed infrastructure nearby (which reduces connection costs), etc. It should be noted that the same factor can be presented both as a risk and as a contribution to suitability, the difference being only in the sign of the influence. In the proposed methodology, all factors are normalized so that a higher numerical value corresponds to a more favorable condition (i.e., greater suitability and/or lower risk). For example, for the "permafrost" factor, areas without permafrost are assigned a high score (close to 1), and areas with permafrost are assigned a low score (close to 0). Similarly, for the "relief (slope)" factor, flat areas receive a high score (as more suitable), while steep slopes receive a low score. For continuous quantitative parameters (e.g., surface slope angle, distance to the river, groundwater depth), normalization is performed—conversion to a dimensionless scale, usually from 0 to 1. Normalization can be performed linearly, relative to the minimum and maximum permissible values or standards. Thus, for a slope of 0°, suitability 1 (maximum) is set, and for a slope of, say, >15°, suitability 0 is set, with intermediate values interpolated linearly. The formula for normalizing criteria (1).

$$S_i^j = \frac{x_i^j - x_{min}^j}{x_{max}^j - x_{min}^j} \quad (1),$$

where x_i^j is the value of the j-th factor for the i-th section (or cell of the territory) x_{min} and x_{max} are the minimum and maximum favorable values of this factor. After calculation and normalization, the indicators become comparable on a scale.

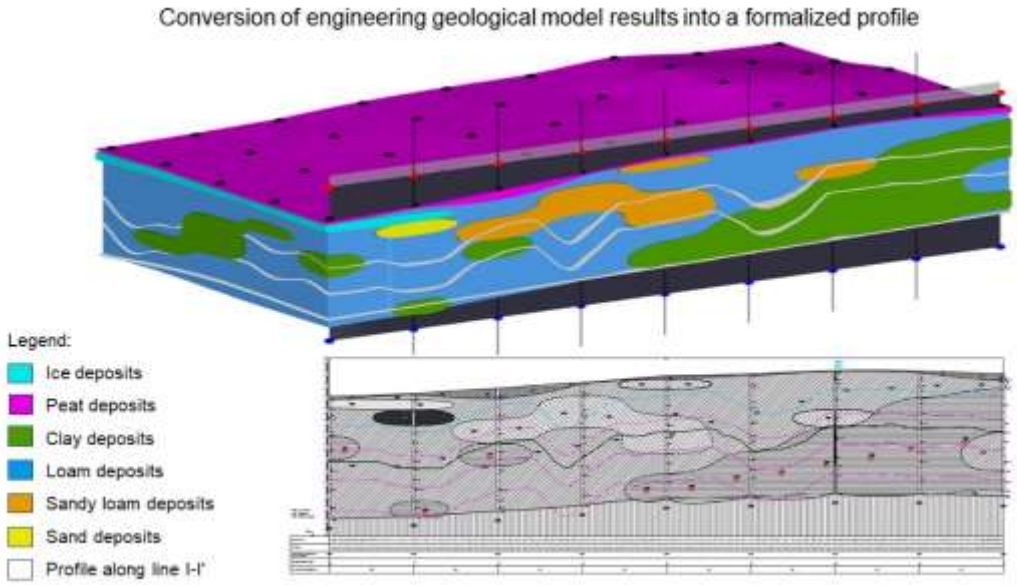


Fig. 1: *Conversion of engineering geological model results into a formalized profile*

The third stage involves weighing factors and calculating integral indices. Since different factors have varying degrees of influence on the overall success of the project, they are assigned weighting coefficients wj according to the importance of the factor for the suitability of the site. The sum of all weights is normalized to 1: ∑jwj=1. Weights can be determined by experts (for example, using the paired comparison method or the rank sorting method). Experts compare factors in pairs according to their importance, on the basis of which priorities are calculated; in the ranking approach, factors are ordered, and weights are calculated based on the ranks. For example, if the soil factor has the greatest impact on cost (foundation task), it can be assigned a weight wgr = 0.3. Next in importance are the presence of permafrost wfz = 0.25, terrain slope wsl = 0.2, flood risk wfl = 0.15, and other factors collectively wothers = 0.1. These weights reflect the expert assessment of each aspect's contribution to the overall risk of the project. After that, for each site under

consideration (or for each elementary zone of the territory), the suitability index S (2) is calculated as the weighted sum of normalized indicators

$$S_i = \sum_j w_j S_i^j \quad (2),$$

where Si is the normalized assessment of the i-th suitability factor (for site j). The higher S (closer to 1), the more suitable the site is in terms of the set of conditions [8]. In parallel, the integral risk index R can be calculated, which is either directly opposite to the suitability index (for example, R=1-S if all important factors are taken into account in S), or calculated separately as the weighted sum of only negative risk factors. In some cases, it makes sense to separate these concepts: for example, two sites may have a similar low risk (R) but differ in suitability (S) due to different advantages—proximity to infrastructure, more convenient location, etc. However, in general, with a competent choice of factor system, the S index correlates with risk.

The fourth stage is site classification and sensitivity analysis. The calculated S values are used to rank alternative sites or to zone the territory into suitability classes. In the simplest case, threshold values can be set: for example, S>0.7 – high suitability (low risk) site, 0.4<S≤0.7 – moderate suitability, S≤0.4 – site unsuitable for construction [9]. When assessing large areas with a continuous distribution of S values, it makes sense to perform clustering or classification, for example, using natural breaks (Jenks) or quantiles, to identify the areas most and least suitable for development. The classification results are clearly presented in the form of thematic suitability maps, where the territory is marked by categories (for example, from green – favorable, to red – extremely unfavorable). In addition, it is useful to perform a sensitivity analysis to check how changes in weight coefficients or initial assumptions affect the distribution of S. This analysis identifies which factors are critical for site selection and allows you to justify the reliability of the recommendation [10].

The fifth stage involves creating a "site passport" and recommendations. For the selected (or each considered) site, a report is compiled that includes: a summary table of values for all factors (e.g., slope – 3°, soil – loam, bearing capacity – 3 kg/cm², permafrost – intermittent at a depth of 1.5 m, groundwater level – 1.2 m, distance to the river – 200 m, protected areas – none, etc.), calculated R and S indices, suitability class, as well as a list of potential risks and recommendations for their mitigation [11]. Engineering recommendations are developed based on the identified risk factors: for example, if there are permafrost soils on the site, it is recommended to provide a special foundation solution (pile field to a depth below the seasonal thawing boundary, soil thermostabilization using thermosiphons or a ventilated subsoil zone) [12]. If the groundwater level is high, a drainage system or raising the planning level is recommended. For sloping sites, shore reinforcement measures, terracing, or refusal to build on the steepest sections. If the site is in a potential flood zone, provide embankments or hydraulic protection, or move the building site to a higher area. At the same time, the recommendations include measures to increase overall reliability and reduce operating costs: for example, insulating foundations and pavements on frozen ground to maintain the temperature regime, using prefabricated monolithic foundations on complex soils to reduce the cost of work, etc. In addition to technical measures, alternative management solutions may be proposed, such as additional surveys in areas of greatest uncertainty (drilling wells to clarify soil conditions), revising the configuration of the planned facility to take into account identified limitations (moving the building outside the area with poor soil), insurance against certain risks, etc. As a result, the site passport serves as a guide for designers and investors: it provides a clear understanding of the strengths and weaknesses of the site even before the design phase begins, and the recommendations proposed will form the basis of the technical design specifications. This ensures proactive risk management: problems are not ignored, but are solved in advance on paper, which is always cheaper than on the construction site.

III. Discussion

The study showed that integrating BIM and GIS with a focus on risk management provides significant advantages in the pre-investment stage. The resulting 3D BIM+GIS model of the site will serve as a common platform for analysis: it will allow for the joint visualization of terrain, geological layers, and potential hazards, facilitating risk identification and communication between specialists (geotechnical engineers, designers, economists) (see fig. 2, 3) [13]. Previously, in practice, engineers often assessed factors separately, in different reports, and it was not easy to link them together for decision-making. The digital approach provides clarity and a quantitative basis for comparing scenarios. It should be noted that such ideas of multi-criteria assessment of territories are not new and have been developed in the field of urban planning and hydraulic engineering surveys [14]. Many authors have successfully applied weighted linear combination and AHP methods to select sites for dams, waste disposal sites, residential development, etc. Thus, in the work of Rodriguez and Mokrova (2020), an approach combining multi-criteria analysis and GIS methods was implemented to support reservoir planning, proving the objectivity and rationality of decisions [15]. The approach under consideration develops this direction as it applies to construction tasks, adding BIM as a means of simulation modeling and cost accounting at the concept stage. In addition, the integrated model facilitates the involvement of experts in the decision-making process: visualizing risks on a map is much clearer for investors or authorities than dry text reports.

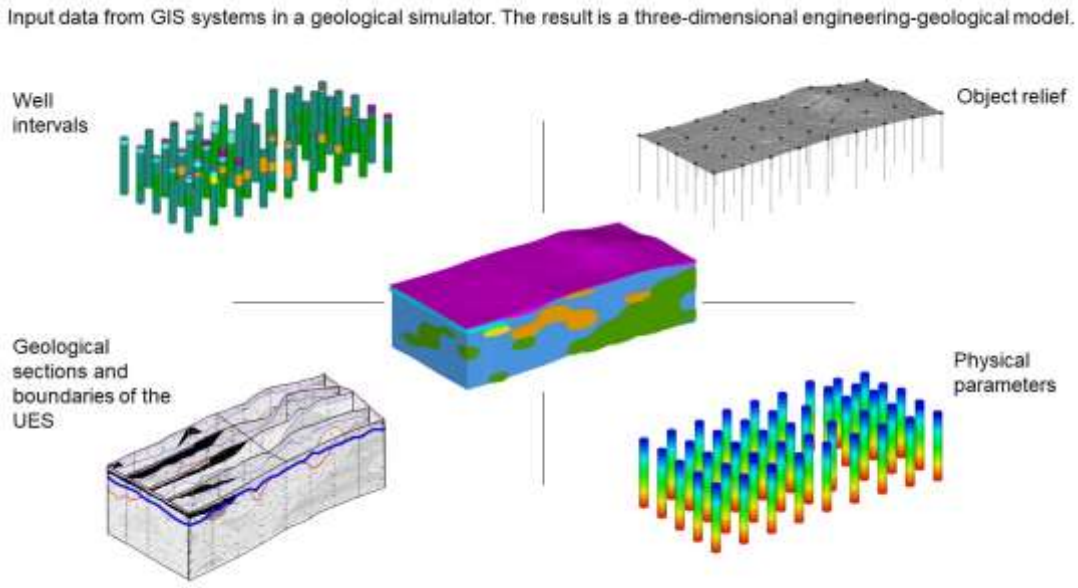


Fig. 2: *Composition of the resulting BIM + GIS terrain model*

The economic effect of the proposed method should also be discussed. The reduction in life cycle costs is achieved not by directly reducing the price of construction work, but indirectly—through more rational planning, prevention of rework and accidents, and optimization of technical solutions. It is well known that making changes to a project during the construction phase is an order of magnitude more expensive than during the documentation phase. The proposed approach essentially minimizes the likelihood of late changes: problems are identified and solved "on paper." In a potential example, the difference in the projected cost between the options reached 10–15%. According to industry data, the introduction of BIM into design reduces direct capital costs by ~5–10% and reduces the likelihood of overspending [16]. The addition of GIS analytics extends these savings by optimizing site selection and land development plans. The effect on project timelines is

noteworthy: early detection of problems reduces downtime and delays, which means that the life cycle is implemented faster, which also translates into cost savings [17].

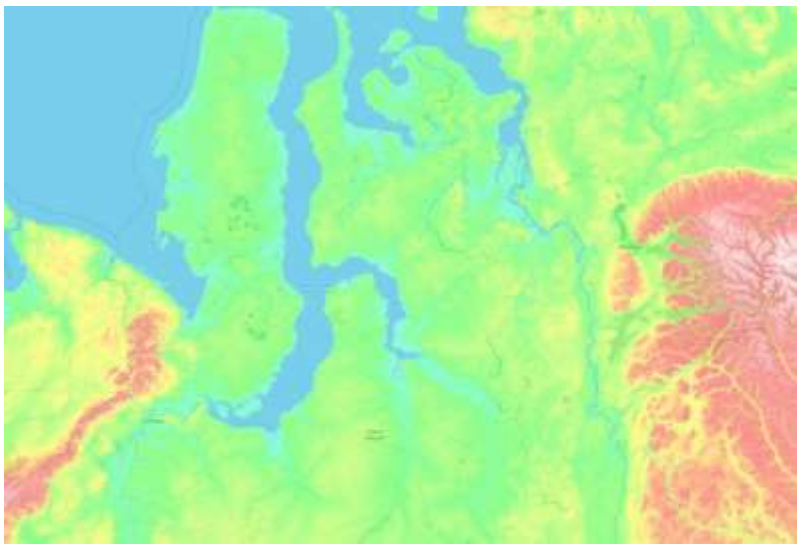


Fig. 3: *Example of analyzed relief with a range of suitable areas*

Additional prospects for developing the method are linked to the use of dynamic and forecast data. In particular, in permafrost regions, it is extremely important to forecast changes in soil conditions in connection with climate trends. Integrating climate change models into GIS would allow us to assess risks not only for the present moment, but also for decades to come—for example, how the depth of seasonal thawing will change by the middle of a building's service life and whether additional measures will be required. Similarly, probabilistic scenarios can be included to estimate the distribution of possible S values instead of deterministic ones. This will provide an understanding of the reliability of the solution: if, despite variations in parameters, the site still maintains a high S, then the choice is justified.

Finally, an important area is the implementation of this approach in regulatory and practical terms. The possibility of creating a "territory passport" with an integrated suitability assessment could be used in complex development, territorial planning, and the selection of sites for public facilities (schools, hospitals) from the perspective of maximum investment efficiency. The tool can form the basis of a decision support system for developers and investors, increasing the transparency and validity of land asset selection.

IV. Conclusion

The presented methodology demonstrates how the combination of modern digital technologies and classic risk management principles can significantly improve the process of preparing construction projects at the earliest stage. The integration of GIS and BIM data provides a comprehensive overview of the site's characteristics in a visual form, while the calculation of suitability (S) and risk (R) indices transforms heterogeneous information into quantitative metrics for comparing alternatives. The end result is the achievement of the main goal: reducing life cycle costs by reducing uncertainty and managing risks in advance.

The main results of the work include: (1) developing a sequence of steps for collecting and integrating spatial data about the territory into a unified BIM+GIS model; (2) proposing a system for standardizing and weighting factors with the calculation of an integral suitability index S for the site; (3) calculation of S and subsequent classification of the territory, allowing for the objective identification of the most advantageous areas for construction; (4) presentation of the results in the

form of a "site passport" with recommendations that directly translate the results of the analysis into design solutions. The practical application of this approach contributes to more informed decision-making: instead of intuitive choices, there is a measurable suitability metric; instead of reacting to problems, there is prevention. The integrated BIM+GIS environment provides a common information base for all participants, reducing the risk of communication gaps and errors.

In the future, the method could be expanded to assess areas for linear infrastructure (roads, pipelines), where early detection of unfavorable sections of the route is also critical. Another direction is the inclusion of sustainability criteria in the S-index, such as carbon footprint or impact on ecosystems, which will allow projects to be optimized according to environmental and social parameters, in addition to purely technical ones. In conclusion, we would like to emphasize that the described method of reducing life cycle costs at the pre-project stage is in line with the general trend of digitalization in construction and the transition to data-driven project management. Its implementation will help make the project preparation process more transparent, scientifically sound, and cost-effective, which will ultimately benefit both investors and society.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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EPOXY–NBR COMPOSITES FOR CRITICAL INFRASTRUCTURE: MATERIAL INNOVATIONS FOR RISK REDUCTION AND RESILIENCE

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Abstract

The increasing exposure of critical infrastructure systems to natural, technological, and climate-induced risks underscores the urgent need for resilient and sustainable material solutions. This study investigates epoxy oligomer (EO-20)–based composites modified with liquid butadiene-nitrile rubber (SKN-18-1), acrylic acid (AA), and coke filler, with maleic anhydride (MA) as a hardener. The compositions were prepared in varying proportions and evaluated for their physical, mechanical, and chemical properties. The results demonstrate that the incorporation of 4–6 p.w. SKN-18-1 significantly enhanced tensile strength, impact resistance, adhesion, and chemical stability compared to unmodified epoxy oligomer. Further modification with 0.75 p.w. AA and the addition of 6.0 p.w. coke provided additional improvements in durability and resistance to aggressive environments. These findings highlight the potential of polymer-modified epoxy systems as advanced protective materials for dams, drainage, and reclamation infrastructures, where resistance to seismic stresses, chemical exposure, and long-term environmental degradation is essential. By linking material performance with infrastructure resilience and risk management, the study contributes to risk-oriented design strategies and sustainable investment in critical infrastructure protection.

Keywords: epoxy oligomer, butadiene-nitrile rubber, maleic anhydride, acrylic acid, critical infrastructure, resilience

I. Introduction

Critical infrastructure systems such as dams, drainage networks, and reclamation facilities face growing threats from natural, technological, and climate-induced hazards. Seismic risks, material degradation, and cascading failures across interdependent systems underscore the urgent need for resilient and sustainable engineering solutions. Conventional design approaches, which focus mainly on structural robustness, have proven insufficient to cope with the complexity of modern risk environments. Instead, resilience-oriented design strategies increasingly emphasize material innovation, environmental sustainability, and multi-criteria decision-making.

Among the key challenges in infrastructure safety is the performance of construction and protective materials under extreme conditions. Epoxy resins are widely used due to their strong adhesion, chemical resistance, and mechanical properties; however, their inherent brittleness and limited impact resistance restrict their application in multi-hazard contexts. This limitation is particularly critical in seismic regions, where energy dissipation and impact resistance are decisive factors in maintaining infrastructure functionality.

To address these shortcomings, researchers have explored the modification of epoxy

oligomers with elastomers and chemical additives. Butadiene-nitrile rubber (NBR) has shown considerable potential in enhancing flexibility, toughness, and adhesion, while additional modifiers such as acrylic acid and coke fillers contribute to improved durability and resistance in chemically aggressive environments. Such material innovations are directly aligned with the objectives of risk-oriented infrastructure design, where enhanced resilience and sustainability are required for long-term safety.

At the same time, the use of chemical precursors such as phthalic anhydride presents a dual challenge. While it is essential for polymer synthesis and performance enhancement, it also raises concerns related to environmental impact and occupational health risks. Balancing these advantages and drawbacks reflects the broader sustainability paradigm, where technical performance must be integrated with ecological and human safety considerations.

Against this backdrop, the present study examines epoxy oligomer–NBR composites modified with acrylic acid and coke filler. The objective is twofold: (i) to evaluate the mechanical and chemical performance of the modified systems, and (ii) to position these findings within the framework of critical infrastructure resilience. By linking experimental material results with risk management and resilience-building strategies, the study contributes to a holistic understanding of how polymer-modified epoxy systems can enhance the safety, durability, and sustainability of infrastructures exposed to multi-hazard environments.

II. Literature Review

The resilience and sustainability of critical infrastructure have become central themes in contemporary engineering and risk management research. Natural hazards such as earthquakes and floods, technological accidents, and climate-induced stresses increasingly threaten the long-term functionality of lifeline systems, including dams, drainage networks, and reclamation infrastructures. Studies in earthquake engineering emphasize that material degradation and insufficient impact resistance significantly increase vulnerability under seismic loading, highlighting the importance of advanced material applications in risk-oriented design.

Polymeric materials, particularly rubbers and their composites, have been widely explored to overcome the limitations of conventional epoxy systems. Epoxy oligomers are known for their excellent adhesion, chemical resistance, and mechanical strength; however, they suffer from relatively low impact resistance and brittleness, which limit their application in hazard-prone environments. To address these challenges, modification with liquid rubbers such as butadiene-nitrile rubber (NBR) has been proposed. NBR introduces flexibility, enhances impact absorption, and improves adhesion properties, making epoxy–NBR composites suitable candidates for critical infrastructure applications exposed to seismic and chemical risks.

Recent research has further investigated the role of modifiers such as acrylic acid and fillers such as coke in enhancing the durability and chemical stability of epoxy-based composites. These modifications result in improved tensile strength, reduced swelling in aggressive environments, and enhanced long-term service life. Such improvements align directly with the objectives of infrastructure resilience, where extended durability and reduced maintenance contribute to sustainable investment strategies.

Beyond technical performance, material selection must also account for broader sustainability and risk management considerations. Compounds such as phthalic anhydride, widely used in polymer synthesis, offer functional advantages but pose potential environmental and occupational health risks. This duality reflects the necessity of balancing material innovation with ecological and human safety concerns, consistent with risk-oriented multi-criteria decision-making frameworks.

In summary, the literature demonstrates a growing convergence between material science and infrastructure resilience research. The adoption of epoxy–rubber composites offer promising solutions for enhancing the safety and reliability of dams, drainage, and reclamation systems, thereby contributing to resilient and environmentally sustainable infrastructure strategies.

III. Methodology

The methodological framework of this study integrates experimental material science with a risk-oriented infrastructure perspective. The approach consists of four main stages:

1. Preparation of Modified Epoxy Composites

In this study, an epoxy oligomer (EO-20) was employed as the primary polymeric matrix due to its well-established mechanical integrity and chemical stability. To enhance the impact resistance, elasticity, and toughness of the resulting composites, liquid butadiene–nitrile rubber (SKN-18-1) was incorporated in controlled proportions ranging from 2 to 8 parts by weight (p.w.). Maleic anhydride (MA) functioned as a crosslinking agent, facilitating the curing reaction and improving the network structure of the epoxy matrix. Additionally, acrylic acid (AA) was introduced as a functional modifier to enhance interfacial adhesion and chemical resistance, while coke powder was utilized as a reinforcing filler to improve mechanical strength and durability. All components were carefully blended under rigorously controlled thermal and mixing conditions to ensure homogeneity of the composite mixtures and to minimize phase separation or agglomeration. The curing process was optimized to achieve a uniform crosslinked network, which is critical for maximizing the performance characteristics of the epoxy-based composites.

2. Evaluation of Physical and Mechanical Properties

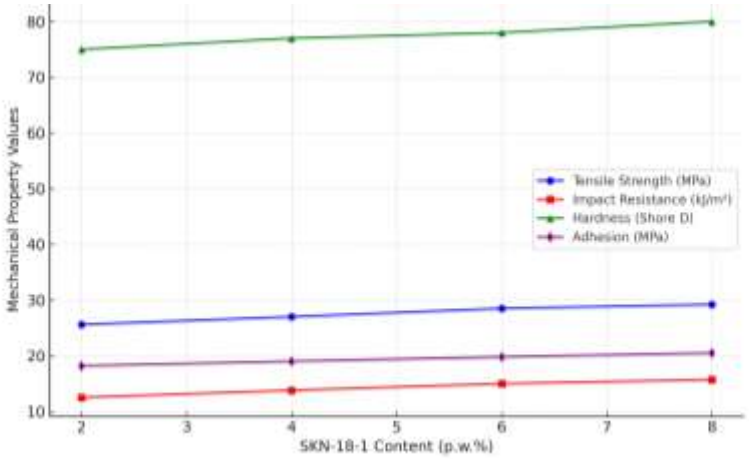


Figure 1. *Effect of SKN-18-1 content on the mechanical properties of EO-20 epoxy composites. The tensile strength, impact resistance, hardness, and adhesion of the composites were evaluated as a function of increasing rubber content (2–8 p.w.%). Incorporation of SKN-18-1 and functional modifiers (acrylic acid and coke filler) enhances toughness, elasticity, and overall mechanical performance, indicating the potential applicability of these composites in dynamic and high-stress infrastructure environments.*

Figure Explanation:

X-axis: SKN-18-1 content (p.w.%). This represents the amount of liquid rubber incorporated into the composite. Increasing rubber content enhances elasticity and energy absorption capacity.

Y-axis: Mechanical property values:

Tensile strength (MPa): Resistance of the material to breaking under tension.

Impact resistance (kJ/m²): Resistance to sudden mechanical shocks.

Hardness (Shore D): Surface hardness of the composite.

Adhesion (MPa): Strength of bonding with the substrate.

All measured properties increase with higher SKN-18-1 content, indicating improved toughness and elasticity.

Tensile and impact strengths show particularly significant improvement, highlighting enhanced resilience under seismic and dynamic loading conditions.

Scientific Significance:

The graph demonstrates the synergistic effect of functional modifiers (acrylic acid and coke filler) and rubber on mechanical performance.

Such data are critical for the design and optimization of high-performance epoxy composites intended for infrastructure applications.

The mechanical performance improvements shown in the graph have direct implications for infrastructure resilience and risk mitigation:

Seismic and Dynamic Load Resistance: The increased tensile strength and impact resistance due to SKN-18-1 modification indicate that the epoxy composites can better withstand sudden mechanical shocks and seismic stresses. This reduces the likelihood of structural failure under natural hazards.

Durability and Operational Safety: Enhanced hardness and adhesion improve the composite's long-term stability and bonding with substrates, minimizing risks of delamination or surface degradation over time, which is crucial in critical infrastructure systems.

Risk Mitigation in Engineering Applications: By incorporating functional modifiers (acrylic acid, coke filler) and rubber, the material demonstrates higher energy absorption and toughness. This reduces vulnerability to unexpected loads, vibrations, and mechanical impacts, effectively lowering operational and structural risks.

Holistic Impact: The combination of improved mechanical properties with the controlled modification strategy supports a risk-oriented design approach, allowing engineers to select materials that increase safety margins and resilience against environmental and operational hazards.

The fabricated epoxy composites were systematically characterized for their physical and mechanical performance. Tensile strength, impact resistance, hardness, and adhesion properties were measured using standardized testing protocols to ensure consistency and comparability with prior literature. These evaluations provide comprehensive insight into the structural integrity, deformation behavior, and energy absorption capabilities of the modified composites. Notably, the enhanced mechanical properties—particularly improved toughness and resilience—underscore the potential applicability of these materials in infrastructure systems subjected to dynamic loading, seismic stresses, and other extreme operational conditions. The results highlight the synergistic effect of rubber modification, functional monomer incorporation, and filler reinforcement in tailoring the mechanical performance of epoxy composites for high-demand engineering applications.3. Chemical and Environmental Resistance Testing

The swelling degree and chemical stability of the composites were assessed in aggressive environments, including acidic and alkaline media. The results are particularly relevant for dams, drainage, and reclamation infrastructures, which are frequently exposed to water-chemical interactions, soil contaminants, and climatic degradation.

4. Integration into Risk-Oriented Infrastructure Assessment

Beyond laboratory evaluations, the study interprets the material performance in the context of risk management. Improved impact resistance and chemical stability are analyzed as key factors in reducing vulnerability under multi-hazard conditions (e.g., seismic events combined with

chemical exposure). A qualitative multi-criteria decision-making (MCDM) framework was applied, linking material performance to resilience indicators such as durability, sustainability, safety, and cost-effectiveness.

This combined methodology ensures that experimental findings on epoxy–rubber composites are not only assessed for their technical value but also situated within the broader objectives of sustainable and resilient infrastructure design.

After extraction of the composition based on solidified EO-20/SKN-18-1 in acetone for 20 hours, the gel fraction was determined to be 95.8%.

After extraction of the solidified composition EO-20/SKN-18-1, IR-spectroscopic analysis was performed and it was shown that the polymers are chemically intercalated with each other.

After extraction of the composition based on EO-20/SKN-18-1/AA, the gel fraction was determined to be 96.5%.

Compositions based on SKN-18-1 and SKN-18-1/AA modified epoxy oligomer were prepared and their properties were compared with the properties of the composition based on EO-20 and it was shown that the properties of the modified compositions were significantly improved compared to the unmodified ones.

The effect of coke as a filler on the properties of the composition based on EO-20/SKN-18-1/At-94/6/0.75 was studied and it was shown that coke plays a significantly important role in improving the properties of the composition.

The overall methodological framework of the study is illustrated in Figure 1, linking hazard risks with material modification, performance evaluation, and infrastructure applications.

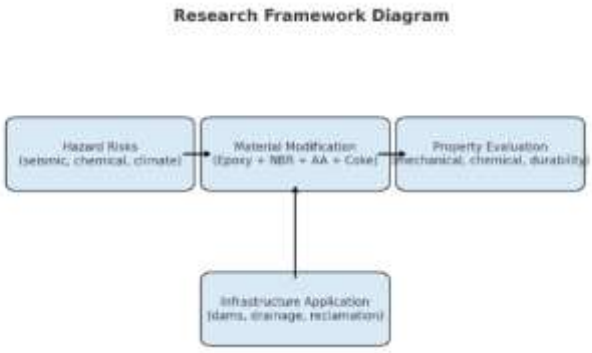


Figure 1. *Research framework linking hazard risks, material modification, property evaluation, and infrastructure applications for resilient and sustainable infrastructure systems.*

V. Results and Discussion

1. Mechanical Performance Improvements

The incorporation of liquid butadiene-nitrile rubber (SKN-18-1) into epoxy oligomer (EO-20) compositions resulted in significant enhancements in impact resistance and elasticity. At 4–6 p.w. SKN-18-1, the composites demonstrated optimal tensile strength and improved adhesion to substrates. These improvements are crucial for seismic-prone infrastructures, where materials must dissipate energy and maintain structural integrity under dynamic loading.

2. Chemical Resistance and Environmental Stability

Chemical testing revealed that epoxy–NBR composites exhibited lower swelling and higher stability in aggressive media compared to unmodified epoxy systems. Additional modification with 0.75 p.w. acrylic acid and 6.0 p.w. coke filler further increased durability, particularly against acidic and alkaline environments. This property has direct implications for dams, drainage, and reclamation systems, where contact with chemically active water and soil is unavoidable.

3. Relevance to Infrastructure Risk Management

The results demonstrate that improved material properties directly reduce vulnerabilities in critical infrastructures. Enhanced impact resistance strengthens resilience against seismic risks, while chemical stability mitigates degradation caused by climate-induced and technological hazards. These outcomes align with risk-oriented design principles, where material performance is integrated into strategies for long-term sustainability and safety.

4. Integration with Multi-Criteria Decision-Making (MCDM)

The experimental findings were evaluated within a qualitative MCDM framework. Criteria such as mechanical performance, environmental resistance, sustainability, and cost-effectiveness were considered. EPDM and NBR-based composites ranked highly in terms of durability and risk reduction, although considerations related to the environmental risks of precursors such as phthalic anhydride remain critical. This dual perspective highlights the need to balance performance gains with ecological and human health concerns.

5. Implications for Infrastructure Systems

The study demonstrates that material innovations can serve as risk-mitigation tools in infrastructure systems. In dams, epoxy–NBR composites can be applied as protective coatings or sealing materials, extending service life and minimizing maintenance needs. In drainage and reclamation systems, their resistance to aggressive environments reduces the likelihood of premature failures. The broader implication is that infrastructure investments should increasingly incorporate advanced material science as a core element of resilience-building.

Table 1. *Performance improvements of epoxy oligomer (EO-20) modified with NBR*

Composition (EO-20 + additives)	Mechanical Properties (tensile, impact, adhesion)	Chemical Resistance (swelling in aggressive media)	Relevance for Infrastructure Applications
Pure EO-20 (control)	High strength but brittle; low impact resistance	Moderate resistance; swelling in acids/alkalis	Limited suitability; prone to cracking under seismic loads
EO-20 + 4–6 p.w. NBR	Increased tensile strength and elasticity; significant improvement in impact resistance	Lower swelling; enhanced stability in aggressive environments	Suitable for seismic zones; protective coatings for dams and drainage
EO-20 + NBR + 0.75 p.w. AA	Additional improvements in durability and adhesion	Improved resistance against acidic/alkaline environments	Longer service life in reclamation and drainage infrastructures
EO-20 + NBR + AA + 6.0 p.w. Coke	Optimal balance: high impact strength, good adhesion, durable performance	Strongest resistance to chemical degradation	Most promising for long-term safety of dams and drainage systems

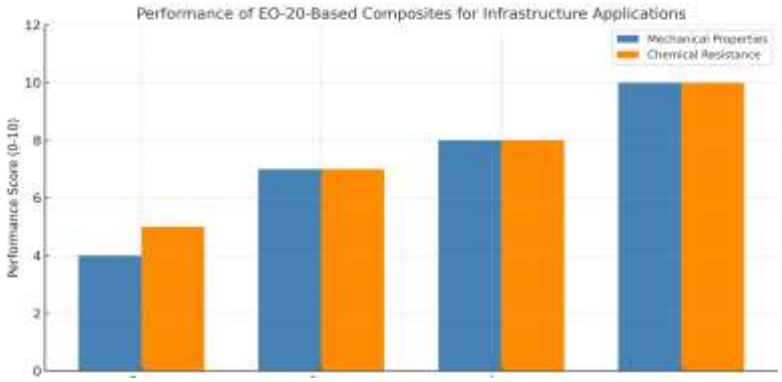


Figure 2. *Performance evaluation of EO-20-based epoxy composites with various additives for infrastructure applications. Mechanical properties (tensile strength, impact resistance, and adhesion) and chemical resistance (swelling in aggressive media) are shown for different compositions: pure EO-20, EO-20 with NBR, EO-20 with NBR and acrylic acid (AA), and EO-20 with NBR, AA, and coke filler. Incorporation of NBR and functional modifiers progressively enhances toughness, adhesion, and chemical stability, indicating improved suitability for seismic zones, dams, drainage, and other critical infrastructure systems.*

V. Conclusion and Recommendations

This study demonstrated that epoxy oligomer (EO-20) composites modified with butadiene-nitrile rubber (SKN-18-1), acrylic acid, and coke filler exhibit significantly improved mechanical and chemical properties compared to unmodified epoxy systems. The addition of 4–6 p.w. SKN-18-1 yielded optimal tensile strength, impact resistance, and adhesion, while acrylic acid and coke filler further enhanced environmental stability. These findings confirm the suitability of polymer-modified epoxy systems for use in critical infrastructure applications such as dams, drainage, and reclamation systems, where materials are exposed to seismic loading, aggressive chemical environments, and long-term climatic degradation.

By linking experimental material science with risk-oriented infrastructure design, the research highlights the role of advanced composites in reducing vulnerabilities and building resilience. Improved impact resistance addresses seismic risks, while chemical stability supports long-term sustainability and reduces maintenance costs. At the same time, the dual nature of chemical precursors such as phthalic anhydride emphasizes the importance of balancing material innovation with environmental and human safety considerations.

Recommendations

Application in Critical Infrastructure: Epoxy–NBR composites should be considered for protective coatings, sealing systems, and structural reinforcements in dams, drainage, and reclamation projects.

Integration into Risk-Oriented Frameworks: Material performance should be explicitly incorporated into infrastructure risk assessments, scenario analyses, and resilience strategies.

Multi-Criteria Decision-Making: Stakeholders and engineers should evaluate material choices based not only on technical performance but also on environmental, economic, and social criteria.

Sustainability Considerations: Alternatives to environmentally hazardous precursors such as phthalic anhydride should be explored to align material innovations with sustainable development goals.

Future Research: Further studies should investigate the long-term field performance of epoxy–NBR composites under real multi-hazard conditions, supported by monitoring technologies and predictive modeling.

By integrating risk management, materials engineering, and sustainability considerations, this study contributes to a holistic framework for developing resilient and environmentally sustainable infrastructure systems.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest

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RISK-ORIENTED APPROACH TO SOCIAL GUARANTEES FOR WORKERS IN HAZARDOUS CONDITIONS FOR SUSTAINABLE DEVELOPMENT

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Abstract

This article presents the development and pilot testing of a new model for providing social guarantees to employees engaged in hazardous and/or dangerous working conditions in the Republic of Kazakhstan, based on a risk-oriented approach. The study addresses the limitations of the current compensatory system and proposes a proactive mechanism for determining the types and volumes of guarantees according to the level of occupational risk.The research methodology included regulatory analysis, professional risk assessment, field measurements of harmful and dangerous workplace factors, and visual monitoring at ten enterprises across various regions of Kazakhstan. For the first time, a comprehensive classification of occupational hazards was applied to determine differentiated guarantees based on workplace-specific risk parameters. The model incorporates indicators such as individual occupational risk scores, historical data on workplace injuries and occupational diseases, and compliance with labor protection regulations. These indicators form a basis for calculating the degree of risk and corresponding guarantees for each professional group. The study used empirical data from over 2,400 occupations and included a comparative analysis of enterprises in the chemical, mining, and transportation industries. The results demonstrate a high prevalence of harmful exposures (ranging from 50% to 80% of working time), confirming the relevance of automation and preventive strategies. The model provides a structured mechanism for calculating social guarantees, including additional paid leave, reduced working hours, and financial compensation, adapted to the severity of working conditions. The proposed model aligns with the national Safe Labor Concept for 2024–2030 (Government of Kazakhstan, 2023) and reflects international labor standards, including ILO Conventions No. 155 and No. 187 (ILO, 1981; ILO, 2006). The novelty of the approach lies in the introduction of a standardized, automated, and scalable methodology that enhances worker protection through targeted social guarantees and risk-based workplace regulation. The study offers practical tools for government agencies, employers, and researchers in the field of occupational safety and health.

Keywords: occupational risk assessment, social guarantees, hazardous working conditions, risk-based approach, additional leave, reduced working hours, compensations, social policy.

I. Introduction

Amid deepening socio-economic transformations, accelerating technological changes, and increasing diffe entiation in working conditions, the issue of determining the scope of social guarantees for workers engaged in arduous, hazardous, and/or dangerous jobs is acquiring particular significance. The constantly evolving production environment requires new approaches to the regulation of working conditions, compensations, and benefits aimed at protecting workers operating in high-risk environments. The main challenge lies in the need to shift from outdated,

universal, and often inefficient schemes of providing guarantees toward more flexible, scientific lly grounded, and economically rational systems.

For decades, many countries have applied list-based approaches, wherein predefined lists of occupations and industries served as the basis for assigning guarantees such as additional leave, reduced working hours, wage supplements, and pension benefi s. While this approach offe s a certain degree of administrative simplicity, it fails to reflect the actual working conditions and the extent of exposure to hazardous and dangerous factors. As a result, situations may arise where workers holding identical positions but working in diffe ent environments receive the same guarantees despite facing varying levels of occupational risk. This leads to both injustice and inefficiency in the allocation of resources.

The development of occupational risk assessment (ORA) systems, including those based on international standards such as ISO 45001 and ILO OSH-2001, creates a foundation for introducing risk-based approaches into the system of social protection for workers. Leading international labor organizations, including the International Labour Organization (ILO), the European Agency for Safety and Health at Work (EU-OSHA), and the U.S. National Institute for Occupational Safety and Health (NIOSH), actively promote risk management-based policies. According to these approaches, compensations and benefi s should be determined not by professional affiliation or industry sector, but by the specific level of hazard present in the workplace, as objectively identifie through workplace assessment procedures.

Thus, there is a pressing need for the scientific development of a methodology that formalizes the process of assigning guarantees based on quantitative and qualitative indicators from occupational risk assessment. Such a methodology should be transparent, reproducible, adaptable to sector-specific contexts, and serve as a practical tool for both state regulation and internal rulemaking by employers.

The aim of this study is to develop a scientifically grounded methodology for determining the scope of guarantees for workers engaged in arduous and hazardous work, based on the results of occupational risk assessment procedures. To achieve this goal, the following objectives are addressed:

- to substantiate the need to transition from a list-based approach to a risk-based approach;
- to review international practices in establishing guarantees that account for occupational risks;
- to develop algorithms and formulas for calculating the volume of guarantees (including leave entitlements, working hours, wage supplements, and pension contributions);
- to propose mechanisms for adapting the methodology to sectoral and regional specifici ies.

The proposed approach is based on the concept of fair compensation, whereby the amount of granted guarantees depends on the actual degree of workplace hazard, the duration of exposure, and the time worked under such conditions. It takes into account the class of working conditions as determined by a specialized assessment, the proportion of time worked in adverse conditions, and an overall integrated occupational risk score.

The methodology relies on the use of risk coefficients determined according to the class of working conditions, and a matrix distribution model that enables the diffe entiation of guarantees based on all influencing factors. Each form of social protection - leave, working hours, wage supplements, and pension contributions - has its own calculation scale and adaptation coefficient.

Unlike existing formalized approaches, the proposed methodology allows for the consideration of dynamic changes in working conditions and enables the prompt recalculation of guarantee volumes in response to improvements or deteriorations in the production environment. This makes it applicable both in the context of current rulemaking (e.g., local regulatory acts and collective agreements) and in the formation of national labor policy.

International experience also demonstrates the eff ctiveness of using risk-based approaches. For example, Germany has a system of occupational risk insurance in which the amount of contributions depends on the level of hazard in a given industry and enterprise. In France, the

«Compte pénibilité» model is applied, which takes into account the severity and duration of harmful exposures within the pension system. In South Korea, the system of compensation for hazardous working conditions is based on a point-based risk assessment and a formalized guarantee scale. These examples illustrate the eff ctiveness of integrating occupational risk assessment into social protection systems and can serve as a reference for the development of a national model.

The methodology proposed in this study was pilot tested at several enterprises in the Republic of Kazakhstan, including industrial sites with varying levels of risk. The results of the pilot testing revealed a high degree of adaptability to sector-specific conditions, ease of implementation, and economic effic ncy: reductions in excessive compensation costs, increased worker motivation, and improved occupational safety and health indicators. Furthermore, the application of this model contributes to the formation of a new culture of occupational safety, in which each employer is incentivized to reduce risk levels both to ensure worker safety and to optimize expenditures.

Particular attention should be given to the regulatory consolidation of the methodology. Considering the ongoing modernization of Kazakhstan's labor legislation and the implementation of the «Safe Labor Concept for 2024-2030», the adoption of this model could serve as a foundation for revising the mechanisms for granting guarantees within the Labor Code, occupational safety and health regulations, and other normative legal acts. The methodology can also be adapted for implementation by insurance organizations participating in the mandatory workplace accident insurance system and used in actuarial assessments of insurance premiums.

Thus, the present study not only addresses the scientific challenge of developing a quantitative model for determining guarantees but also contributes to the formation of a fair and sustainable occupational safety and health system. The results obtained make it possible to propose concrete tools applicable in the practice of social partnership, labor resource management, collective bargaining, and law enforcement in the fi ld of occupational safety and health.

The development of a methodology for determining the volume of guarantees based on occupational risk assessment opens up opportunities for further research directions. In particular, promising areas include the construction of integrated occupational safety indices at the enterprise and regional levels, the integration of the methodology into digital occupational safety and health management platforms, the creation of monitoring systems for guarantee implementation based on automated solutions, and the development of comprehensive policies to incentivize employers to reduce risks. Furthermore, it is advisable to conduct economic and mathematical modeling of the eff cts of implementing the proposed methodology at the industry or national level, which would allow for more accurate forecasting of fi cal and social impacts.

II. Literature Review

Modern approaches to the formation of social guarantee systems for workers engaged in hazardous and/or dangerous work are undergoing signific nt transformation. Leading international organizations and scholars emphasize the need to move away from a universal list-based method toward an individualized system based on occupational risk assessment (Benach et al., 2014; Gallage-Alwis & Weiner, 2022). Such an approach allows for the consideration of actual working conditions, individual risks, and the dynamics of harmful exposure on workers' health, thereby making the system more equitable and economically sustainable.

The French model «Compte pénibilité», cited as one of the successful practices of a risk-based approach, was thoroughly analyzed by Mahieu et al. (2021). The model is built on a point-based system that takes into account the intensity and duration of harmful exposures, and the accumulated points affe t eligibility for early retirement and other entitlements. This has helped reduce abuse of the system and redirect resources to the workers who are genuinely in need.

Reports from the European Union bodies and the International Labour Organization (ILO, 2019; EU-OSHA, 2022) emphasize that integrating risk assessment procedures into the policy

framework for providing guarantees signific ntly reduces the incidence of occupational diseases, lowers public spending, and strengthens employers' motivation to improve working conditions.

For the post-Soviet space, and Kazakhstan in particular, the transition to a risk-based approach remains a pressing issue. As noted by Utepov et al. (2023), outdated methods based on occupational lists still dominate in practice, failing to reflect the actual hazards present in the workplace. This leads to distortions in the system of social guarantees and creates tension between employers and employees.

Particular attention in research is given to the economic aspects of diffe entiated guarantees. Friedrich & Gathmann (2020) demonstrated that the use of insurance rates based on risk levels leads to a reduction in the number of occupational accidents and incentivizes employers to implement preventive measures against workplace risks. This is further supported by Quadrini (2011), who notes that excessive regulation without consideration of actual risks may exacerbate cyclical fluctuations and contribute to instability in the labor market.

Digitalization plays a significant role in the reform of the guarantee system. The digital workplace monitoring system developed by Kaptanoglu et al. (2020) enables real-time assessment of risk parameters and the adjustment of entitlements accordingly. This approach is particularly applicable to large-scale enterprises and organizations with high staff turnover, where static models prove ineff ctive.

Mathematical models underlying the assessment of guarantee volumes are explored in the work of Mathur et al. (2021), who proposed an integrated calculation method that takes into account the frequency, intensity, and duration of exposure to harmful factors. Such a formalized methodology allows for an objective calculation of additional leave, wage supplements, reduced working hours, and other entitlements.

Of special importance is the relationship between working conditions, occupational risks, and workers' long-term health. Shahidi & Howard (2019) emphasize that exposure to harmful factors leads to the accumulation of chronic diseases, reduced work capacity, and increased costs for medical and pension provision. This was previously established in the classical work of Leigh (1983), which identified a statistically signific nt correlation between occupational risk, reduced income, and shortened working life.

In South Korea, according to the study by Kim et al. (2018), a system has been implemented in which the level of workplace hazard influences pension contributions and retirement age. This system is not only equitable but also incentivizes both workers and employers to reduce occupational risks.

From a global macroeconomic perspective, it is also important to consider the influence of fi ancial depth and inclusion on the system of labor guarantees. As demonstrated by Baskaya et al. (2016) and Dabla-Norris & Srivisal (2013), excessive financial burdens on employers-if not aligned with actual risk levels-may become a destabilizing factor for the entire social protection system.

The issue of fi ancial sustainability in social guarantee systems is also examined through the lens of financial accessibility. Studies by Ozili (2020), Čihák et al. (2016), and Sahay et al. (2015) emphasize the importance of maintaining a balance between coverage and the financial capacities of both the state and employers. Without an adequate risk assessment, such a balance cannot be achieved.

Thus, three key development directions in the scientifi literature on social guarantee systems clearly emerge:

1.the shift from a formalistic to a risk-based principle grounded in the quantitative assessment of occupational risks;

2.the integration of digital technologies and mathematical models that ensure objectivity and adaptability in social guarantee systems;

3.the international experience of integrating risk assessment into pension, insurance, and labor mechanisms, enabling a balance between social justice and economic sustainability.

The methodology for determining the volume of guarantees proposed in this article, developed on the basis of international best practices and adapted to the specific context of Kazakhstan, represents a scientific contribution to the modernization of the social protection system for workers and may serve as a foundation for further regulatory reforms in the fie d of occupational safety and health.

III. Materials and Methods

3.1 Methodological basis

The methodological framework of this study is based on a systematic analysis of legal and regulatory acts and statistical sources governing issues related to occupational safety and health, occupational risk assessment, and the provision of social guarantees in the Republic of Kazakhstan. The primary data sources include official statistics from the Bureau of National Statistics under the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan on occupational injuries and work-related illnesses for the period 2014-2023. The analysis of the dynamics of workplace accidents, their severity, and sectoral distribution made it possible to identify critical segments of the labor market characterized by high levels of occupational risk.

The assessment of working conditions is conducted in accordance with the requirements of the national methodology for the Special Assessment of Working Conditions (SAWC), approved by the authorized labor authority. Hygienic standards, which defi e the maximum permissible levels of exposure to physical, chemical, biological, and psychophysiological factors, serve as the reference scales. Working conditions are classified into four categories based on the degree of deviation from regulatory limits.

The point-based system for assessing working conditions includes the following elements:

- the magnitude of deviation from the permissible exposure limit (in points);
- the duration of exposure (as a percentage of the work shift);
- the identified risk level (high, signific nt, moderate, acceptable).

Additionally, sectoral and regional coefficients, as well as the frequency and severity of outcomes (accidents, identifie occupational diseases), are taken into account in the calculation.

3.2 An approach to occupational risk assessment

The assessment of occupational risk in this study is conducted to quantitatively evaluate the degree of harmful exposure to workplace factors affe ting workers' health. Each factor is assigned an integrated risk score, calculated using the following formula:

$$R_i = \sum_{j=1}^{n} w_j * x_{ij}$$

where:

R_i - total risk score at the i-th workplace;

x_{ij} - level of exposure to the j-th factor;

w_j - weighting coefficient representing the significance of the j -th factor,

n - total number of factors being assessed.

Based on the resulting risk score, the corresponding level of occupational risk is determined and classified as acceptable, moderate, high, or extreme. This classific tion serves as the foundational basis for the subsequent calculation of the volume of social guarantees.

3.3 Calculation of the amount of social guarantees

For the purpose of objectifying the process of granting benefits and compensations based on the degree of risk, a model is proposed in which the volume of guarantees provided to a worker G is a function of the risk level R, the class of working conditions C, the duration of exposure to harmful factors T, and the sectoral coefficient α::

$G = \alpha * f(R, C, T)$

where:

G - the volume of social guarantees provided (including additional leave, wage supplements, reduced working hours, and early retirement);

R - the integrated occupational risk indicator;

C - the class of working conditions as determined by the results of the Special Assessment of Working Conditions;

T - the duration of exposure to harmful factors during the workday (as a percentage);

α - the sectoral and/or regional adjustment coeffic nt.

Assignment of risk categories and the corresponding volume of guarantees is carried out based on predefi ed threshold values. For example, employees whose risk scores exceed the established threshold are entitled to an extended package of guarantees, including increased leave duration and higher compensation payments.

3.4 Data sources and structure

To implement the proposed approach, the following resources were utilized:

– Official statistical data on the number of occupational accidents, their severity, and distribution by region and type of economic activity (data from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan for 2014–2024);

– Methodological guidelines for the assessment of working conditions and occupational risks, including evaluation scales and coefficients (based on current regulatory documents of the Republic of Kazakhstan);

– Analytical materials on sectoral and regional diffe ences in working conditions, reflecti g the specifics of the production environment and the typical level of occupational risk.

Data processing was carried out in the following areas:

– aggregation of data by year, sector, and region;

– normalization of indicators related to harmful exposure factors;

– construction of risk indices and comparative analysis of working conditions;

– ranking of worker categories by level of social guarantees.

IV. Results

4.1 Duration of Reduced Working Hours and Additional Leave

Modern social and labor policy in Kazakhstan is focused on protecting the rights of workers employed in conditions associated with occupational risks. According to data from the Bureau of National Statistics of the Republic of Kazakhstan, in 2024, the number of workers employed in hazardous and/or dangerous working conditions reached 1,619,995 people. This significant figure underscores the need for a well-founded methodology for determining the scope of social guarantees - one that is oriented not only toward regulatory and sector-specific requirements but also toward a realistic assessment of occupational risks.

As part of this study, an original Methodology for Determining the Volume of Guarantees for Workers Engaged in Arduous, Hazardous, and Dangerous Work was applied. This methodology is based on a point-based assessment system for risk factors, diffe entiates types of exposures, and takes into account individual worker characteristics and production-specific onditions.

Classical approaches to defi ing guarantees and compensations are based on the sanitary-hygienic classific tion of working conditions, as regulated by normative documents. However, such systems often fail to reflect the full scope of risk exposure, as they:

– only record exceedances of maximum permissible concentrations (MPCs) and thresholds;

– do not account for the cumulative and combined effects of multiple factors;

– do not consider individual worker parameters such as age, experience, gender, or sensitivity to harmful exposures.

The application of a risk-based methodology allows for a shift from a static assessment of conditions to a dynamic model in which each workplace scenario is considered as a combination of occupational risk elements.

In the Republic of Kazakhstan, social guarantees for workers engaged in arduous work and in conditions involving hazardous and harmful factors include reduced working hours and additional paid leave, established by the state based on the List of industries, workshops, occupations, and positions with hazardous working conditions. The annual working time balance is used when preparing shift schedules, rotational work schedules, and flexible work arrangements. Payment is made for the actual hours worked within a 36- or 40-hour workweek according to the working time accounting schedule. Employers independently determine the work schedules for shifts and rotational work, based on the requirements of labor legislation.

The working time balance reflects the standard number of working hours by month and accounts for limitations imposed by the 36- and 40-hour workweeks. Particularly strict limits apply to underground work, where working hours must not exceed 6 hours per day.

Social guarantees perform a protective function: by reducing working time and providing additional leave, the system helps limit workers' exposure to harmful factors, supports their well-being, and aids recovery. However, the current scheme is based on a list-based approach, where the same leave entitlement is granted regardless of the actual severity and danger of the job. This supports the research hypothesis that the list-based approach is neither fair nor evidence-based.

Instead, the proposed Methodology introduces a diffe entiated model based on occupational risk assessment-taking into account the intensity, duration, and actual exposure of the worker to adverse working conditions. This approach contributes to disease prevention and the preservation of workers' health.

For a justified evaluation, the following aspects must be considered:

– Actual working conditions;

– Presence of health risks;

– Results of the occupational risk assessment.

The model is based on Table 1, which links the degree of occupational risk to the duration of additional leave.

Table 1: Model for determining the duration of additional leave depending on the degree of occupational risk

Types of Social Guarantees	Level of Occupational Risk				
	1-Acceptable	2-Low	3-Medium	4-High	5 - Very High
Duration of Additional Leave (in calendar days)	-	6-15 days	9-18 days	15-24 days	18-36 days

Source : Compiled by the authors

Table 1 defi es the ranges of leave duration by risk category; however, it does not account for the actual time spent in hazardous working conditions. To ensure a more accurate calculation, Table 2 is introduced, which simultaneously considers both the level of occupational risk and the proportion of time exposed to harmful conditions.

Table 2: Distribution of Additional Leave Duration Based on the Proportion of Time Spent in Hazardous Working Conditions and the Degree of Occupational Risk

The proportion of calendar days in harmful conditions, %	Degree of occupational risk			
	2-low	3-Medium	4-High	5 - Very High
1,00 - 5,00	6	9	15	18
5,01 - 10,00				19
10,01 - 15,00	7	10	16	20
15,01 - 20,00				21
20,01 - 25,00	8	11	17	22
25,01 - 30,00				23
30,01 - 35,00	9	12	18	24
35,01 - 40,00				25
40,01 - 45,00	10	13	19	26
45,01 - 50,00				27
50,01 - 55,00	11	14	20	28
55,01 - 60,00				29
60,01 - 65,00	12	15	21	30
65,01 - 70,00				31
70,01 - 75,00	13	16	22	32
75,01 - 80,00				33
80,01 - 85,00	14	17	23	34
85,01 - 90,00				35
90,01 - 100,00	15	18	24	36

Source: Compiled by the authors

This system provides a transparent mechanism for calculating additional leave by taking into account actual exposure and the corresponding risk category. This is particularly important in the context of modernizing the legislative framework and transitioning toward adaptive mechanisms of social protection.

4.2 Increased wage rate

The wage system is determined by the provisions of the employment contract, collective agreement, and/or employer-issued acts, taking into account the wage conditions established by agreements, employment and collective contracts, and employer acts, as well as the specifics and types of the organization's activities confirmed by the results of ORA.

According to subparagraph 4) of paragraph 5 of Article 153 of the Labor Code of the Republic of Kazakhstan, the minimum values of inter-grade coefficients are established by sectoral agreements.

For the practical application of the tariff-based wage system, the use of professional standards is required; in their absence, qualification and tariff-qualification reference books should be applied.

Professional standards-or, if unavailable, the Qualification Handbook and the Unified Tariff and Qualification Reference Book (UTQRB)-serve as the basis for establishing qualification requirements for employees and are used to address issues related to the regulation of labor relations and the implementation of an effective human resource management system.

The classification of workers employed in various sectors of economic activity is carried out in accordance with the UTQRB based on eight wage grades. For employees (non-manual workers), grading is determined by organizations using the Qualification Handbook (QH).

When developing a wage scale, it is essential to ensure that it provides for the distribution of workers according to the complexity and intensity of labor, working conditions (confirmed by the results of ORA), and qualification level.

In this regard, a clear procedure must be established for determining the minimum wage rate for a first-grade worker, including those engaged in arduous work or work with hazardous and/or dangerous conditions. This should be stipulated in the collective agreement or an employer's act, taking into account sectoral coefficients that classify working conditions by degree of harmfulness and danger, as defined in the relevant sectoral agreement.

Thus, the application of various wage systems depends on the specifics of the technological process and forms of work organization.

In addition to the base wage rate (or official salary), in order to differentiate employee efforts assess the quality of their work, enhance material incentives, and increase labor productivity, supplements and allowances are granted based on working conditions.

These supplements and allowances are divided into two types: compensatory and incentive-based.

Compensatory supplements include payments for combining job roles, expanding service areas or performing the duties of temporarily absent employees, as well as for working in arduous, hazardous, and/or dangerous conditions, for mentoring, and for overtime work under piece-rate payment systems, among others.

These wage conditions apply specifically to workers whose employment in arduous or hazardous conditions is confirmed by the results of occupational risk assessment (ORA).

In certain economic sectors, when concluding sectoral agreements-which are binding on all employers-a unified procedure for establishing supplements for workers engaged in arduous and hazardous work is set in accordance with subparagraph 4) of paragraph 5 of Article 153 of the Labor Code of the Republic of Kazakhstan. When collective agreements are concluded, their provisions are determined by the parties in accordance with the general, sectoral, and regional agreements signed.

In the collective agreement, employment contract, and/or employer's regulatory act, the amounts of supplements must be clearly differentiated based on working conditions, taking into account the results of ORA and the specific nature of the organization. These documents must reflect the real difference compared to the remuneration of employees working in normal conditions.

Furthermore, these documents must clearly define, in compliance with legislative requirements:

– the criteria for assigning specific supplements and allowances by personnel category;

– the quantitative and qualitative indicators upon which such payments are based;

– the conditions under which the payment of certain supplements and allowances may be suspended or terminated.

Wages under summarized working time accounting are paid based on the actual number of hours worked, as recorded in the working time log. In this case, wages are calculated using an hourly wage rate, derived from the base wage (official salary) and the monthly standard of working time according to the working time balance for the corresponding calendar year.

For the analysis of compensatory payments for work under hazardous and/or dangerous conditions across economic sectors, data from the Bureau of National Statistics of the Republic of Kazakhstan were used, including tables on the Real Wage Index for 2024. Based on these data, average wage supplement coefficients were calculated across types of economic activity (Table 3).

The calculated coefficients reflect current differences in the level of compensatory payments across economic sectors and can serve as a reference point for revising wage regulations under conditions of harmful exposure. For example, the elevated coefficient for the «Electricity, gas, and steam supply» sector (1.2006) may be taken into account when planning wage budgets in energy companies, while the coefficient for «Information and communication» (1.2134) may be used when analyzing digital workload and occupational burnout levels.

Table 3: Wage coefficients by type of economic activity

Economic Activity	Bonus Coefficient (k)
Agriculture, forestry and fishing	1.1622
Industry (total)	1.1259
Mining and quarrying	1.1035
Manufacturing	1.1323
Electricity, gas, steam and air conditioning supply	1.2006
Water supply; sewerage; waste management and remediation activities	1.2166
Construction	1.0448
Wholesale and retail trade; repair of motor vehicles and motorcycles	1.1227
Transportation and storage	1.1217
Accommodation and food service activities	1.0683
Information and communication	1.2134
Financial and insurance activities	1.2166
Real estate activities	1.1964
Professional, scientific nd technical activities	1.1355
Administrative and support service activities	1.0000
Public administration and defense; compulsory social security	1.0598
Education	1.0555
Human health and social work activities	1.0576
Arts, entertainment and recreation	1.1718
Other service activities	1.0747

Source: Compiled by the authors

These coefficients can also be applied:

– in the development of standard wage guidelines and recommendations,

– in the formation of sectoral agreements and collective bargaining agreements,

– in the justific tion of social support measures for workers engaged in arduous or hazardous working conditions.

4.3 Mandatory occupational pension contributions

According to Article 250 of the Social Code, mandatory occupational pension contributions to be paid to the Unified Accumulative Pension Fund on behalf of the individuals specifie in paragraph 5 of Article 248 of the Social Code are established at a rate of 5 percent of the employee's monthly income used as the basis for calculating such contributions.

Mandatory occupational pension contributions are funds transferred by agents (employers) from their own resources to the Unified Accumulative Pension Fund in favor of employees engaged in work under hazardous conditions, whose occupations are included in the official List of Industries, Jobs, and Occupations with Hazardous Working Conditions.

Mandatory occupational pension contributions are made on behalf of employees whose occupations are included in the "General Occupations" section of the List, regardless of the specifi industries or workshops in which they work, provided that these occupations are not explicitly listed in other corresponding sections or subsections of the List.

Employers are required to make mandatory occupational pension contributions payments for employees who have worked in hazardous (or particularly hazardous) working conditions for at least 80% of their working time in a given month.

The OPPC rate refers to the amount the agent is obligated to pay to the Unified Accumulative Pension Fund, expressed as a percentage of the employee's income used for calculating mandatory occupational pension contributions. As of current legislation, the mandatory occupational pension

contributions rate is 5%.

If hazardous working conditions are eliminated-confir ed by the results of workplace certific tion or ORA - employers (agents) are no longer required to make mandatory occupational pension contributions payments.

Article 79 of the Labor Code of the Republic of Kazakhstan stipulates that working time must be recorded in documents as defi ed by the employer.

According to subparagraph 19 of paragraph 2 of Article 23 of the Labor Code, employers are obligated to maintain accurate records of working time, including overtime, and work performed under hazardous (especially hazardous), dangerous conditions, or arduous jobs for each employee.

The procedure for the payment of mandatory occupational pension contributions is regulated by Order No. 170 of the Minister of Labor and Social Protection of the Population of the Republic of Kazakhstan, dated May 24, 2023, «On the Approval of the List of Industries, Jobs, and Occupations of Employees Engaged in Work under Hazardous Conditions, for Whom Agents Shall Make Mandatory Occupational Pension Contributions from Their Own Funds».

4.4 Standards for the provision of milk or equivalent food products, and standards for the provision of specialized dietary (therapeutic and preventive) nutrition

Free distribution of milk or other equivalent food products, as well as dietary (therapeutic and preventive) nutrition, is provided to employees on days when they are actually engaged in work involving hazardous working conditions, caused by the presence of harmful production factors at the workplace as specified in the List of Harmful Production Factors (hereinafter – the List).

Milk or equivalent food products are provided to employees if harmful production factors specified in the List are present in the workplace, and their levels are confirmed by the results of the workplace conditions assessment.

Milk or equivalent food products are to be distributed in specially equipped rooms that comply with officially approved sanitary and hygienic standards. The amount provided is 0.5 liters of milk (3.2% fat content) per shift (during the break), regardless of the shift duration, on days when the employee is actually engaged in work involving the production or use of chemical substances. If the time spent working under harmful conditions is less than the full shift duration, milk is provided only if the employee has worked at least half of the shift under such conditions.

For employees who are medically restricted from consuming milk (as determined by a periodic medical examination and certified by a dietitian), milk may be substituted with other equivalent food products upon the employee's consent. This substitution must be formalized through the collective agreement or an employer-issued act.

Employees who come into contact with inorganic lead compounds must be provided, in addition to milk, with 2 grams of pectin in the form of canned plant-based food products, fruit juices, or beverages enriched with pectin (with actual pectin content indicated by the manufacturer). These products may be substituted with natural fruit juices with pulp in quantities of 250–300 milliliters.

In cases of regular exposure to inorganic compounds of lead, mercury, cadmium, phosphorus, chromium, carbolic acid, as well as hydrocarbons and their derivatives, it is recommended that fermented dairy products be consumed instead of milk. When working in the production and processing of antibiotics, fermented milk products enriched with probiotics (bifidobacteria, lactic acid bacteria) or colibacterin prepared from whole milk should be provided instead of fresh milk.

At the same time, it is important to note that milk is hazardous in cases of poisoning with carbolic acid, hydrocarbons, phosphorus, and their derivatives. When fat-soluble poisons (such as dichloroethane, carbon tetrachloride, gasoline and its derivatives, and many organophosphorus compounds) enter the stomach, the consumption of milk, as well as plant- or

animal-based oils and fats, is strictly contraindicated-these substances enhance the absorption of such toxins and may aggravate the poisoning.

In this regard, the authors recommend that production councils, employers, and trade unions consider replacing milk with specialized beverages with high detoxification activity, provided per shift regardless of its duration, on days when the employee is actually engaged in the production or handling of such substances.

Dietary (therapeutic and preventive) nutrition must be provided to employees before the start of the work shift. In certain cases, it is allowed to distribute dietary (therapeutic and preventive) nutrition during the lunch break, subject to approval by the organization's medical and sanitary unit. For employees working under increased pressure conditions (in caissons, hyperbaric chambers, or performing diving work), dietary nutrition is provided after decompression.

Dietary (therapeutic and preventive) nutrition is provided to employees when harmful production factors are present in the workplace and their levels, based on the results of the workplace conditions assessment, correspond to hazard classes 3 and 4, or are classified as dangerous working conditions.

Retroactive distribution of milk or dietary (therapeutic and preventive) nutrition for past shifts, advance distribution for multiple future shifts, as well as monetary compensation for unclaimed milk or dietary nutrition, is not allowed.

The procedure for the distribution of milk or equivalent food products and/or specialized dietary (therapeutic and preventive) nutrition in the Republic of Kazakhstan is regulated by:

– Order No. 1056 of the Minister of Health and Social Development of the Republic of Kazakhstan, dated December 28, 2015, «On the Approval of Norms for the Distribution of Milk or Equivalent Food Products and/or Specialized Products for Dietary (Therapeutic and Preventive) Nutrition to Employees»;

– Order No. 1054 of the Minister of Health and Social Development of the Republic of Kazakhstan, dated December 28, 2015, which regulates the Rules for the Distribution of Milk or Equivalent Food Products and/or Specialized Products for Dietary (Therapeutic and Preventive) Nutrition, Special Workwear and Other Personal Protective Equipment, and Provision of Collective Protective Equipment and Sanitary Facilities at the Employer's Expense.

To ensure a unified approach to determining the amount of supplements and to enhance the transparency of the wage system across economic sectors, a draft algorithm has been developed for distributing the types and volumes of social guarantees based on the degree of individual occupational risk of the employee, as determined by the results of ORA (Table 4).

The provided coefficients reflect the wage prioritization level across specific sectors, taking into account technological complexity, hazardous working conditions, and occupational risks. At the same time, the actual bonus calculation may be adjusted within collective agreements and employer-issued local acts, subject to mutual agreement between the parties.

For more precise calculations-particularly in industries such as the nuclear sector-a mathematical model is used, which accounts for the level of occupational risk, the proportion of days worked under hazardous conditions, and the total number of working days.

The presented matrix illustrates the relationship between increasing coefficients, the degree of occupational risk, and the number of days worked under hazardous conditions out of a 31-day calendar month.

To refine the approach to coefficient calculation using a specific sector as an example, the following formula is applied to determine the individual increasing coefficient.

Table 4: Matrix for the Allocation of Increasing Coefficients Based on a Risk-Based Approach, Taking into Account the Proportion of Days Worked (out of 31 Calendar Days) in Hazardous Working Conditions

		Degree of occupational risk			
		2 (3.1)	3 (3.2)	4 (3.3)	5 (3.4)
Number of days worked in harmful conditions	1	1,0500	1,0917	1,1333	1,1750
	2	1,0542	1,0958	1,1375	1,1792
	3	1,0583	1,1000	1,1417	1,1833
	4	1,0625	1,1042	1,1458	1,1875
	5	1,0667	1,1083	1,1500	1,1917
	6	1,0708	1,1125	1,1542	1,1958
	7	1,0750	1,1167	1,1583	1,2000
	8	1,0792	1,1208	1,1625	1,2042
	9	1,0833	1,1250	1,1667	1,2083
	10	1,0875	1,1292	1,1708	1,2125
	11	1,0917	1,1333	1,1750	1,2167
	12	1,0958	1,1375	1,1792	1,2208
	13	1,1000	1,1417	1,1833	1,2250
	14	1,1042	1,1458	1,1875	1,2292
	15	1,1083	1,1500	1,1917	1,2333
	16	1,1125	1,1542	1,1958	1,2375
	17	1,1167	1,1583	1,2000	1,2417
	18	1,1208	1,1625	1,2042	1,2458
	19	1,1250	1,1667	1,2083	1,2500
	20	1,1292	1,1708	1,2125	1,2542
	21	1,1333	1,1750	1,2167	1,2583
	22	1,1375	1,1792	1,2208	1,2625
	23	1,1417	1,1833	1,2250	1,2667
	24	1,1458	1,1875	1,2292	1,2708
	25	1,1500	1,1917	1,2333	1,2750
	26	1,1542	1,1958	1,2375	1,2792
	27	1,1583	1,2000	1,2417	1,2833
	28	1,1625	1,2042	1,2458	1,2875
	29	1,1667	1,2083	1,2500	1,2917
	30	1,1708	1,2125	1,2542	1,2958
	31	1,1750	1,2167	1,2583	1,3000
for 36 hours a week	%	3,89%	4,81%	5,74%	6,67%
for one hour of work	%	0,11%	0,13%	0,16%	0,19%

Source: Compiled by the authors

Sectoral increasing coefficients kkk are calculated using the following formula:

$$k = \left(\frac{k_{max} - k_{min}}{2}\right) \times \left(\frac{i-2}{3} + \frac{j-1}{N-1}\right)$$

where:

- k_{min} и k_{max} - lower and upper bounds of sectoral inter-grade coefficients;
- i - occupational risk level indicator;

- j - number of days worked under hazardous conditions out of N total working days.

Example.

Let us assume that it is necessary to determine the increasing coeffic nt for workers in the nuclear industry.

According to the formula mentioned above, the desired coefficient is calculated as follows.

$k = 1{,}05 + \left(\frac{i-2}{3} + \frac{j-1}{N-1}\right)$

This model ensures flexibility in determining wage supplements while maintaining predictability and fairness in remuneration—an especially important factor in industries with high safety standards and qualific tion requirements.

The application of such a matrix is recommended for assessing fair compensation within the framework of occupational safety and health management systems and for the diffe entiation of incentive payments.

The national model of occupational safety management in Kazakhstan is based on a compensatory principle, categorizing working conditions as either safe (optimal, acceptable) or unsafe (hazardous and dangerous). This approach partially incentivizes workers to remain employed in unfavorable working conditions.

At the same time, employers are not sufficiently incentivized to improve working conditions, reduce the number of hazardous workplaces, modernize production processes, or introduce automation in production and technology.

From a regulatory policy perspective, there are legal barriers caused by conflicts, gaps, and declarative (non-enforceable) provisions, as well as weak systemic linkages within and across sectors in the national legal framework for social guarantees.

Among the key problematic issues is the unjust nature of the current mechanism for providing social guarantees under the list-based approach, whereby at the same workplace, one employee may be granted benefit while another is not.

Research into existing practices in leading countries with high occupational safety culture has highlighted the relevance of diffe entiating workplaces based on the degree of occupational risk, where the volume of social guarantees corresponds to the level of risk: high risk – full benefit package.

Taking into account international experience and an analysis of the practical application of labor legislation across enterprises in various sectors, a draft Methodology has been developed for assigning social guarantees to workers employed in hazardous and/or dangerous industries, based on consultations with representatives of both employees and employers (hereinafter – the Methodology).

The Methodology is based on the principles of a new occupational safety ideology, under which the diffe entiation of workplaces, followed by the provision of personal protective equipment and social guarantees, is carried out according to the degree of occupational risk.

Currently, during the certific tion of production facilities based on working conditions, a classification is used that establishes whether working conditions are either safe or hazardous and dangerous. This principle will be retained even after the certific tion procedure is replaced with ORA.

The new approach will rely on diffe entiating the workplace by the level of occupational risk and the degree of protection the employer is obligated to provide.

The Methodology aims to establish and implement a socially just model (mechanism) for determining the parameters and provision of social guarantees.

The level of protection will vary from the minimum, corresponding to low levels of risk, to the maximum, in cases of very high risk. This new approach implies that both the type and volume of social guarantees will be diffe entiated based on the degree of occupational risk. A higher level of risk must correspond to a greater volume of social guarantees [1-22].

Regarding the improvement of regulatory policy during the transition period (including the elimination of the certific tion of workplaces and the full-scale shift to ORA, the gradual phase-out

of the list-based approach, substitution of milk, etc.), it is necessary to develop a dedicated Roadmap for improving the relevant normative legal acts.

V. Conclusions

In sum, the fi ancial analysis underscores a growing prioritization of occupational health and safety across diverse industries. The diffe ences in timing, volume, and category–specific focus point to varying levels of maturity and strategic orientation in safety management, offe ing valuable insights for policy development, benchmarking, and future enterprise–level planning.

Notably, 2024 marked the firs year in which all enterprises began allocating funds to occupational risk assessments and workplace certifi ation, highlighting a sector–wide transition toward more proactive and standardized safety practices, likely influenced by evolving regulatory frameworks.

Altai, while initially exhibiting moderate expenditures, made substantial one–time investments in specific areas—particularly in nutrition and compensation—during 2023, followed by more moderate levels in 2024. This may indicate reactive or restructuring–driven safety fi ancing rather than a sustained programmatic strategy.

Across all three enterprises, there has been a noticeable intensific tion of investment in key safety domains, particularly in personal protective equipment, compensation for hazardous working conditions, and training. Fosfat maintained a leading position in overall spending, reflecting a robust and systematic approach to occupational safety, with consistently high investments across nearly all categories. Project demonstrated a steady and strategic increase in funding, signaling a long–term commitment to safety infrastructure and workforce support.

Companies that actively invest in OSH achieve lower injury rates, higher labor productivity, and enhanced competitiveness. The identified sectoral specifics emphasize the importance of a diffe entiated approach to planning and allocating OSH expenditures, which ultimately contributes to the sustainable development of enterprises and the improvement of working conditions.

The analysis of data from five enterprises across various sectors of the economy has made it possible to identify the key characteristics of the modern system of occupational safety and health (OSH) cost accounting within the context of Kazakhstani practice. The fi dings reveal both common patterns in expenditure allocation and variations driven by industry–specific factors and the internal policies of the organizations.

The expenditure structure demonstrates a high degree of standardization. Across all the analyzed enterprises, the main cost categories include: personal protective equipment, mandatory insurance, employee training and instruction, specialized nutrition, medical examinations, and compensation for hazardous working conditions. This confi ms that the regulatory framework for occupational safety and health has a systemic influence on budget formation, and that enterprises – regardless of industry – rely on established expenditure categories.

There is evidence of uneven and unstable fi ancing across certain areas of occupational safety and health. For example, in several cases, a sharp increase or decrease in expenditures was observed for specialized nutrition, sanitary and hygiene facilities, risk assessments, and collective protection measures. This may indicate the project–based nature of many initiatives, a lack of systematic planning, and limited enterprise resources, which affect the consistency and continuity of OSH investments.

Occupational safety and health fi ancing is directly linked to sector–specific risks. In the mining and manufacturing industries, a higher share of expenditures is allocated to protective measures, training, and compensations, reflecting the increased hazards of the production environment. In contrast, in the energy and chemical sectors, the focus shifts toward material support and preventive measures, highlighting diffe ing priorities in managing occupational risks.

Occupational risk assessment and workplace certifi ation remained underrepresented in previous years and only began to appear in reporting from 2024 onward. This indicates a delayed

implementation of legislative requirements and a lack of integration of risk assessment procedures into the overall cost accounting system.

Conclusion. Investments in employee training show a positive trend, which may indicate growing managerial awareness of the importance of preventive measures.

In conclusion, the analysis indicates that while Kazakhstani enterprises generally strive to comply with occupational safety and health regulations, in practice, cost accounting is often fragmented and lacks completeness. The fi dings derived from the analysis of actual data will be further applied in Chapter 3 to develop recommendations for enhancing the occupational safety and health cost accounting system.

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CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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A NATURE-INSPIRED, DROPLET-SHAPED FLOATING PLATFORM FOR OFFSHORE WIND TURBINES

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Abstract

Floating offshore wind energy harnesses high-quality wind resources in deep waters, but traditional platform designs face challenges in mitigating extreme marine forces and maintaining cost-effectiveness. This paper introduces a nature-inspired, droplet-shaped floating platform that addresses these challenges through innovative design and hydrodynamic optimization. Conventional floating platforms such as Spar, Tension Leg Platform (TLP), and Semi-Submersible concepts each provide unique advantages, including stability, reduced motion, and robust mooring systems, yet encounter limitations like extreme load variability and high dynamic response under harsh conditions. Drawing inspiration from the streamlined geometry of water droplets, the proposed platform leverages biomimetic principles to enhance hydrodynamic efficiency, minimize drag, and improve stability. A mathematical framework is developed to define the droplet shape, integrating linear and semicircular functions to optimize angles, radii, and submerged volumes. Analytical derivations establish boundary conditions, enabling precise calculations for structural parameters and buoyancy. The droplet-shaped design aims to mitigate pitch, heave, and surge motions, offering a robust foundation for supporting multi-megawatt wind turbines in extreme environments. This study proposes a cost-effective, scalable alternative to existing platforms, highlighting the potential of biomimicry to revolutionize floating offshore wind technology. Further validation through numerical simulations and experimental wave-tank testing is recommended to optimize performance and reliability. This novel approach signifies a step toward innovative, sustainable solutions for harnessing renewable energy in deep-water regions, paving the way for the next generation of offshore wind deployment.

Keywords: Floating offshore wind, droplet-shaped platform, biomimetic design, hydrodynamic optimization, renewable energy, multi-megawatt turbines

1. Introduction

The exploitation of offshore wind resources in deep-water environments represents one of the most promising pathways toward sustainable energy generation. Conventional floating platforms—including Spar, Semi-Submersible, and Tension Leg Platforms (TLP)—offer partial advantages in terms of stability and load management, but they are limited by large dynamic responses, extreme loading conditions, and high construction costs. Addressing these challenges requires innovative geometries that enhance hydrodynamic efficiency while ensuring structural robustness.

This study introduces and develops a biomimetic droplet-shaped floating platform, inspired by naturally optimized hydrodynamic forms observed in water droplets, icebergs, and marine mammals. The central premise is that the droplet's streamlined profile can substantially reduce drag forces, minimize pitch, surge, and heave motions, and optimize buoyancy distribution. A mathematical framework is formulated to define the geometry of the droplet, integrating linear and semicircular functions subject to specific boundary conditions. Analytical derivations provide

closed-form solutions for volume, cross-sectional area, and buoyancy requirements, enabling scalability for multi-megawatt turbine applications.

The proposed design offers a cost-effective and hydrodynamically efficient alternative to traditional platforms. By leveraging biomimetic principles, the droplet-shaped concept aims to mitigate extreme environmental loads, improve structural survivability, and enhance performance under harsh marine conditions. The geometry further demonstrates potential scalability and adaptability, aligning with current industrial needs for robust, deployable solutions in deep-water regions.

Future research will focus on numerical and experimental validation of the proposed concept. High-fidelity Computational Fluid Dynamics (CFD) simulations, coupled aero-hydro-elastic modeling, and wave-basin testing are recommended to assess drag coefficients, hydrodynamic stability, and long-term fatigue behavior. Additional investigations into mooring-line configurations and material optimization will strengthen the platform's applicability for commercial deployment.

In conclusion, this thesis advances floating offshore wind technology by presenting a nature-inspired structural paradigm that unites mathematical precision with biomimetic insight. The droplet-shaped platform contributes to the development of next-generation offshore wind systems by offering enhanced stability, reduced costs, and sustainable scalability, thereby supporting the global transition toward renewable energy.

2. Methodology

One of the most aerodynamically and hydrodynamically stable shapes found in nature is the droplet (Figure 1). Its streamlined geometry minimizes resistance and maximizes stability, making it an ideal inspiration for various design applications. This natural form is not only visually elegant but also functionally optimized, as it allows for minimal drag in both air and water. When a droplet falls, it adopts a shape that balances surface tension, gravitational forces, and fluid dynamics, forming an efficient structure that reduces energy loss.



Figure 1. A Droplet Hanging from a Leaf, Illustrating Natural Streamlined Geometry

The principles derived from these natural forms have far-reaching applications in engineering and design. For instance, they inspire the hydrodynamic profiles of ships, submarines, and now floating wind turbine platforms. By mimicking the droplet's streamlined structure, these platforms can achieve reduced drag, improved stability, and enhanced durability, even in harsh marine environments. The droplet serves as a testament to nature's ability to create solutions that balance form and function, making it a cornerstone for biomimetic engineering.

As depicted in Figure 2, the shape of an iceberg closely resembles an inverted droplet beneath the water, with its wide base providing stability, while the portion above water mimics the shape of a falling droplet. This dual geometry plays a critical role in its ability to remain resilient against dynamic marine forces. The submerged section, which constitutes the majority of the iceberg's mass, provides buoyancy and resists tipping by maintaining a low center of gravity. Meanwhile, the above-water portion serves as a streamlined form, reducing wind resistance and minimizing wave impacts on the exposed surface. This natural design is an exquisite example of evolutionary optimization for harsh environments. Icebergs are subjected to constant wave motion, varying currents, and environmental changes, yet their shape ensures equilibrium and durability. The droplet-like profile beneath the waterline contributes to smooth hydrodynamic interactions, effectively dissipating energy from waves and stabilizing the iceberg. Additionally, the wide submerged base enhances the structural balance, acting as a natural counterweight to the forces acting above the water. In the context of engineering, the iceberg's structure offers invaluable insights into designing offshore platforms. Its dual nature—a wide, stable base and a streamlined, minimal-resistance profile—can inspire floating structures that must endure similar challenges, such as strong ocean currents, high winds, and rough seas.

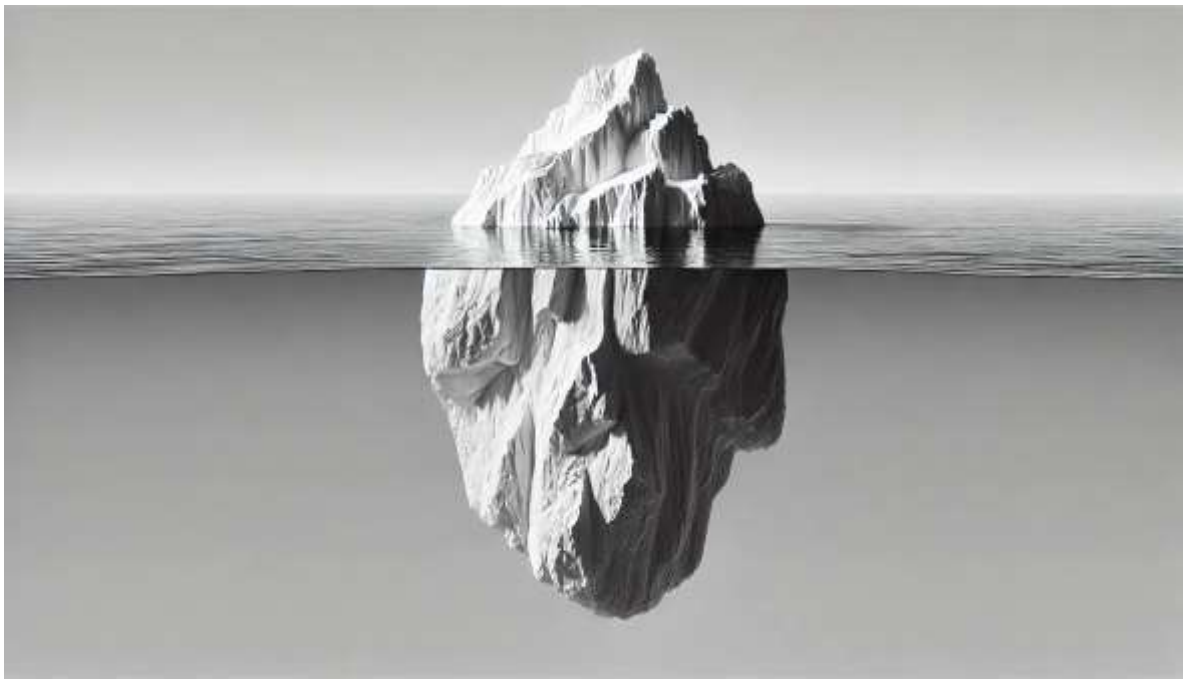


Figure 2. An Iceberg with Submerged and Above-Water Portions, Demonstrating Natural Hydrodynamic Stability.

Similarly, large marine mammals such as whales (Physeter macrocephalus) demonstrate remarkable balance and stability. These creatures have been observed resting near the water's surface in a vertical position, relying on their streamlined bodies and slight movements to maintain equilibrium. Studies, such as those published in Current Biology (Miller et al., 2008), reveal that

whales often enter brief, near-vertical resting states. During these periods, they leverage their body shape to stabilize themselves, even amidst surface currents and wave activity [33].

As illustrated in Figure 3, the body of a whale resembles an inverted droplet, further emphasizing the prevalence of this efficient geometry in nature. This alignment between form and function provides critical insights for biomimetic design. By studying these natural examples, we can develop advanced engineering solutions, such as stable and efficient offshore platforms. The droplet-shaped geometry serves as a guiding principle, enabling the creation of structures that not only withstand environmental challenges but also operate efficiently in dynamic marine conditions.



Figure 3. Whales Resting in a Vertical Position, Exemplifying Natural Hydrodynamic Balance [34].

Likewise, centuries of trial and error have led to the development of highly effective fishing floats, which serve as simple yet robust markers on the water. Their shapes have evolved to minimize oscillations, maintain buoyancy, and reliably signal fish bites, as shown in Figure 4. Notably, fishing floats share a key objective with floating wind turbine platforms—namely, remaining upright and stable in a dynamic marine environment. Although wind turbines operate at a vastly different scale and carry much heavier loads, the underlying principle of distributing volume and mass for optimal stability is remarkably similar.



Figure 4. Various Fishing Floats Showcasing Hydrodynamically Stable Designs.

By integrating such natural design insights, the droplet-shaped floating platform proposed in this study mimics the hydrodynamic advantages of streamlined shapes found in nature. Its tapered submerged profile, akin to an iceberg's hidden volume or a whale's vertical resting posture, aims to minimize drag and wave excitation forces. This approach directly supports the platform's goals of reducing pitch, heave, and surge motions while providing the buoyancy required to support multi-megawatt turbines under extreme conditions.

To translate these principles into a functional design, the study employs a mathematical framework to define the droplet shape with precision. By systematically analyzing the relationships between boundary conditions, geometric parameters, and hydrodynamic performance, the design ensures maximum stability and efficiency.

The mathematical model, depicted in Figure 5, illustrates a mathematical representation of the drop shape, which can be obtained by rotating the function $f_1(x) = x \cdot \tan\alpha$ (1) over the interval $[x_1, x_3]$ and the function $f_2(x) = \sqrt{y_3^2 - (x - x_4)^2}$ (2) over the interval $[x_3, x_5]$ around the x-axis.

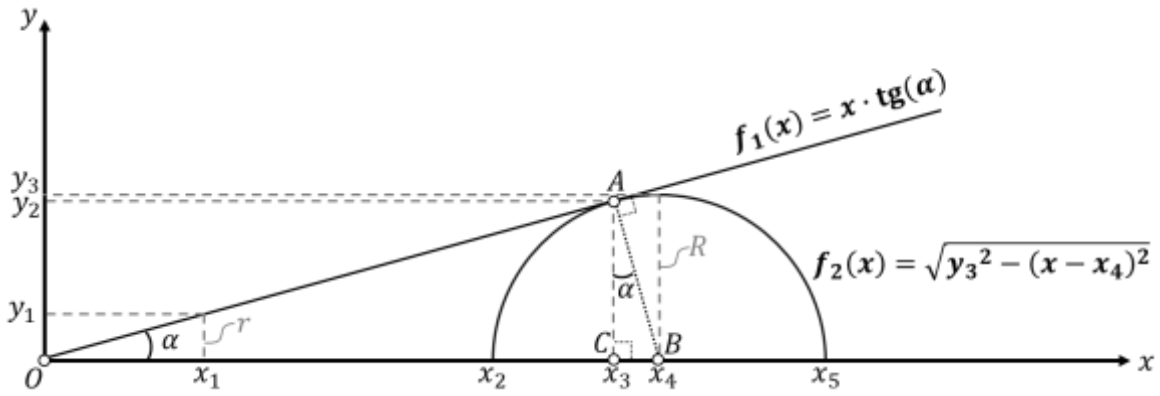


Figure 5. Mathematical Model of Drop Shape Defined by Boundary Conditions.

From Figure 5, we aim to determine the values of all relevant coordinates by applying the defined boundary conditions and using the mathematical model of the drop's shape. The boundary conditions are as follows:

1. *First Boundary:*

$$y_1 = r \tag{3}$$

Here, *r* is the top radius of the conical section in the droplet's profile. This boundary corresponds to the narrower (lower) limit of the droplet shape.

2. *Second Boundary:*

$$y_3 = R \tag{4}$$

Here, *R* denotes the radius of the semicircle and represents the largest cross-sectional width (upper limit) of the droplet.

3. *Third Boundary:*

$$x_1 = r \cdot \cot\alpha = r \cdot \frac{\cos\alpha}{\sin\alpha} \tag{5}$$

This condition defines the horizontal position of the boundary as a function of the angle of inclination, α. Here, α is the angle between the tangent at the boundary and the horizontal axis.

From triangles OAB and ABC in Figure 5 we can see that:

1) AB is the radius of the semicircle which is equal to R:

$$AB = R \tag{6}$$

2) From triangle OAB:

$$\sin\alpha = \frac{AB}{OB} = \frac{R}{x_4} \tag{7}$$

3) From triangle ABC:

$$\cos\alpha = \frac{AC}{AB} = \frac{y_2}{R} \tag{8}$$

From (7) we will find x_4:

$$x_4 = \frac{R}{\sin\alpha} \tag{9}$$

From (8) we will find y_2:

$$y_2 = R \cdot \cos\alpha \tag{10}$$

From (1) and (10) we will find x_3:

$$f_1(x_3) = y_2 = R \cdot \cos\alpha = x_3 \cdot \tan\alpha$$

then

$$x_3 = R \cdot \frac{\cos\alpha}{\tan\alpha} = R \cdot \cot\alpha \cdot \cos\alpha = R \cdot \frac{\cos^2\alpha}{\sin\alpha} \tag{11}$$

From Figure 5 we can see that:

$$x_2 = x_4 - R \tag{12}$$

and

$$x_5 = x_4 + R \tag{13}$$

From (9) and (12) we find x_2:

$$x_2 = \frac{R}{\sin\alpha} - R = R \cdot \left(\frac{1}{\sin\alpha} - 1\right) \tag{14}$$

From (9) and (13) we find x_5:

$$x_5 = \frac{R}{\sin\alpha} + R = R \cdot \left(\frac{1}{\sin\alpha} + 1\right) \tag{15}$$

After defining analytical values all vertical y_1, y_2, y_3 and horizontal x_1, x_2, x_3, x_4, x_5 coordinates we will write them into Table 1.

Table 1. Analytical Values of Vertical and Horizontal Coordinates for the Drop Shape with given boundary conditions r, R and α.

Vertical Coordinates (y):	**Horizontal Coordinates (x):**
$f_1(x) = x \cdot \tan\alpha$	$x_1 = r \cdot \frac{\cos\alpha}{\sin\alpha}$
$f_2(x) = \sqrt{R^2 - \left(x - \frac{R}{\sin\alpha}\right)^2}$	$x_2 = R \cdot \left(\frac{1}{\sin\alpha} - 1\right)$
$y_1 = r$	$x_3 = R \cdot \frac{\cos^2\alpha}{\sin\alpha}$
$y_2 = R \cdot \cos\alpha$	$x_4 = \frac{R}{\sin\alpha}$
$y_3 = R$	$x_5 = R \cdot \left(\frac{1}{\sin\alpha} + 1\right)$

Table 1 represents all coordinates values for defining drop shape that represented by combination of two functions: linear function $f_1(x) = x \cdot \tan\alpha$ and semicircular function $f_2(x) = \sqrt{y_3^2 - (x_3 - x_4)^2}$ with offset x_4.

The total volume for drop shape represented by combination of two functions: linear function - $f_1(x) = x \cdot \tan\alpha$ and semicircular function - $f_2(x) = \sqrt{y_3^2 - (x - x_4)^2}$ with offset x_4 will be calculated as:

1. For the interval $[x_1, x_3]$:

$$V_1 = \pi \int_{x_1}^{x_3} [f_1(x)]^2 \, dx$$

2. For the interval $[x_3, x_5]$:

$$V_2 = \pi \int_{x_3}^{x_5} [f_2(x)]^2 \, dx$$

The total volume of the drop is given by:

$$V_{total} = V_1 + V_2 = \pi \int_{x_1}^{x_3} [f_1(x)]^2 \, dx + \pi \int_{x_3}^{x_5} [f_2(x)]^2 \, dx \tag{16}$$

Substituting the limits in (16) from Table 1, the total volume is:

$$V_{total} = \pi \cdot \left\{ \int_{r \cdot \frac{\cos\alpha}{\sin\alpha}}^{R \cdot \frac{\cos^2\alpha}{\sin\alpha}} (x \cdot \tan\alpha)^2 \, dx + \int_{R \cdot \frac{\cos^2\alpha}{\sin\alpha}}^{R \cdot \left(\frac{1}{\sin\alpha}+1\right)} \left[\sqrt{R^2 - \left(x - \frac{R}{\sin\alpha}\right)^2} \right]^2 dx \right\} \tag{17}$$

After solving and simplifying (17):

$$V_{drop} = \frac{\pi \cdot [(1 + \sin\alpha)^2 \cdot R^3 - r^3 \cdot \cos\alpha]}{3 \cdot \sin\alpha} \tag{18}$$

When designing a floating body, the buoyant force—determined by the weight of the displaced (submerged) water—must equal the total weight of the structure itself, including both the platform and the wind turbine. Because we can calculate the required displaced-water volume, it is crucial to express all geometric relationships in terms of that submerged volume. In our case, these geometric unknowns are r (the smaller radius of the droplet), R (the maximum radius of the droplet), and the angle α. Rearranging the volume formula (18) for R gives:

$$R(V_{drop}) = \sqrt[3]{\frac{3 \cdot V \cdot \sin\alpha + \pi \cdot r^3 \cdot \cos\alpha}{\pi \cdot (1 + \sin\alpha)^2}} \tag{19}$$

In this study, r is assumed to be equal to the wind turbine tower's bottom diameter. Meanwhile, α can be obtained experimentally or via simulations of drag force, since the angle affects the frontal cross section on which the drag force depends.

The cross-sectional area A of the droplet-shaped platform can be found by integrating the functions $f_1(x)$ and $f_2(x)$ (without rotation), namely:

$$A = 2 \cdot \int_{x_1}^{x_3} f_1(x)dx + \int_{x_3}^{x_5} f_2(x)dx \tag{20}$$

After evaluating these integrals, the result is:

$$A = (R^2 - r^2) \cdot \cot\alpha + R^2 \cdot \left(\frac{\pi}{2} + \alpha\right) \tag{21}$$

where

$$\alpha \in \left[0; \frac{\pi}{2}\right]$$

When analyzing the hydrodynamic performance of the droplet-shaped platform, it is important to consider the drag force, F_{drag}. This force is given by:

$$F_{drag} = \frac{1}{2}\rho v^2 \cdot A \cdot C_D$$

where ϱ is the fluid (or air) density, v is the flow velocity, A is the characteristic area (often taken as the projected area on the plane perpendicular to the velocity vector), and C_D is the drag coefficient, determined experimentally or via CFD simulations.

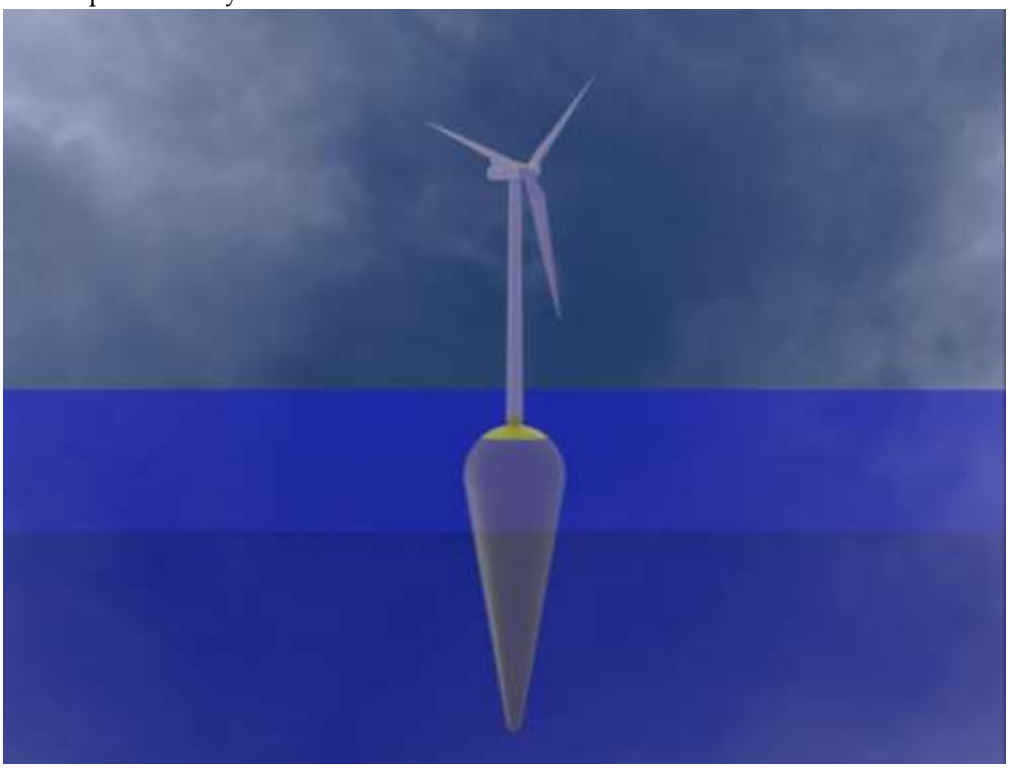


Figure 6. Design concept of droplet-shaped floating platform for offshore wind turbines.

Understanding and accurately estimating F_{drag} is essential for evaluating the platform's overall stability and performance, particularly under high wind and wave conditions.

The mathematical derivations described thus far form the foundation for a biomimetic droplet-shaped platform, which aims to balance hydrodynamic efficiency with sufficient buoyancy for multi-megawatt wind turbines. By systematically arranging the conical lower section and semicircular upper region, the design seeks to reduce wave-induced motions and structural loads. To offer a

clearer perspective, Figure 6 presents a conceptual rendering of the droplet-shaped floating platform, highlighting its overall geometry, approximate immersion depth, and turbine placement.

As illustrated in Figure 6, the narrow base of the platform transitions into a broader hull near the water surface, maximizing stability and minimizing wave-excitation forces. The conical profile in the submerged section helps control hydrodynamic drag and vertical motions, whereas the semicircular upper portion enhances buoyancy and overall structural robustness. This integrated form directly corresponds to the derived volume expressions and boundary conditions outlined earlier, ensuring that the required displaced water volume can support the turbine's mass while maintaining optimal trim and pitch characteristics. It is recommended to conduct numerical simulations and wave-tank tests to refine the droplet-inspired geometry and validate its performance under various operational and extreme sea conditions.

3. Conclusion

1. This paper introduced a biomimetic droplet-shaped floating platform designed to harness wind energy in deep-water regions. The proposed geometry combines a linear (conical) function with a semicircular profile to mitigate extreme wave-induced loads and platform motions—specifically pitch, heave, and surge—while supporting multi-megawatt wind turbines.
2. Analytical formulations were provided for boundary conditions, key geometric parameters, total volume, cross-sectional area, and drag force. These closed-form expressions facilitate rapid estimation of buoyancy requirements based on a targeted submerged volume, simplifying scaling for different turbine capacities.
3. The droplet-shaped platform concept leverages efficient hydrodynamic principles inspired by nature, offering the potential for improved motion response in harsh marine environments.
4. Validation of this geometry through numerical simulations, including coupled aero-hydro-elastic analyses, and wave-basin experiments is recommended to confirm its performance and reliability.
5. Further studies should focus on exploring mooring-line layouts, structural optimization, and cost trade-offs. These aspects are critical for refining the platform design and enhancing its practical implementation.
6. This innovative approach aims to advance floating offshore wind technology by providing a hydrodynamically efficient and adaptable solution suited to a wide range of environmental conditions.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest

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DEPTH-DEPENDENT CHANGES İN SOİL THERMAL PROPERTİES: EVİDENCE FROM GOBUSTAN, AZERBAİJAN

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Abstract

This study investigates depth-dependent variations of soil thermal properties in the Gobustan region of Azerbaijan, an area characterized by a semi-arid climate and significant energy infrastructure development. Field measurements were conducted in trial pits excavated up to 3.0 m depth, using the thermal needle probe method in accordance with IEEE Std 442-1981 and ASTM D5334-00 standards. Soil thermal resistivity (R), thermal conductivity (λ), temperature, and moisture content were measured at 0.5 m intervals to capture detailed depth-related trends. The results revealed a consistent depth-dependent pattern: with increasing depth, soil temperature decreased, while thermal conductivity increased and thermal resistivity correspondingly declined, indicating more efficient heat transfer in deeper layers. However, clear spatial variability was also observed across different soil types. In silty soils (Trial Pit-1) and clayey soils (Trial Pit-2), resistivity decreased sharply with depth due to greater compaction and moisture retention in lower horizons, accompanied by significant increases in conductivity. The argillite profile (Trial Pit-3) differed, showing the highest overall surface temperatures (up to 36.7 °C) and elevated resistivity values, though conductivity still increased gradually with depth. By contrast, the clay–argillite profile (Trial Pit-4) exhibited more stable and balanced results, with moderate increases in conductivity and only slight decreases in resistivity, reflecting a relatively homogeneous soil structure. Overall, the findings highlight both vertical and lateral variability in soil thermal properties across Gobustan, controlled by lithology, soil structure, and moisture content. From a practical standpoint, these results provide baseline data critical for the design and optimization of underground cable systems, geothermal energy projects, and other engineering applications under semi-arid conditions. From a scientific perspective, the study represents one of the first systematic applications of IEEE and ASTM international standards for assessing depth-dependent soil thermal properties in Azerbaijan, contributing valuable new insights and a reference framework for future research in the South Caucasus region.

Keywords: Soil thermal resistivity, thermal conductivity, trial pits; Gobustan, Azerbaijan

I. İntroduction

Soil thermal properties, particularly thermal conductivity and thermal resistivity, play a crucial role in multiple engineering and environmental applications. They determine how efficiently heat is transferred through soil, directly affecting the design and performance of underground electrical cable systems, geothermal energy extraction, and building foundations [1]. These properties are fundamental physical parameters that regulate the processes of heat transfer and storage within soils [2,3]. Accurate knowledge of these properties is essential to prevent overheating in buried power cables, optimize geothermal heat exchange systems, and improve predictions of soil-atmosphere

energy fluxes [4]. Knowledge about soil thermal properties is also crucial for modeling soil thermal regimes and mass–energy exchange processes occurring in the soil–plant–atmosphere system [5].

Extensive research has been carried out worldwide to investigate soil thermal properties under various climatic and geological conditions. For instance, Ochsner et al. (2001) highlighted the influence of soil water content and bulk density on thermal conductivity[6]. Mengistu et al. (2017) investigated the effects of soil water content and temperature on the thermal properties of different soil types in South Africa under laboratory conditions [7]. Literature further indicates that soil thermal properties are significantly dependent on water content, with both linear and non-linear responses being observed [8,9,10]. Sun et al. (2020) examined the correlation between thermal conductivity and electrical resistivity of silty clay soil across temperatures from −20 °C to +10 °C under varying moisture conditions [11]. Al Nakshabandi and Kohnke (1965) investigated how soil thermal conductivity and diffusivity are influenced by moisture tension and other physical properties[12]. Studies have also shown that thermal conductivity and diffusivity generally increase with decreasing temperature and increasing water content, although responses vary with soil type and conditions [13,14]. These studies consistently confirm that soil thermal properties are depth-dependent and highly sensitive to environmental and physical soil conditions.

Despite the abundance of international studies, research on soil thermal properties in Azerbaijan remains limited. In particular, the Gobustan region characterized by semi-arid climate, diverse soil textures, and significant energy infrastructure development has not been systematically studied in terms of depth-dependent variations in soil thermal conductivity and resistivity. This knowledge gap restricts the optimization of underground cable installations and geothermal applications in the region.

Therefore, the objective of this study is to investigate the depth-dependent changes in soil thermal properties in Gobustan, Azerbaijan. Measurements were conducted in a 3-meter-deep trench at 0.5-meter intervals using the thermal needle probe method in accordance with IEEE Std 442-1981 and ASTM D5334-00 standards. The results provide new evidence on how soil thermal characteristics vary with depth under local conditions, offering both scientific insights and practical implications for engineering and energy applications in semi-arid environments.



Figure 1: Location Map of Gobustan Area on Google Earth

The field investigations were conducted approximately 30 km west of Baku city, in the elevated areas surrounding Chayly village of Gobustan district. The study sites are mainly located to the north and northeast of the village, with one section positioned toward the west. To the north of Chayly village, the Ilxidagh massif is observed, while in the western direction the Qara Islam and Balaga Aday mountain ranges dominate the landscape. These geological and geomorphological features significantly influence the soil conditions and the development of its thermal properties (Fig 1).

Geological Setting

The study area is situated within upland zones where Upper Cretaceous rock complexes are widely distributed. Lithologically, these deposits are represented by clay, argillite, sandstone, and their interbedded sequences with sandy and marly layers.

Outcrops of clays along anticlinal structures are observed within the region. These strata occur in thin layers and beds, typically dipping at angles of 70–80°, with a general strike direction extending from southeast to northwest.

In addition, within the study sites, a thin soil–vegetation cover overlies the bedrock. Around the slopes, eluvial–deluvial deposits have formed as a result of the weathering and erosion of parent rocks, further influencing the soil composition and local geomorphology [15].

II. Methods

Soil Thermal Resistivity and Conductivity

One of the most critical factors affecting the reliable operation of underground cable systems is soil thermal resistivity. Thermal resistivity (measured in °C·m/W or K·m/W) expresses the resistance of a material to heat flow, while thermal conductivity (measured in W/m·K) represents its reciprocal property [1].

$$R=\frac{1}{\lambda}$$

Here, R denotes thermal resistivity, and λ denotes thermal conductivity.

Experimental Setup

Trial pits up to 2.0 m deep were excavated, and measurements were conducted at 0.5 m intervals (0.25 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m). During the measurements, a constant heat flow was applied using the KD2 Pro Thermal Properties Meter, and the resulting temperature response of the soil was recorded. A minimum of 90 seconds was allowed for temperature stabilization, and each test lasted approximately 10–15 minutes. In parallel, undisturbed soil samples were collected to determine soil moisture content [16].

Thermal Needle Probe Method

The thermal needle probe method was applied to determine the thermal properties of the soil. In this method, a heating wire embedded in the probe generates a constant heat flow, while a temperature sensor located within the same probe records the temperature change as a function of time. From the linear portion of the temperature–time curve, soil thermal conductivity (λ) is determined, and subsequently, soil thermal resistivity (R) is calculated [17].

Standards Applied

The tests were conducted in accordance with international standards. For determining soil thermal resistivity, the IEEE Std 442-1981 – Guide for Soil Thermal Resistivity Measurements was applied, which is widely used in the design of underground electrical cables [17]. For determining the thermal conductivity of soils and soft rocks, the ASTM D5334-00 – Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure

was followed [16]. These standards define internationally accepted guidelines for applying the needle probe method, measurement conditions, and processing of results.

Data Collection and Processing

The following parameters were obtained from each measurement:

- Soil thermal resistivity (R)
- Soil thermal conductivity (λ)
- Temperature (T)
- Moisture content

The recorded temperature–time data were analyzed using computer software, and the average values of three repeated tests at each depth were calculated. The results were presented in the form of graphs and tables.

IV. Results

In Trial Pit-1, thermal resistivity tests were conducted at depths ranging from 0.25 m to 2.0 m in soils classified as silt according to the geological–lithological column (Fig. 2). The results show a clear depth-dependent trend in soil thermal properties. As depth increased, soil temperature decreased, while thermal conductivity increased, leading to a reduction in thermal resistivity. This indicates that deeper soil layers transfer heat more efficiently compared to near-surface layers. Detailed results are presented in Table 1 and Fig. 2–3 below.

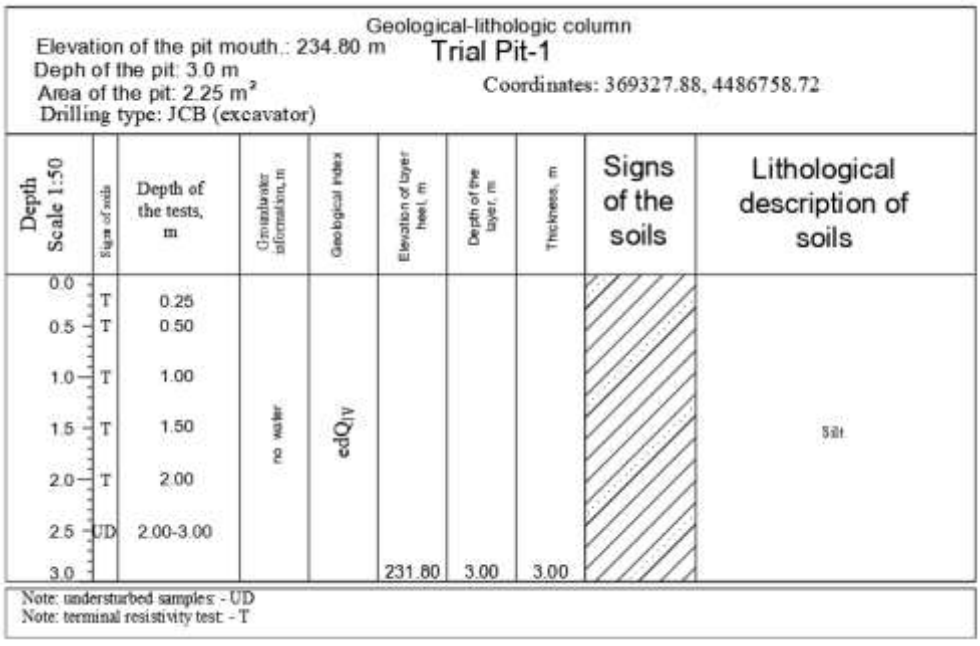


Figure 2: Geological–lithological section of Trial Pit-1

Table 1: Thermal Resistivity test results (Trial Pit-1)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	27.7	0.396	2.415	5	HPM
0.5	25.1	0.452	2.215	5	HPM
1	23.38	0.603	1.658	5	HPM
1.5	20.79	0.624	1.603	5	HPM
2	18.96	0.756	1.322	5	HPM

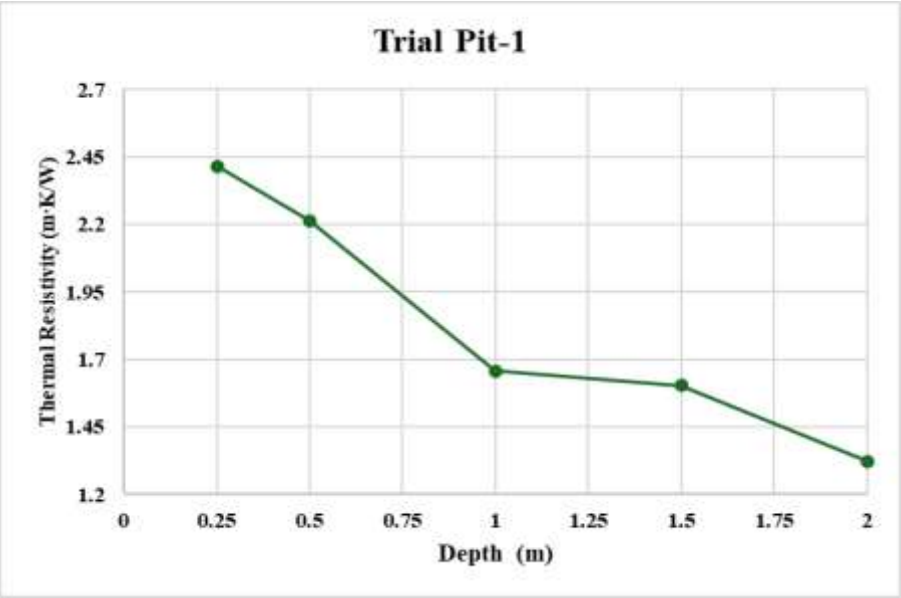


Figure 2: Variation of thermal resistivity with depth.

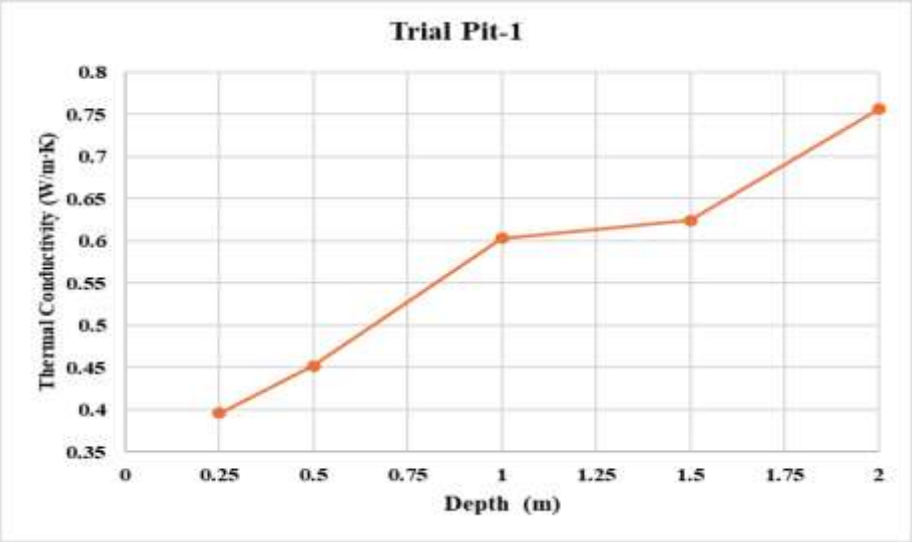


Figure 3: Variation of thermal conductivity with depth.

In Trial Pit-2, thermal resistivity tests were carried out at depths ranging from 0.25 m to 2.0 m in soils classified as clay according to the geological–lithological column (Fig. 4). The results demonstrate a depth-dependent variation in soil thermal properties similar to Trial Pit-1. With increasing depth, soil temperature decreased progressively, while thermal conductivity increased, resulting in a reduction in thermal resistivity. This pattern indicates that deeper layers exhibit better heat transfer capacity compared to shallow layers. The detailed outcomes are presented in Table 2 and Fig. 5–6 below.

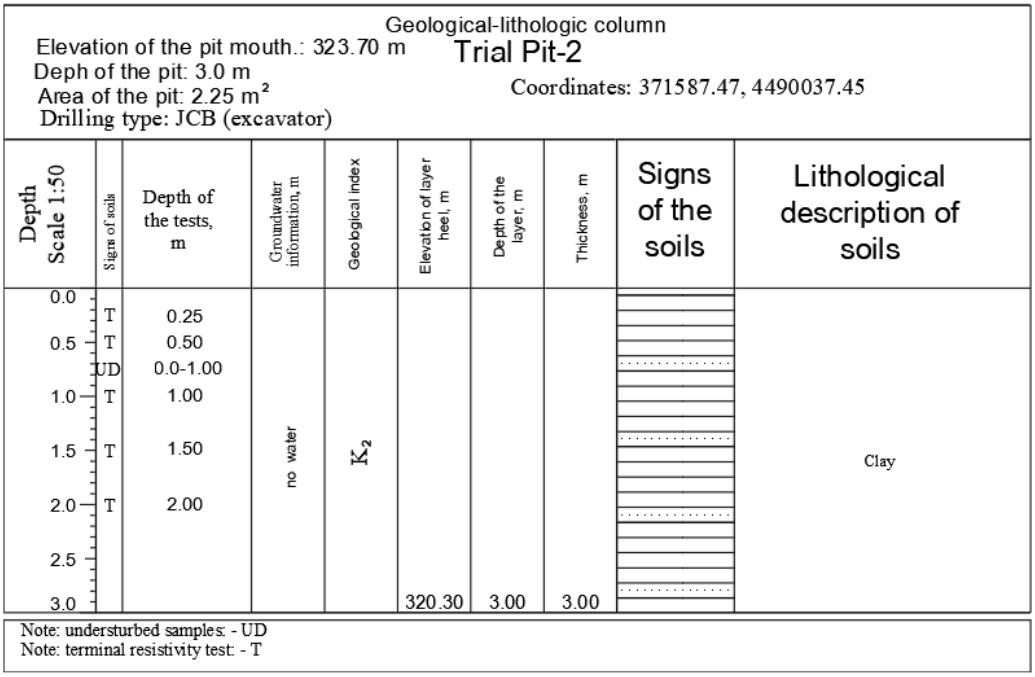


Figure 4: Geological–lithological section of Trial Pit-2

Table 2: Thermal Resistivity test results (Trial Pit-2)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	25.9	0.662	1.644	5	HPM
0.5	23.17	0.733	1.365	5	HPM
1	21.6	0.801	1.285	5	HPM
1.5	20.2	0.864	1.145	5	HPM
2	18.69	0.927	1.079	5	HPM

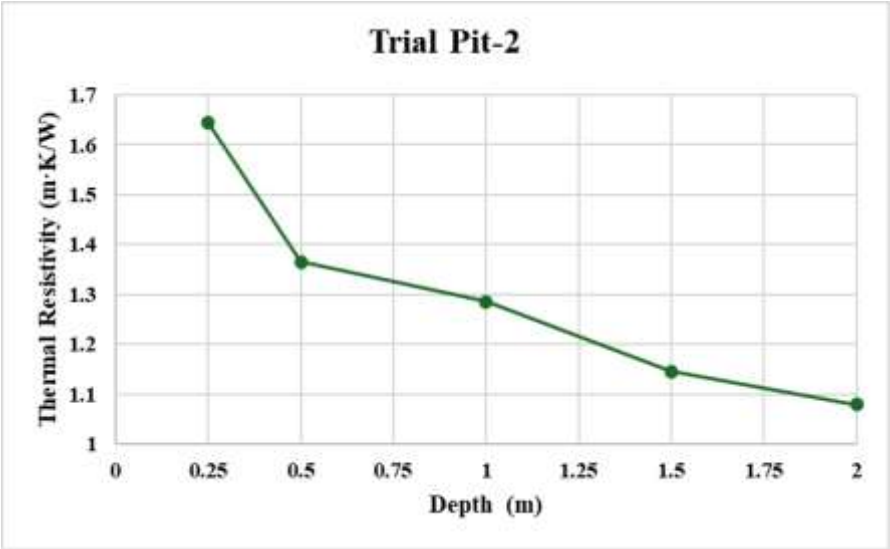


Figure 5: Variation of thermal resistivity with depth.

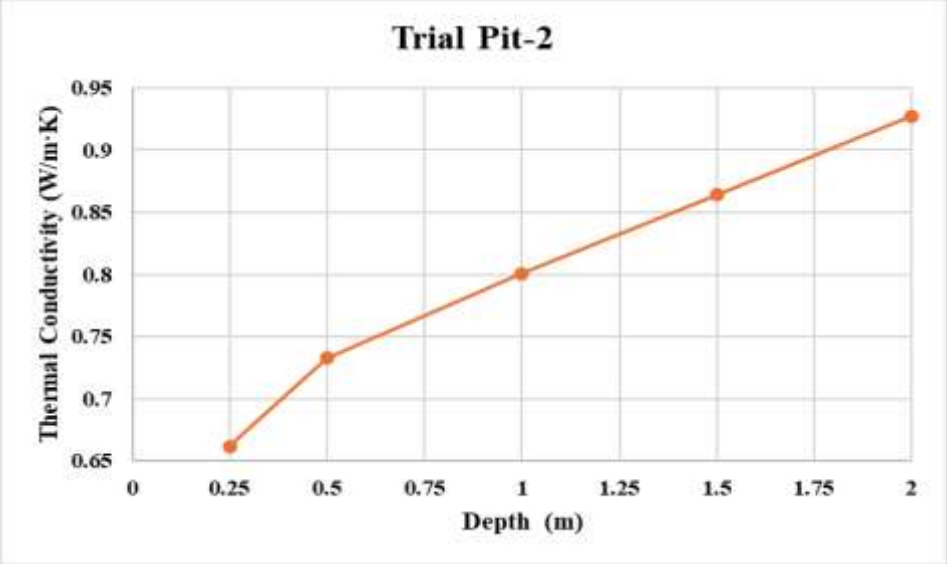


Figure 6: Variation of thermal conductivity with depth.

In Trial Pit-3, thermal resistivity tests were conducted between depths of 0.25 m and 2.0 m in soils classified as argillite according to the geological–lithological column (Fig. 7). The observed results differ from Trial Pits 1 and 2, showing significantly higher soil temperatures across all measured depths. Thermal conductivity increased gradually with depth, while thermal resistivity decreased correspondingly. This pattern suggests that despite the higher surface temperature, deeper soil layers exhibit improved heat transfer efficiency. The detailed results are summarized in Table 3 and Fig. 8–9 below.

Geological-lithologic column

Elevation of the pit mouth.: 199.50 m
Deph of the pit: 3.0 m
Area of the pit: 2.25 m²
Drilling type: JCB (excavator)

Trial Pit-3

Coordinates: 374249.13, 4488224.89

Depth Scale 1:50	Signs of soils	Depth of the tests, m	Groundwater information, m	Geological index	Elevation of layer heel, m	Depth of the layer, m	Thickness, m	Signs of the soils	Lithological description of soils
0.0	UD	0.0-0.50	no water	K_2	196.50	3.00	2.80		Argillite
	T	0.25							
0.5	T	0.50							
1.0	T	1.00							
1.5	T	1.50							
2.0	T	2.00							
2.5									
3.0									

Note: understurbed samples: - UD
Note: terminal resistivity test: - T

Figure 7: Geological–lithological section of Trial Pit-3

Table 3: Thermal Resistivity test results (Trial Pit-3)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	36.73	0.41	2.441	5	HPM
0.5	35.6	0.562	2.123	5	HPM
1	34.7	0.669	1.842	5	HPM
1.5	32.2	0.784	1.254	5	HPM
2	29.7	0.805	1.096	5	HPM



Figure 8: Variation of thermal resistivity with depth.

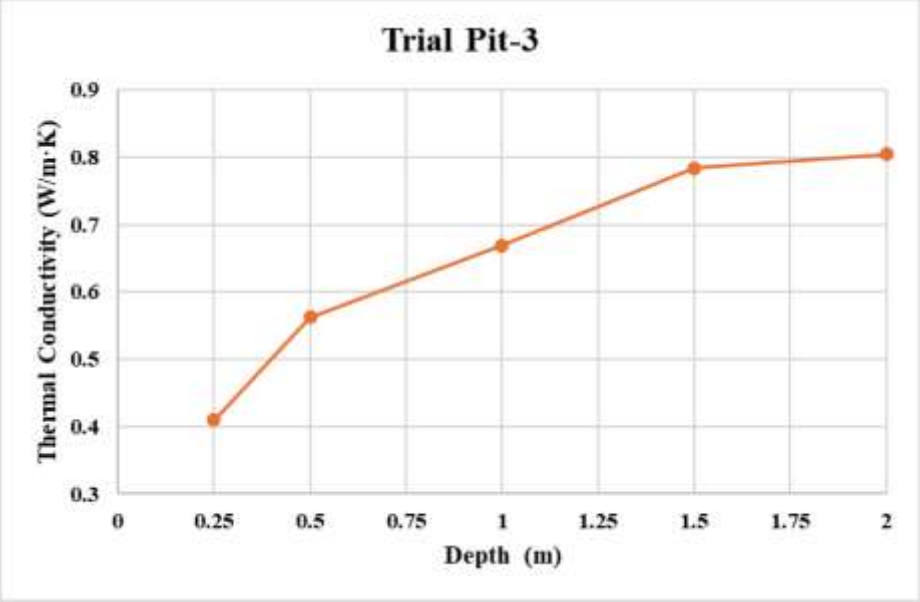


Figure 9: Variation of thermal conductivity with depth.

In Trial Pit-4, thermal resistivity tests were performed between depths of 0.25 m and 2.0 m. According to the geological–lithological column (Fig. 10), the soil profile consists of clay from the surface down to 1.0 m and argillite between 1.0 m and 3.0 m. The results show a relatively stable trend compared to other pits, with soil temperature gradually decreasing with depth. Thermal conductivity increased slightly with depth, while thermal resistivity remained relatively consistent, showing only minor decreases. This indicates that the soil profile in Trial Pit-4 maintains a more uniform heat transfer capacity across depths compared to other test sites. The detailed results are presented in Table 4 and Fig. 11–12 below.

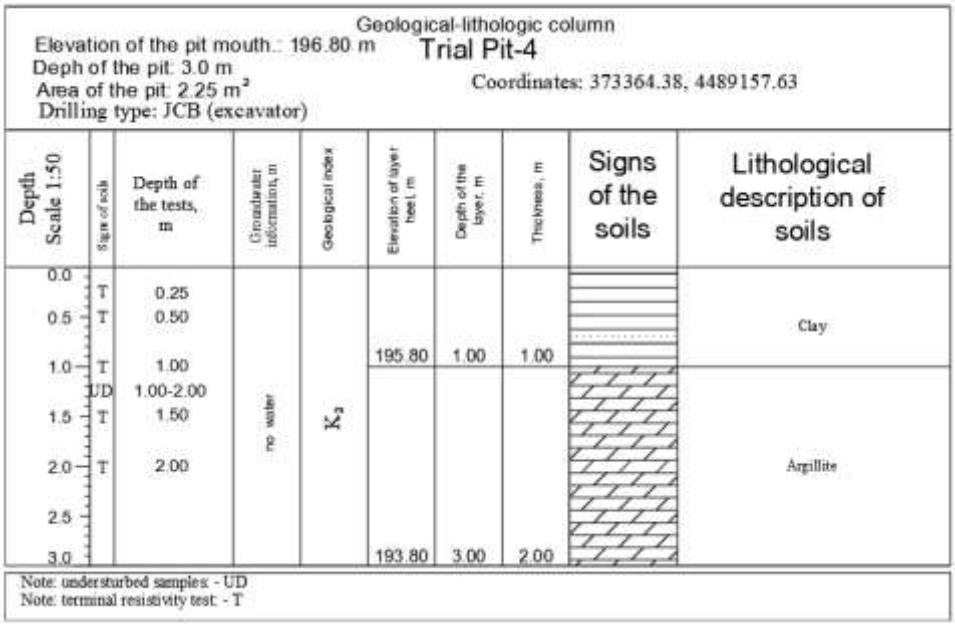


Figure 10: Geological–lithological section of Trial Pit-4

Table 4: Thermal Resistivity test results (Trial Pit-4)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	25.11	0.65	1.539	5	HPM
0.5	24.5	0.71	1.49	5	HPM
1	23.2	0.745	1.462	5	HPM
1.5	22.6	0.786	1.426	5	HPM
2	20.2	0.821	1.402	5	HPM

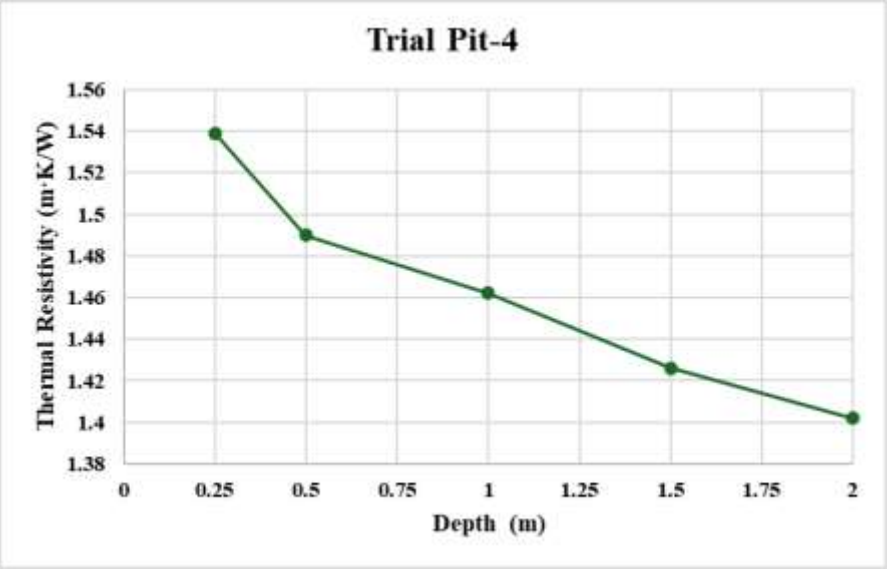


Figure 11: Variation of thermal resistivity with depth.

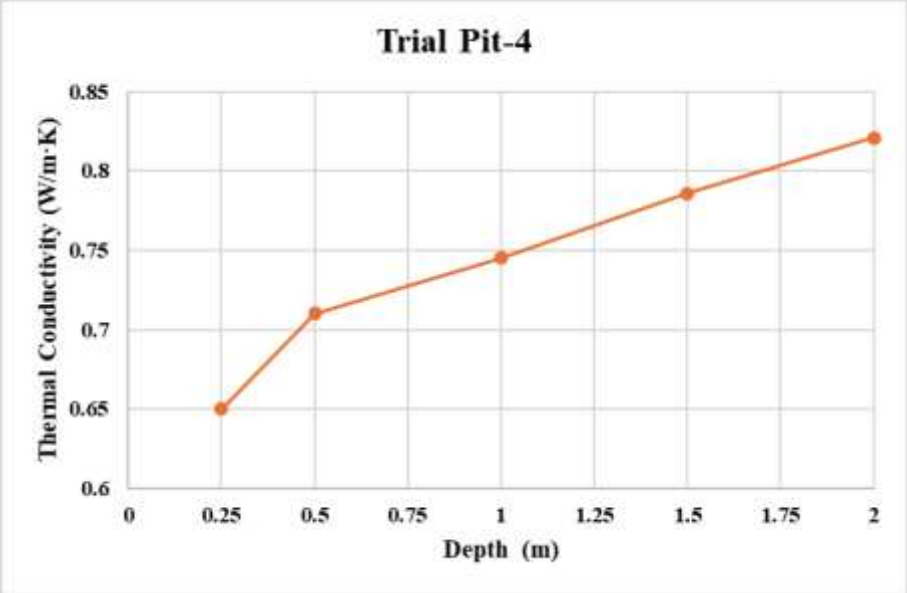


Figure 12: Variation of thermal conductivity with depth.

When comparing the results of all Trial Pits, it becomes evident that the thermal properties of the soil exhibit variability both with depth and spatially.

1. **Depth-Dependent Variation of Thermal Resistivity Depth (ϱ):** In all pits, soil thermal resistivity showed a decreasing trend with increasing depth. This behavior is attributed to higher density and moisture content in deeper layers, which enhance thermal conductivity. In Trial Pit-1 and Trial Pit-2, a sharp decrease was observed. In Trial Pit-3, resistivity values remained high with only a slight reduction, while Trial Pit-4 exhibited more stable results.
2. **Thermal Conductivity(λ):** Thermal conductivity increased with depth in all pits. The highest increase was recorded in Trial Pit-2 (from 0.662 W/m·K to 0.927 W/m·K). In Trial Pit-3 and Trial Pit-4, the increase was more gradual and consistent.

3. **Soil Temperature:** Surface layers showed higher temperatures (particularly in Trial Pit-3, reaching 36.7 °C), while deeper layers exhibited decreasing values. The lowest temperatures were recorded in the deeper sections of Trial Pit-2 and Trial Pit-4 (around 20 °C).
4. **Comparison Among Pits:**
    - Trial Pits 1 and 2 demonstrated significant variability.
    - Trial Pit-3 exhibited the highest temperatures and resistivity values.
    - Trial Pit-4 produced more stable and balanced results.

IV. Conclusion

This study presented the results of soil thermal resistivity and conductivity measurements conducted in Gobustan, Azerbaijan, across four trial pits excavated to a depth of 3.0 m. Tests were carried out at 0.5 m intervals (starting from 0.25 m), allowing for detailed depth-dependent assessment of soil thermal behavior. The findings revealed a consistent pattern: as depth increased, soil temperature decreased, thermal conductivity increased, and thermal resistivity correspondingly decreased. This indicates that deeper soil layers provide more efficient pathways for heat transfer compared to near-surface horizons.

Comparison among the trial pits highlighted the influence of lithology. In silty soils (Trial Pit-1) and clayey soils (Trial Pit-2), sharp reductions in resistivity with depth were observed due to higher density and moisture retention in deeper layers. The argillite profile (Trial Pit-3) exhibited the highest surface temperatures (up to 36.7 °C) and resistivity values, although conductivity still increased gradually with depth. Trial Pit-4, consisting of clay in the upper 1.0 m and argillite below, showed more stable results with moderate increases in conductivity and only slight reductions in resistivity, reflecting a relatively homogeneous soil profile.

Overall, the study confirms both vertical and spatial variability of soil thermal properties in the Gobustan region, governed by lithology, soil structure, and moisture content. From a practical perspective, the results provide essential baseline data for the optimization of underground cable systems, geothermal energy applications, and infrastructure design under semi-arid conditions. From a scientific standpoint, this work represents one of the first systematic applications of IEEE Std 442-1981 and ASTM D5334-00 standards in Azerbaijan, contributing valuable new insights and a reference database for future studies on soil thermal regimes in the South Caucasus.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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RISK ASSESSMENT OF OIL-GAS PERSPECTIVES OF DEEP-SEATED SEDIMENTS BASED ON GEOCHEMICAL MODELS OF MUD VOLCANOES WITHIN ABSHERON REGION

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Abstract

In the article, in order to identify the variability of the isotopic-chemical composition of mud volcano gases within Absheron oil-gas-bearing region and to grade the oil-gas perspectives of deep-lying sediments, the characteristics of the variability in the composition of methane gases, HHC, CO_2, nitrogen, at the same time isotopic structure of methane gas and carbon dioxide were investigated. The gas emissions of Azerbaijan mud volcanoes contain more than 90% methane. During the analysis of samples taken from the study area of mud volcanoes in the Absheron region, the methane content was determined to be 92-98.53%. At the same time, a regular decrease of methane gas in the gas composition (98.53-83.94%) is noted in the southwestward. Maps were compiled and a comparative analysis was conducted to analyze the characteristics of noted gases changes in gases of mud volcano along the studied area. According to the analyses, it stands to mention the west-southwest part is characteristic with the lowest value of methane, and the high value of HHC and carbon dioxide. In the southwestward, mud volcano gases are expressed with less amount of methane and with high amount of HHC. Carbon dioxide has an average value. According to the analyses, mud volcano gases of the Absheron oil-gas-bearing region are also characterized nitrogen, and compounds of nitrogen. The amount of nitrogen varies between 0.11-10.89%, and the highest amount is observed in the Shorbulag (10.89%) mud volcano situated along the west of the peninsula. Within Absheron oil-gas-bearing area, almost all structures associated with mud volcanoes are prospective with hydrocarbons. Comparison of mud volcanoes and oil field gases is given as the case of the Lokbatan field. The chemical constituent gases of mud volcanoes consists mainly of combustible hydrocarbons and is predominantly associated by the gases of oil, and gas fields. However, it is fact that the violent or weak eruption of mud volcanoes also depends on the underground reserves of these gases and, at the same time, on the plasticity of the rocks. The violent eruption occurs when the gas reserves are high and the plastic rocks are thick, and when they are insignificant, weak eruption occurs. The existing an oil films in the composition of the eruption products that throughout by mud volcanoes shows the accumulation of petroleum along with gas.

Keywords: mud volcanoes, organic carbon, methane, eruption products, nitrogens, distribution.

I. Introduction

The Absheron oil-gas-bearing area, located in the nortwest of the South Caspian depression, covers the plunge of depression of the same name. This region includes the Absheron Peninsula and the part of the Azerbaijan sector of the Caspian Sea covering from Absheron-Pre-Balkan zone to the Kapaz structure (Absheron archipelago). Tectonically, corresponds to the southeastern plunge of the Greater Caucasus megaanticlinorium. The maximum thickness of the sedimentary layer of the region is

noted in the southern part of the Peninsula, within shelf zone of sea. It is more than 24 km. 3500-4000 m of the section consist of the Productive series (PS) sediments (Lower Pliocene) [1].

the geological structure of the Absheron oil-gas-bearing region consists of terrigenous-carbonate rocks of the Upper Cretaceous-Cenozoic age. Lower Pliocene sediments (PS) are quite widespread and are represented by alternations of sand, sandstone, siltstone and clay. The maximum oil saturated sediments are PS sediments was determined in the central part of the Absheron Peninsula (Balakhani-Sabunchu-Ramana, Surakhani, Bibiheybat fields), where the number of productive horizons is about 40. The spreading of oil-gas and the location of their deposits in the areas depend on lithological and structural-tectonic factors. An increase in the gas saturation of the layers is observed in the direction of regional subsidence. The oil-gas perspectives of the Miocene-Paleogene, Mesozoic deposits are highly assessed [2,3].

The folds of the Absheron oil and gas-bearing region have a diapir form and are complicated by numerous normal faults and thrusts associated with mud volcanoes.

40 fields have been identified on the Absheron Peninsula and in the water area of the Absheron archipelago. According to the emplacement of the fields, 21 of them are classified as oil, 9 as oil-gas, 3 as gas-condensate, and 7 as oil-gas condensate. Majority of the fields are related to mud volcanoes. Half of them the mud volcanoes are located predominantly within them [4,5].

Mud volcanoes of the Absheron region are located on the Absheron Peninsula and the archipelago of the same name adjoining it from the north, east and south (Fig. 1). There are 69 active, extinct and buried volcanoes. Of these, 39 are located on land and 30 are located offshore [6].

The largest mud volcanoes in the Absheron region are located in its southwestern part: Otmanbozdagh is the highest volcano in Azerbaijan (404 m). Bozdagh-Gobu, Sarinja, Lokbatan and Bozdagh-Guzdak volcanoes are higher than the surrounding area by 105-225 m.

The largest mud volcanoes in the central part of Absheron are Abikh and Keyreki. Height is 95 and 116 m, respectively. In the Absheron archipelago, the largest volcanoes, rising 100-116 m above the bottom of the Caspian Sea, have been identified in the Gunashli and Chirag fields [7].

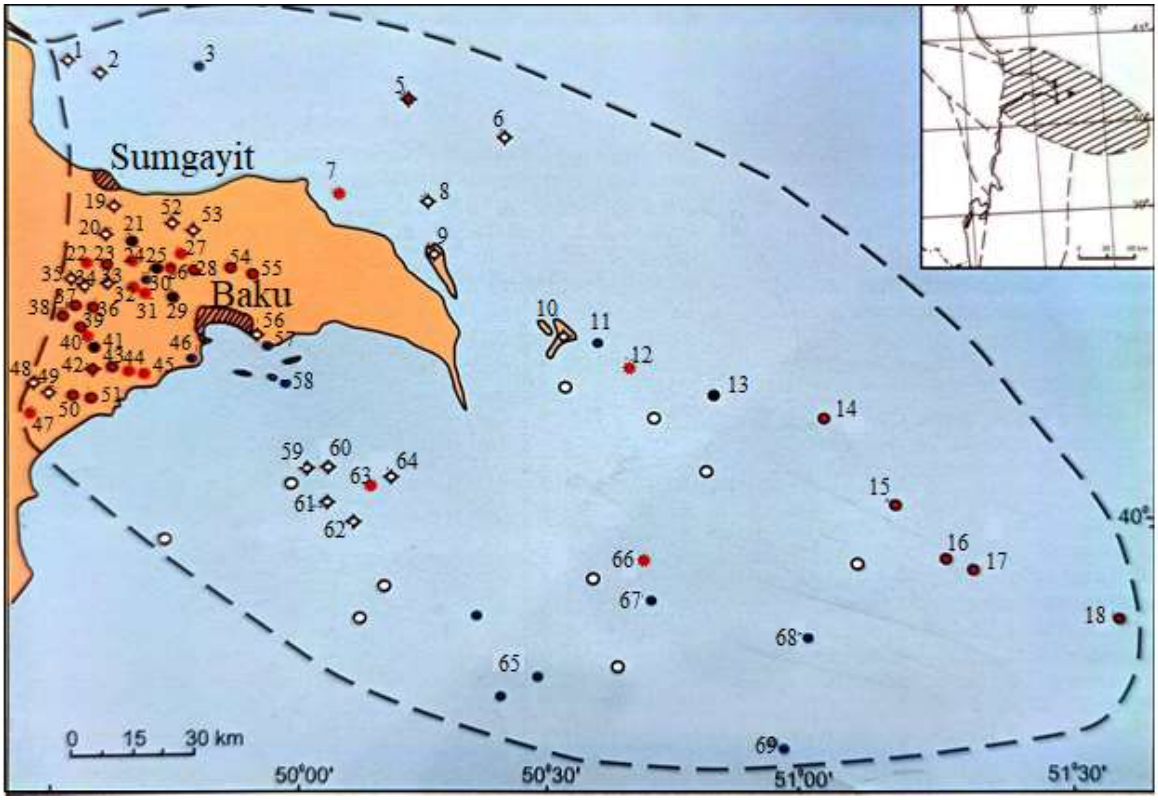


Fig. 1. Location map of mud volcanoes in the Absheron oil and gas-bearing region

Mud volcanoes: 1-Yashma-deniz, 2-Shurabad-deniz, 3-Two brothers, 4-Aghburun-deniz, 5-Absheron Bank, 6-Gilavar, 7-Buzovna Pilpila, 8-Darwin Bank, 9-Pirallahi Island, 10-Chilov Island, 11- Hazi Aslanov, 12-Palchig Pilpila, 13-Neft Dashlari, 14-Gunashli, 15-Chirag, 16-Azeri-west, 17-Azeri-east, 18-Kepez, 19-Giralti, 20-Komuratan, 21-Sengar, 22-Uchtepe, 23-Atbatan, 24-Kecheldagh, 25-Abikh, 26-Keyraki, 27-Boyukdagh, 28-Kichikdagh, 29-Zigilpiri, 30-Sulutepe, 31-Bozdagh-Hokmeli, 32-Bozdagh-Gobu, 33-Agzikhezri, 34-Qaraheybat, 35-Damlamaja, 36-Bozdagh-Guzdek, 37-Deveboynu, 38-Shorbulag group, 39-Gulbakht, 40-Sarinja, 41-Shongar, 42-Giziltepe, 43-Guskhana, 44-Akhtarma-Puta, 45-Lokbatan, 46-Bibiheybat, 47-Otmanbozdagh, 48-Ceyranuchan, 49-Pilpila Garadagh, 50- Torpagli-Akhtarma, 51-Akhtarma-Garadagh, 52-Pilpila-Goradil, 53-Kullutepe, 54-Kirmaki, 55-Bogh-bogha, 56-Pilpila-Zygh, 57-Zygh, 58-Gum-deniz, 59-1906, 60-1960, 61-Seyyar, 62-Saba, 63-Bahar-deniz, 64-1933, 65-Shah-deniz group, 66-1908, 67-Absheron-west, 68- Absheron-east, 69-A.Yagubov

The formation of volcanoes along the oil-gas-bearing areas and closely relation to the processes of formation of folds and faults are significates of the presence of oil-gas fields in these areas. It's a fact that the power sources of mud volcanoes are located in deep-lying reservoir layers which produce hydrocarbon gases. The chemical compound of gases of mud volcanoes is not similar where the mud volcanoes are developed. And change due to the thermo-dynamic medium of the subsoil, as well as the characteristics of the geological structure of these areas. The geochemical properties of mud volcano emissions are the main indicators in identifying the gas and oil-bearing of the subsoil. The mud volcanoes develop onshore and offshore, and determine the world over spacing of hydrocarbons within the Earth's interior. At the present, volcanoes, as a significant component of the ecological system, ensure draining out of gases of deep submerged deposits [8]. During the eruption of mud volcanoes and during the quiet period, enormous gases is emitted from the Earth's interior into the atmosphere [9]. It is fact, the layer of the sediments of the areas where is mud volcano is formed have a very large amount of gas reserves. The focus of gases of mud volcanoes developed in Azerbaijan is the Cretaceous and Paleogene sediments. The learning of gas-bearing is important.

The complication of the folds with longitudinal and transverse faults associated with mud volcanoes located in the Absheron-Pre-Balkan megasaddle and the South Absheron archipelago of the Absheron region, the existing of Paleocene, Cretaceous (K), Eocene age rock fragments in the eruption products, indicates the presence of a crushed area rich in natural gases below the base of volcanoes. This is also confirmed by the occurrence of gas flowing in a number of fields.

In the study region, Upper Cretaceous (K_2), Eocene and Paleocene rock particles are found within erupted wastes of Bozdagp-Gobu, Bozdagp-Guzdek, Sarinja, Gulbakht, Shongar, Lokbatan, Pilpila Garadagh, Torpagli-Akhtarma, Boyukdagh, Kichikdagh, and Ziyilpiri mud volcanoes. The oil and gas-bearing of the fields associated with the noted mud volcanoes varies in a wide range [10].

In preparation for deep exploration drilling, 14 wells were drilled in the Shongar field, which the Shongar mud volcano is associated. Gas flowing was obtained from the horizon VIIa in well 10.

The Post-Kirmaki sandy (PKS) suite (horizon VIII) on the southern limb of the Garadagh fold is highly productive. 250-350 th.m^3 of gas and 40-50 tons of condensate were obtained from wells located in the buried part of the southeastern limb of the fold per day. The most productive well was well 130, located in the buried part of the southeast of the fold. During testing 800 th.m^3 of gas and 100 tons of condensate per day was obtained [11].

The Shah-deniz mud volcano group is located on the crest and plunge of the fold of the same name, located in the Fatmayi-Garachukhur-Zygh-Gum-adasi anticline zone, which was formed by the Pliocene-Quaternary sediments and became more complicated by thrust faults.

The confirmed (discovered) reserves of the Shah-Deniz field are: more 1 tr.m^3 of gas, >300 million tons of condensate.

As of 2007, three wells were in operation in the field. These wells produce 15 million m^3 of gas and 4,000 tons of condensate per day. Since 2008, four wells have been in operation in the field, and the average daily production of these wells is 19 million m^3 of gas and 4,500 tons of condensate. Since the beginning of operation (2006) to this date, 5.9 billion m^3 of gas and 1.6 million tons of condensate have been produced from the field [12].

II. Method

When mud volcanoes activate, significant amounts of liquid, solid, as well as gaseous substances are released onto earth's surface. These substances mainly used for searching of oil-gas accumulations. Drawing on the ends of laboratory studies of these substances of mud volcanoes, it is achievable to get detail data for oil, and gas-bearing of deeply-seated sediments. In this regard, studying of geo-chemical compounds of mud volcanoes of the Absheron oil-gas-bearing area are a main factor for discovering of more and more oil-gas, and gas condensate fields.

In order for studying mud volcano emissions, luminescent-bituminological, and geo-chemical studies of sediment fragments included in the breccias were conducted [6]. Organic carbon, components of bitumen, humus matters are determined by studies. Organic carbon varies most often in the mud volcano product of the Absheron region, ranging from 0.17 to 4.68%.

On the basis reasoning from the studies of bitumen, it was identified that oil-series bitumens predominate in the rocks of mud volcano wastes [6]. Prevalently, bitumen is found in the form of spills, proves that this is original with the rocks that contain them. The above shows that the geo-chemical and geological features of rocks where mud volcano associated are similar to these characteristics of the rocks that form oil and gas deposits.

The test report of some analyzes show that the mud volcanoes gases of Azerbaijan don't different than in chemical composition gases from the hydrocarbon deposits and, contain mainly of heavy hydrocarbons, methane, also accompanying carbon dioxide, at the same time nitrogen. Along with this, as a result of these analyzes, carbon oxide, hydrogen-2, hydrogen sulfide, also inert gases were detected in some cases.

III. Results and discussion

In order to clarify changes in the isotopic, chemical compoud of mud volcano gases within Absheron area and for assessment of prospect for oil-gas-bearing, distribution maps of CH_4 (Fig.2), HHC, CO_2, N_2, also the isotopic compoud of methane and carbon dioxide over the areas have been constructed.

The gas emissions of Azerbaijan mud volcanoes contain more than 90%, in some cases 98% methane. The amount of carbon dioxide in these gases varies from one to 6-7%, the rest percent are heavy hydrocarbons and nitrogen. In some cases, hydrogen, hydrogen sulfide and inert gases are also noted [13].

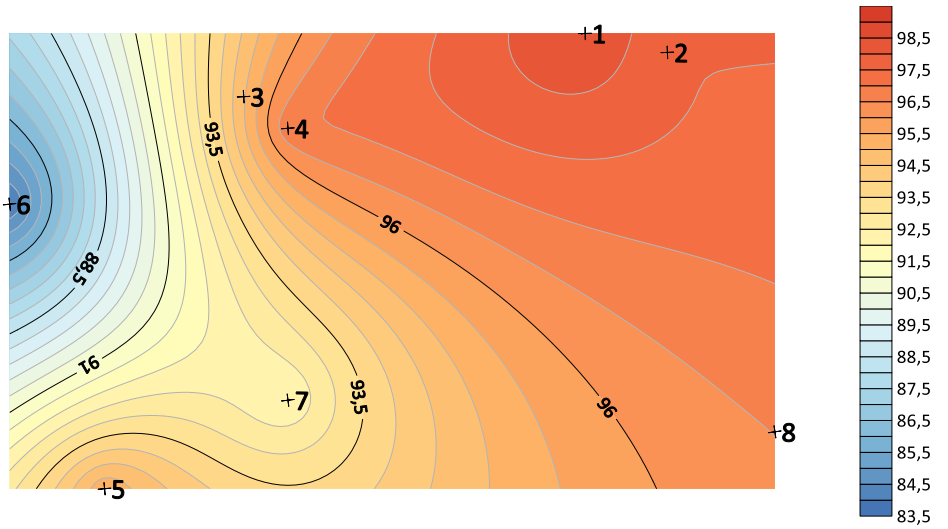


Fig. 2. Distribution map of methane along the Absheron oil and gas-bearing region
Legend: Mud volcanoes: 1-Kirmaki, 2-Bogh-Bogha, 3-Bozdagh-Gobu, 4-Bozdagh-Hokmeli, 5-Akhtarma-Garadagh, 6-Shorbulag, 7-Lokbatan, 8-Otmanbozdagh

In the study area, the methane content in 1 sample taken from the Kirmaki, Bogh-Bogha, Bozdagh-Gobu, Bozdagh-Hokumali, Akhtarma-Garadagh, Lokbatan mud volcanoes and in 6 samples taken from the Shorbulag mud volcano ranged from 92% to 98.53% [6,7]. As we can see from the map, there is a regular decrease in the amount of CH_4 (98.53-83.94%) (Fig. 2).

The value of HHCs along study area varies between 0.09% -0.53%. The value of methane of gas content of mud volcanoes inversely related to the value of HHCs.

In the Absheron oil and gas-bearing region, the highest amount of heavy hydrocarbons was determined in the gases of the Bozdagh-Hokmely mud volcano, is amounted 0.53% (Fig. 3). The value of HHC slightly increases and is associated with the gas flow from oil-gas-condensate deposit to the volcanic crater [14].

Depending on the value of HHCs of gases released from volcanoes, it is possible to determine what type of deposits are they belong, to oil or gas. The value of HHCs in the gases of volcanoes related to oil accumulations is relatively maximum, and the noted maximum amount of HHCs is associated to the oil hydrocarbon accumulations of the individual uplifts whereabouts volcanoes are located. This situation is also affirmed with oil gush in individual well drilled along the Lokbatan fold, whereby the Lokbatan mud volcano is developed.

First exploration well 62 was drilled onto seashore, eastern part of Lokbatan uplift, whereby oil gush was obtained from the horizon II of the PS sediments. In well 45, a strong oil gushes (20 thousand t/day) were got from the VIa horizon of the PS. The sandy layers of both the horizon VII, in addition, the horizon VIIa is more promising. Wells, drilled here put into development with flow rate of 200/300 tons per day.

The well 45 was drilled eastern of the mud volcano conduit (by the recommendation of Sultanov B.I.), which covered breccia from above, gave a strong oil gush of 15000-20000 t/day from the horizon VIa of the PS for three days [15].

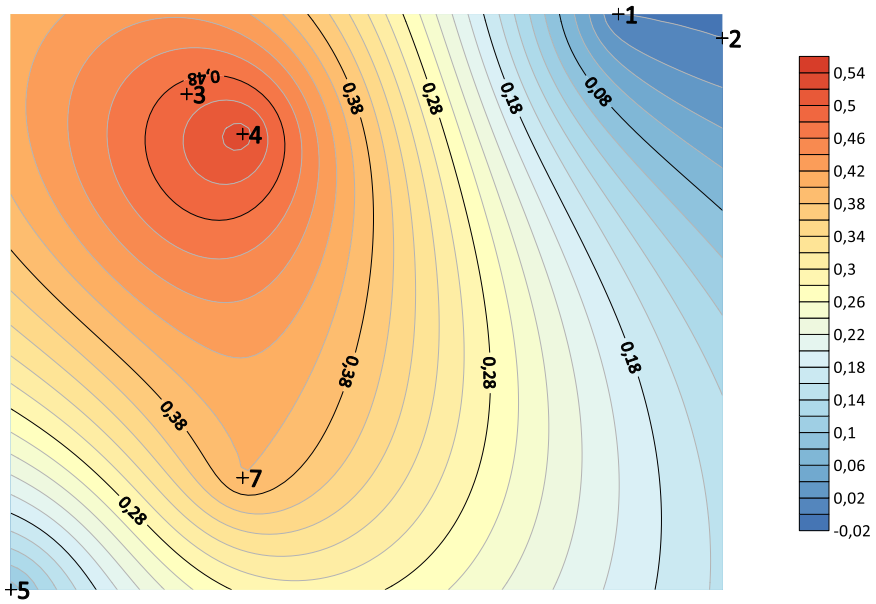


Fig. 3. Heavy hydrocarbons distribution map along the Absheron OGR
(Legend, see fig.2)

The content of heavy hydrocarbons in the Bozdagh-Hokmeli mud volcano is also 0.56% (Fig. 3). The volcano is located at the junction of two anticlines: one of them is located southeast of Bozdagh (Shabandagh-Lokbatan-Puta anticline), the other (Khirdalan-Binagadi anticline) is located northwest. An exploration well drilled in the southern part of the Shabandagh field yielded 50 tons per day of hydrocarbon along the Kirmaki suite [16].

As mentioned above, one can conclude that the released gases from erupted materials of mud volcanoes gradually become get rich off with HHCs separated from oil-gas fields, while they move via along sedimentary stratum.

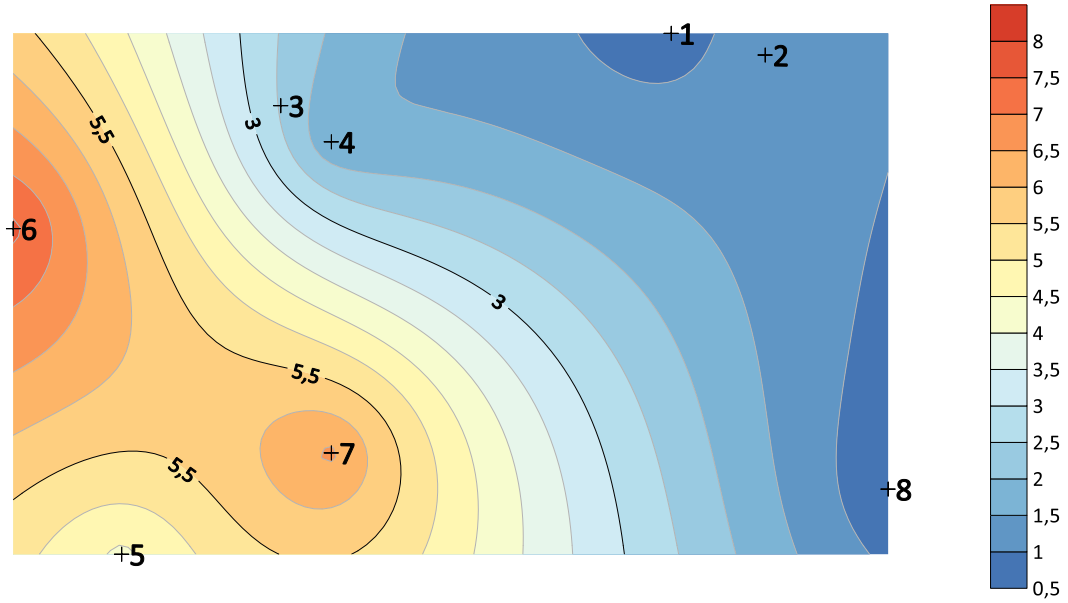


Fig. 4. Carbon dioxide distribution map along the Absheron OGR (Legend, see fig.2)

The distribution map explained that the content of carbon dioxide in the composition of gas products released from mud volcanoes in the Absheron OGR, changes in a large diapason (Kirmaki-0.71%, Bogh-Bogha-1.39%, Lokbatan-2.48%, Shorbulag-7.62%) (Fig. 4). It is appreciable that the content of CO_2 in the composition of gases of oil field is mean, consist of 7-8%.

Referring to the comparative analysis of the distribution maps of CH_4, HHCs and CO_2 associated with gases of mud volcanoes of the region, can be noted that the west-southwest part is characterized by the lowest content of methane and the highest content of heavy hydrocarbons and carbon dioxide. Mud volcano gases in the southwestward are characterized with lowest content of CH_2 and high content of HHCs. The content of CO_2 is average. However, calculated gas releasing from mud volcanoes increases from northwest to southeast.

N_2 and nitrogen compounds are also associated with gases and oils of mud volcanoes, although in small quantities. The value of nitrogen related with gases of mud volcanoes different. It is value in mud volcanoes in the Absheron oil and gas-bearing region varies between 0.11-10.89%, and the highest amount is observed in the Shorbulag (10.89%) mud volcano located in the west of the peninsula. The value of N_2 associated with mud volcanoes of the peninsula varies from 2.28% to 23.6% (according on the 6 sample analysis). The average value is 10.89% (Fig. 5).

The generation of N_2 in the field gases is different. Half of it is formed by the exogenous waters infiltrated from atmosphere through the soil, and half of it is formed due to the decomposition of nitrogen-containing organic substances in rocks, waters and oils. Nitrogen is also formed at the depth [7]. Study has shown that the value of HHCs and N_2 increase towards the base of the Mesozoic [14]. The maximum nitrogen value is observed at the Shorbulag mud volcano, and this is most likely due to the decomposition of nitrogen-containing organic matter, at the same time moving via fracture zones, and entry to the top of the section from the surface.

Porphyrins are first decomposition products of the complex nitrogenous compounds, associated with a number of oils. The existing of nitrogenous components in oils are the main factor confirmed that oil is generated from organic components. Be sensible of the fact that C is the basic compoud in hydrocarbons, its isotopic composition is also interested. The both isotopes C_{12} and C_{13} of carbon are constant, because the isotope (C_{13}) increases by the carbon oxidation. The isotopic structure of HC gases

and petroleum cut is different. Methane is richer in the C_{13} isotope. The change in the isotopic composition of gases during emigration is of special interest. Molecules of gases with the isotope C_{12} exceed the isotope C_{13} along the migration. The methane isotopic compound depends on the lithofacial content of rocks. However, when methane gas moves via existing faults within areas with high porous and permeable rocks, the isotopic composition does not change. Thus, it can be supposed that when migration occurs in dense and low-porous rocks (clay), the value of isotopes C_{13} within sediments increase [17].

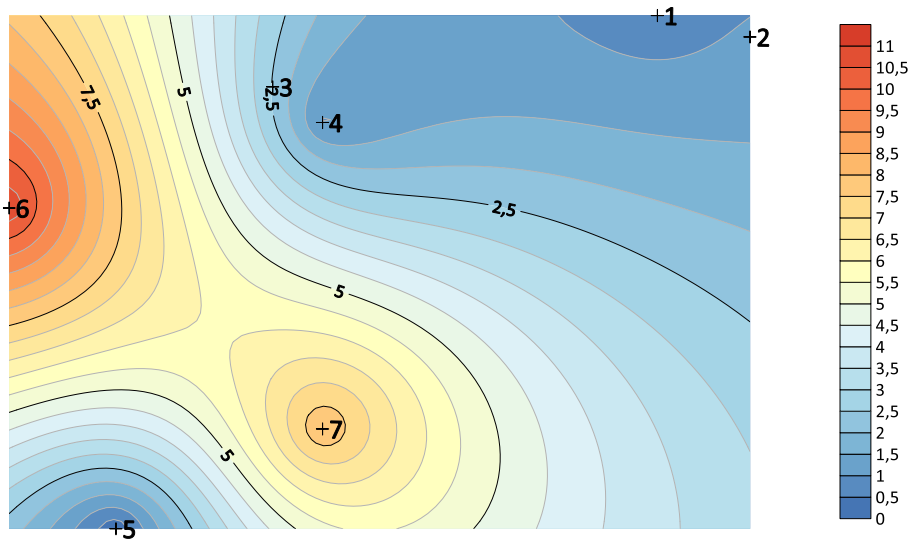


Fig. 5. Nitrogen distribution map along the Absheron OGR (Legend, see fig.2)

As can be seen from the maps of changes in carbon isotope composition established for the Absheron OGR, the C isotope of CH_4 fluctuate from 43.4 to 56.8‰ (Fig. 6). This fluctuation is associated to the lithofacial composition of the sedimentary layer of the depression. Thus, since the sedimentary layer made up by dense and low porous carbonate rocks, the value of isotopes C_{13} in the rocks get larger, while in the west and southwest, since it made up by clayness-carbonate, sandiness rocks, the value of isotopes C_{13} within rocks does not change enormously (Fig. 6).

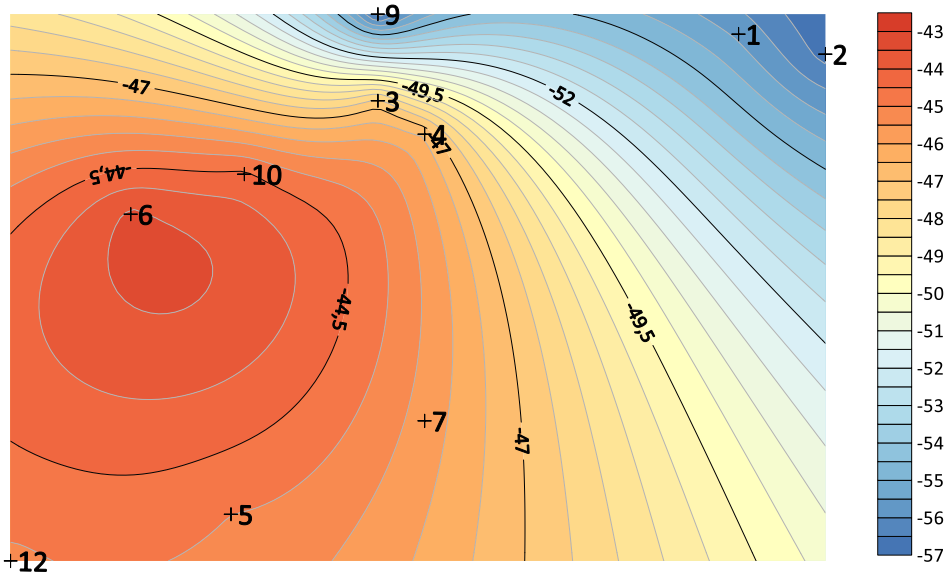


Fig.6. Change map of methane isotope composition along the Absheron OGR

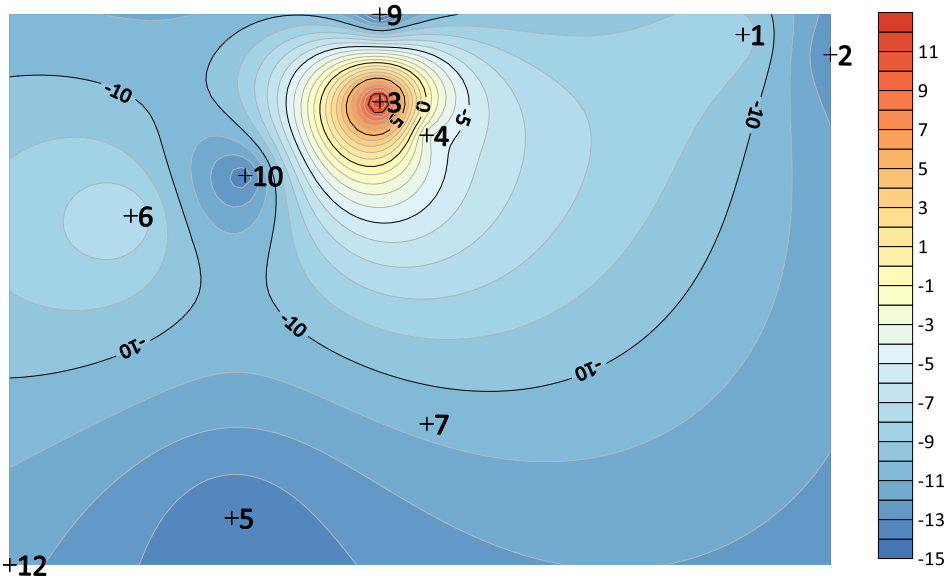


Fig.7. Change map of carbon dioxide isotope composition along the Absheron OGR

The carbon isotope of CO_2 within research region changes from -3.9‰ to 13.1‰. The high content of the carbon isotope is observed mainly in the center of the peninsula (13.1‰) (Fig. 7), whether concurs with the zone where the maximum content of CO_2 is distributed. It is most likely related to the fact that in the studied region, the amount of the isotope C13 is larger in CO_2 and carbonates [8].

Within Absheron OGR, almost all mud volcano structures are prospective with hydrocarbons. One of the richest oil-gas field of the Absheron Peninsula is the Lokbatan field. Conducted exploration works cover along the area covered by mud volcano breccia.

Memories of the history of oil production in Azerbaijan are associated with the Lokbatan mud volcano. For a long time, areas with mud volcanoes were considered unpromising for the search for industrial hydrocarbon resources. Mud volcanism was considered a factor in the collapse of oil and gas fields. However, many geologists disagreed with this idea and accepted the opposite. Some even suggested drilling oil wells in volcanic areas. In this regard, well 45 drilled in the Lokbatan mud volcano erupted with a flow of 20 thousand tons, thereby proving that volcanoes do not destroy deposits. However, initially in the Lokbatan volcano, the genetic links of mud volcanoes-oil deposits were estiblished, and the need to search for mud volcanoes arose. It is interesting that during the exploitation of the Lokbatan field, over 27 mil.t. of hydrocarbons and 1 bil.m^3 of gases were extracted from the subsoil. The famous well 45 is still being exploited.

The gases of the Lokbatan mud volcano consist of hydrocarbons by their chemical composition. According to gas analyses taken from the volcano, it consists of 92% methane, 2% heavy hydrocarbons, and up to 2.5% carbon dioxide.

During the eruption of Lokbatan volcano, the volume of gas released in the first phase was 300,000 m^3. The gas released in the second phase was 2,500,000 m^3, and in the third phase was 4,200 m^3. As can be seen, a large volume of gas was released into the atmosphere with one eruption. When we compare this volume with the gas extracted from the field during the development process, it can be seen that it is a very small amount less than the half-yearly production of this enterprise. Taking into account the intensity of the gases released in previous eructation, ground that there is an extremely large gas reserve in the interior of the area.

If we exsamin the chemical compound of oil field gases, especially gas fields, we see that they, like the composition of mud volcano gases, consist mainly of methane, with a few content of HHCs, carbon dioxide, and a few content of nitrogen gas. A comparison of mud volcano and oil field gases is given in Figure 8.

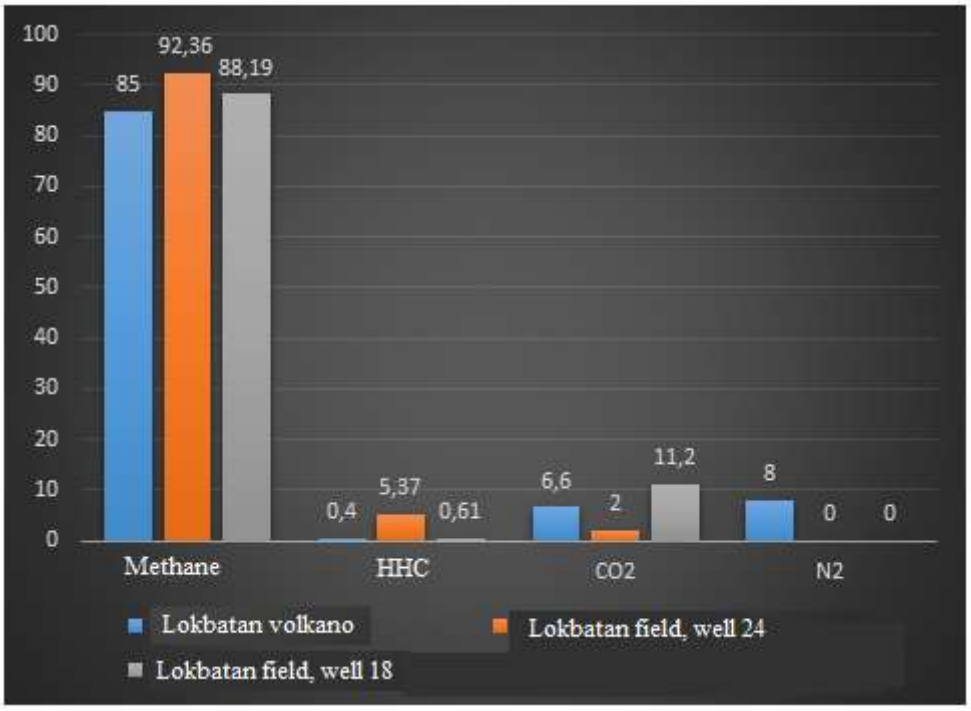


Fig. 8. Comparison histogram of gases of the Lokbatan mud volcano and Lokbatan oil field

As show the histogram, the chemical compound gases of mud volcanoes consists mainly of combustible hydrocarbons and are close associated to the gases of oil and gas fields. If there were no natural gas deposits in the deep layers of the areas where mud volcanoes are located, then mud volcanoes would not have formed. The violent or weak eruption of mud volcanoes also depends on the underground reserves of these gases and, at the same time, on the plasticity of the rocks. When the gas reserves are high and the plastic rocks are thick, violent eruptions occur, and when they are low, weak eruptions occur.

Underground waters also have a great influence on the eruption of mud volcanoes. Analysis of the chemical features of water samples collected from mud volcanoes show that the compound of these waters is the same as the waters of oil fields located in the mud volcano area or in the neighborhood. Mud volcano waters contain chlorine, sodium, potassium, bicarbonates, etc., as in oil field waters. Elements such as naphthenic acid, iodine, boron, bromine, which are characteristic of oil field waters, are distributed in all mud volcano waters in greater or lesser amounts. Mud volcano waters are divided into alkali and hard water types. The degree of mineralization of mud volcano waters varies according to the degree of mineralization of oil field waters nearby. So, mud volcano waters are also related to oil field waters.

24 samples were taken from the Paleogene-Miocene sediment complexes for determination the organic substances dispersed in the solid waste of Lokbatan mud volcano [6]. These samples consist of sandstone, siltstone, clay, marl, limestone and dolomite. The amount of bitumen and organic carbon in them was determined.

Bitumen in the noted rocks increases from 0.03 to 0.8%, in rare cases increases up to 1.56%. The high content of bitumen (0.8-1.56%) is not due to the presence of bitumen in a dispersed state, but is due to the enrichment of rocks with epigenetic bitumens as a result of migration. High content of bitumen is noted in oil-saturated limestone samples (sample 3, 70,71,72,73). Bitumen content is 2.3, 4.69, 1.56, 2.34, 6.25 respectively.

The content of organic carbon ($C_{org.}$) varies from 0.01-1.05%. In a sample No.70 its content increases to 1.83%, which are also strongly saturated with oil (Fig. 9).

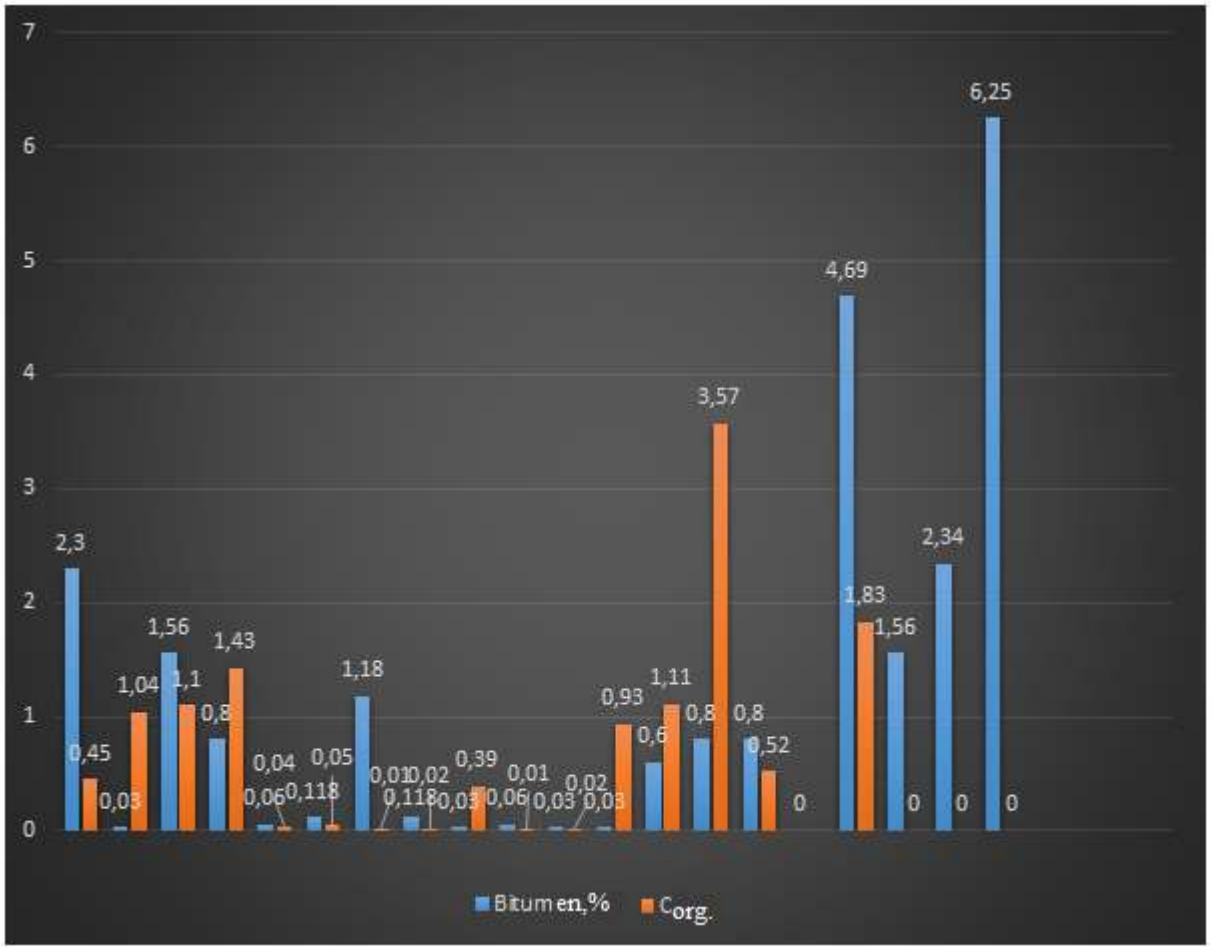


Fig.9. The content of bitumen and organic matter in the solid waste of the Lokbatan mud volcano

The oil-gas-bearing all fields is associated with upper and lower stages of the PS. One of the largest hydrocarbon deposit depending on the size and volume of oil reserves is the sandiness layer of the horizon VI of the PS.

The oil and gas-bearing of the Kirmaki field, where the mud volcano of the same name is located, is mainly related to the sediments of the lower section of the PS. Currently, all horizons of the Kirmaki (KS) and Pre-Kirmaki (PK) suites of the PS have been put into operation.

The Qum-deniz fold forms the southern edge plunge of the Fatmai-Garachukhur-Zygh anticline line, which is considered the main anticline line of Absheron region.

21 objects are in operation in the Qum-deniz field. Initially, Ga and PK suites were put into operation in the II block. Later, Xa, IXa, IXo, VIy and others are developed. 27,083 thousand tons of oil, 15,375 mln. m^3 of dissolved gas, 10397 mln. m^3 of free gas and 832 th.t. of condensate was exploited from objects by wells [1].

A comprehensive study of mud volcano products of the Absheron oil-gas-bearing region allows us to distinguish zones suitable for collecting of hydrocarbon and gases.

The degree of development of diapir and local folds and mud volcanoes complicating them along the three tectonic zones of the area is related to the tectonic conditions of these zones and the intense of compressional stresses affecting them. According to the results of the analysis, the least intensity of compressional stress is noted on the north slope of the Absheron-Pre-Balkan megasaddle. It is explained by the weakening of compressional stresses in the direction of the Scythian-Turanian plate to the north. For this reason, diapir folds (Goshadash, Aghburun-deniz, Absheron Bank) and their cryptodiapiric types (Khazri, Dan Ulduzu, Arzu, Gilavar, Ashrafi, Garabagh, Hamdam, North Absheron) have developed here. Mud volcanoes have not developed in the northern zone. Only in the Absheron Bank

the griffon with natural gas manifestations along the longitudinal fault, which complicates the arch part of the fold, mud volcano manifestations in the Gilavar structure, and a buried mud volcano in the Goshadash structure are observed [9].

The test results of exploration wells drilled in the Khazri, Garabagh, Ashrafi folds of North Absheron confirmed the presence of industrially significant hydrocarbon accumulations in separate layers of the lower section of the PS.

In the exploration well 2 drilled in the Garabagh field 770,000 m^3 per day of gas from the Pre-Kirmaki suite (PK), 707,000 m^3/day of gas from the Post- Kirmaki sandy suite (PKS) and 82 m^3 per day of condensate flow was obtained.

In the Hamdam fold, from well 3, 798,000 m^3 per day of gas and 27 m^3 per day of condensate from the PK suite, while 300 m^3/day of oil flow from the PKS suite was obtained.

Exploration well 1 in the Ashrafi area produced 640,000 m^3/day of gas and 70 m^3/day of condensate from the PK suite, and 556 t/day of oil and 27,000 m^3/day of gas from the PKS suite was gotten.

During the test work of well 4 in the Khazri area, the gasbearing of the lower Cretaceous deposits was determined and 6-7,000 m^3 per day of gasflow was gotten at the 4327-4319 m interval. The gas obtained from the Hauterivian stage of the Lower Cretaceous in the Khazri-4 prospecting well, drilled in the hypsometrically higher area of the North Absheron fold zone, show that these sediments will be industrially important oil and gas in the parts of the noted fold zone with suitable lithofacies and structural-tectonic conditions.

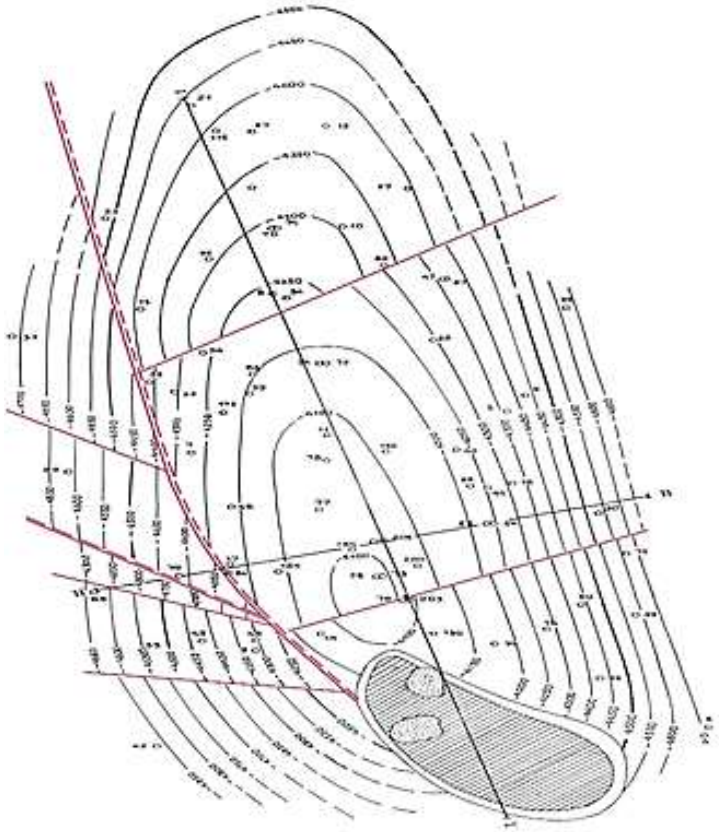


Fig.10. Bahar field. Structural map on the horizon IX of the Productive series (Lower Pliocene)

During drilling from well 1 in the Goshadash area, a strong gas gush was obtained from Miocene sediments. During drilling from exploration well 4 drilled in the Absheron Bank, 150-200,000 m^3 per day of gases and 15-20 m^3 per day of condensate were gotten via the PK suite. Gases also was gotten from the Gala suite in exploration well 42 with a production rate of 82,000 m^3/day. 10 t of oil from PK suite in exploration well 48, and 7 t of oil from KS in exploration well 49 was obtained [11].

In the North Absheron fold zone, hydrocarbon fields are replac with oil-gas, gas fields with gas condensate, with the weakening of the degree of deformation and dislocation of structures in the northwest-southeast direction along anticlinal lines. Along the southern slope of the Absheron-Pre-Balkan megasaddle, majorly diapir structures have developed and are complicated by mud volcanoes. In the southern zone, Sulutepe, Shubani diapir folds, Surakhani, Hovsan, Turkan, Gala, Buzovna-Mashtagha cryptodiapir folds have developed. Along the Absheron Peninsula, 11 active, 11 periodically erupting, 4 extinct, 4 buried mud volcanoes and Lokbatan, Guzdek, Garadagh, and in the aquatorium, Bahar, Gum-deniz gas-mud volcanoes have developed [6].

According to the results of deep drilling, the Bahar fols is represented by a brachyanticlinal fold, has an asymmetric structure, dimensions 10x4.5 km (on the top of the horizon IX), and a height of up to 450 m. The structure is complicated by faults and tectonic faults and is divided into 8 tectonic blocks. There is a mud volcano in the southwestern part of the transverse longitudinal fault along the entire western limb.

As mentioned above the field is divided into 8 tectonic blocks, blocks I, II, III are considered the major according to the amount of hydrocarbons.

15 hydrocarbons (gas, condensate, oil) objects have been identified in the Bahar field through exploration and prospecting [13].

During the development of a number of wells in the lower part of the section of the Gala suite in the Turkan area, industrial oil was obtained, and well 1216 operated with a production of 100 tons per day.

In the areas noted in the South Absheron zone, oil deposits are spread across the entire section of the PS.

The deep dislocation extending on the axis of the Absheron-Pre-Balkan megasaddle is specified by the formation of cryptodiapir, diapir-type structures, mud and gas-mud volcanoes. Diapir folds such as Janub, Janub-2, Gunashli cryptodiapir, Gurgan-deniz have developed here. The remaining structures are complicated by mud volcanoes and gas-mud volcanoes (Neft-Dashlari, Azeri, Chirag).

The Gunashli structure is situated within Absheron-Pre-Balkan tectonic zone to the south-east of the Neft Dashlari field, and the oil and gas content of the fold is associated with PS sediments. As a result of test work from well 4, an oil gush was obtained with a production of 230 t/day from the horizon X of the Balakhani suite, and 320 t/day from the Fasila suite from well 6. The lower suites of the PS (PKS, PK, GaS) are gas condensate. Oil and gas-condensate deposits are related with tubular and tectonic screened types of traps.

The Neft-Dashlari fold is formed by the crushed clayey sediments of Miocene-Upper Paleogene age, complicated by large longitudinal faults and numerous transverse faults. In the southeastern part of the fold, where transverse and radial faults intersect with longitudinal faults, there is a mud volcano and numerous griffons that regularly emit oil and gas. The mentioned mud volcano is a gas mud volcano. The base of the mud volcano is made up of Oligocene-Miocene sediments, and Eocene and Upper Cretaceous rock fragments are found in the volcanic breccia. Here, 26 oil objects covering all its series and horizons have been identified along of the PS section. Oil-bearing layers are thick within the tectonic blocks has a minimum value in the northwest of the structure, and a maximum value in the southeast, while the mud volcanoes are replaced. The oil-bearing of the GaS, which forms the base of the PS, has been determined in all blocks of the field. The GaS-4, GaS-3 horizons are oil-bearing, while the GaS-2, GaS-1 horizons contain oil with gas gap. The fact that the entire section of the PS is oil-bearing and the fault is complicated by a gas-mud volcano gives reason to say that the sediments underlying the PS are oil-bearing.

The Chirag gas-mud volcano is located on the southeastern plunge of the fold of the same name, above the crushed zone at the intersection of longitudinal and transverse faults.

During testing, 154-355 t\day of oil and 201000 m^3\day of gas flow were obtained from 2 objects from the Fasila suite of the PS and 1 object from the Balakhani suite (horizon X) of the Chirag field. Later, gas-condensate was obtained from horizons IX, VI, V and IV of the PK, PKS and Balakhani suites, and oil from horizons VII, VIII.

The Azeri gas-mud volcano is situated along the south limb of the structure of the same name. Later, another volcano was identified in the central part of the northern wing. 9 objects of the MG were opened in the southwestern wing of the structure. Oil-gas mixture was obtained from horizons X, IX, VIII, VI and V of the QUQ, FLD (2 objects) and Balakhani formations. Hydrocarbon flow rate up to 155-300 t/day, and gas flow rate was 12-75 m^3 per day. Gas condensate was gotten via PKS, from horizons VI, V, the output of which was 245-300 th. m^3 per day and 30-70 tons per day, correspondingly [1].

The morphological characteristics of the folds and the analysis of the relationships of the structural-formational complexes of different ages show that mud volcanoes are associated with structures complicated by faults in a thick sedimentary layer and subjected to sharp folding.

A comparison of the tectonic structure of depressions located in the mobile belts of the earth's crust shows that since separate subsidence areas complicated by large faults and subjected to sharp folding are noted only in the eastern part of Azerbaijan and the adjacent South Caspian water area, most mud and gas-mud volcanoes are concentrated here. The basic point for the development of the latter in the mentioned zone is the significant increase in the thickness of the rock layer, the content of clayness along intersection and the oil and gas-bearing in the southeast direction within folds of the South-Caspian mega-depression [18].

The compressional stresses arising along the area is a main factor for formation of its structural tectonic plan, the dispersion of fluid, and reformation of different type of accumulations, the collection, also storage of sediments and OM in them, which are subsequently turned to oils, by the environment of non-compensated intense sinking floor of the South Caspian depression, and the development of diapirism and mud volcanism.

In areas with appropriate quality distribution of compressional stresses and in the absence of large-scale research in areas where mud volcanism develops, it is possible to predict the oil-gas bearing of the area.

IV. Conclusion

1. The focusing of HHCs into mud volcano gases within Absheron OGR is inverse proportional to the content of methane in them.

2. Increasing of the content of methane in mud volcanoes along the northeast-west direction on the Absheron Peninsula, also decreasing of the content of CO_2, HHCs, gives grounds to say that there are significant oil-gas, gas-condensate reserves in this zone.

3. The sediments building up of the mud volcanoes root of in the Absheron OGR are Maykop and Pliocene age, but the presence of rock fragments of Upper Cretaceous, Paleocene, Eocene ages in the erupted materials of 16 mud volcanoes gives grounds to say that there are crushed zones enriched in natural gases under the roots of the volcano.

4. According to isotope analysis, the mud volcano gases in the Absheron OGR are characterized by a lighter isotope composition of carbon.

5. Separate subsidence areas, complicated by large faults and subjected to sharp folding, is noted along the east part of Azerbaijan and adjacent South Caspian water area. Therefore, a significant increase in the thickness of the sedimentary layer, the percentage of clay content of the section and oil and gas-bearing in the southeastward has led to the development of most mud and gas-mud volcanoes here.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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IDENTIFICATION OF LINEAMENTS ON THE SEABED BASED ON A DIGITAL RELIEF MODEL USING THE EXAMPLE OF THE CASPIAN SEA

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Abstract

This paper focuses on the application of geomorphometric methods to analyze a digital model of the seabed to identify lineaments on a regional scale, using the Caspian region as an example. The active development of remote sensing methods and geoinformation technologies has led to lineament analysis becoming widespread in both scientific and applied geological and geophysical research. This work demonstrates the use of geomorphometric methods to identify regional-scale lineaments in the Caspian region, using the bathymetric model as the initial data. The study's results demonstrated the effectiveness of shadow analysis methods and the identification of keel shapes by calculating relief curvature to detect large-scale lineaments. Combining the results of geomorphometric analysis with data on the distribution of earthquake epicentres enables active fault zones to be identified, which could be very useful for assessing seismic hazards and identifying areas of possible earthquake source zones (PES zones) on the shelf. There are still issues to be resolved, such as verifying that the selected lineaments comply with active faults in aseismic areas, determining the block-hierarchical structure of the studied areas and determining the magnitude of the displacement of blocks, both vertically and horizontally. Methods for detecting lineaments based on the DRM of the bottom should be developed and combined with the selection of lineaments based on magnetic and gravitational field anomalies. Experiments should be conducted on filtration methods and geomorphometric analysis to select the optimal complex.

Keywords: Caspian Sea, lineaments, geomorphometric analysis, relief curvature, earthquake epicenters

I. Introduction

The active development of remote sensing methods and geoinformation technologies has led to the widespread use of lineament analysis, both in scientific research and in applied geological and geophysical research [4, 10, 12 and others].

The understanding of the term "lineament" is ambiguous. It was introduced at the beginning of the twentieth century by W. Hobbs, who formulated it as a rectilinear relief element depicted on a geographical map reflecting a deep fault [13]. Later, this concept expanded to such an extent that various researchers now use this term to understand the most diverse structures of the Earth's crust – from giant deep-seated faults on a planetary scale to weakly expressed local fracture zones. Lineaments are considered as linear and arc-shaped elements of the geological and geophysical environment, reflected in the relief and including a variety of objects: fractures and cracks, zones of increased concentration of deformations, gradient zones of geophysical fields, elements of structural

and material heterogeneity of the geological environment, they can also reflect the supply channels of various fluids and solutions. Accordingly, the allocation of lineaments according to relief maps is possible due to the fact that they represent the exits to the earth's surface of discontinuous faults and their direct mapping features: the actual faults and cracks.

Modern lineament analysis is one of the methods of processing and decrypting Earth remote sensing data in order to study the deep structure of a particular territory. The essence of the method is to identify extended linear elements – lineaments, both rectilinear and arcuate (ring structures) in the image of the earth's surface, usually associated with disjunctive disturbances of the earth's crust of various origins. Geo-indicators of decoding are mainly geomorphological and landscape heterogeneities formed at the latest stage of tectonic development.

The use of lineament analysis has shown that the lineaments expressed on the surface largely reflect violations of the foundation structure, even overlain by a powerful sedimentary cover. The features of the deep structure of the basement are projected onto the daytime surface through the sedimentary cover, controlling the relief shapes [3, 11, 14, 15, 17]. Large lineaments in most cases are the surface manifestation of active faults, including deep ones. This gave rise to the use of lineament analysis in identifying tectonic disturbances.

In marine conditions, it is not possible to use lineament analysis based on remote sensing data of the Earth's crust. The use of modeling methods based on the analysis of digital models of the bottom relief and geophysical fields can be considered promising. In particular, geomorphometric methods and high-frequency filters for selecting threshold, extreme, and gradient areas can be used.

Currently, the rapid development of computing hardware, geoinformation technologies, remote sensing methods and equipment, which led to the creation and development of databases on digital terrain models, has led to the active progress of geomorphometry, an interdisciplinary field that emerged at the end of the twentieth century. Geomorphometry is based on the principles of morphometric analysis implemented in computational modules of geoinformation systems. Geomorphometric methods are increasingly being used to solve various problems in land-based geo-surveys, including for detecting tectonic disturbances [2, 32].

Until recently, geomorphometric analysis based on the digital bottom relief model (DRM) was not widely used due to the lack or low reliability of digital bathymetry in most seas. Nevertheless, the regular updating of the General Bathymetric Chart of the Oceans – GEBCO [8], the creation of new bathymetric maps based on multipath sonar creates conditions for the application of geomorphometric analysis for a regional scale based on the bathymetric model. It should also be noted that the identification of lineaments (faults) on a regional scale does not require a high-level DRM. In this regard, it is possible to use a DEM with a low grid discreteness: from 1 to 5 km, or the detailed DRM of the bottom is pre-filtered with a low-frequency filter (low-pass filter) to smooth out local relief deviations.

For example, [37] presents the results of the identification of neotectonic disturbances on the shelf of the Barents Sea using geophysical (seismic) methods and morphometric characteristics of the curvature of the relief. The allocation of lineaments along the shadow relief made it possible to identify a series of rift volcanic formations and zones of large discontinuities in the continent-sea transit zone [6, 7]. Shadow analysis and a method for identifying morphometric characteristics of relief curvature were also used to locate faults in the Pechersk Sea [27] and in the Laptev Sea. The results of the lineament analysis showed their applicability for further use in the development of possible earthquake source zones (PES zones) and seismic hazard assessment [30].

The Caspian region seems to be a successful scientific platform for the further development of the methodology: the area is seismically active, has been studied extensively for a long time, and there is a significant amount of data available to verify the modeling results.

II. Methods and data

A relief map of the bottom of the Caspian Sea and the adjacent territory with data used to verify the proposed method of lineament extraction is shown in Fig. 1. The map shows the distribution of earthquake foci, shows previously identified [35] geo-fluido-dynamic objects "pipes", some of the fault detection points according to continuous seismic profiling (CSP), as well as the results of the actual manifestation of active fault zones [16]. Data on active faults from the Active Faults of Eurasia Database (AFEAD) [1] are also presented.

Geomorphometric analysis

In this work, the Caspy-30 DEM was used as the initial data for the geomorphometric analysis of the Caspian Sea bottom relief' [5]. The sampling step of the 5000 m grid corresponded to the task of selecting regional-level lineaments.

To identify the faults according to the DRM, methods of geomorphometric terrain analysis were applied: shadow analysis and identification of keel shapes using the calculation of the curvature of the bottom relief. All calculations and constructions of possible fault lines were performed using the Surfer Golden Software V.16 software package. Data analysis modules of geographic information systems (GIS) software complexes can also be used for geomorphometric calculations.

Shadow analysis of the bottom morphology is performed visually using grayscale images (shadow maps) The DRM with its conditional illumination is sequentially illuminated at different azimuths of the virtual light source so that all linear elements of the relief deflections are clearly distinguishable. The vertical illumination angle was 45°, and the azimuths were equal 45°, 135°, 225°, 315°. The supposed lineaments (faults) were manually highlighted on each shadow map. As a result, all the lineaments highlighted at different positions of the conditional light source were reduced to one map. This approach allows you to quickly perform a preliminary analysis of the shape of the bottom relief and identify the most pronounced gradient zones.

To identify regional scale lineaments, you can use a DRM with a grid discreteness of 1 to 5 km. When using a detailed grid, the bottom DRM is pre-filtered with a low-pass filter (low-pass filter) to smooth out local relief deviations and artifacts possible due to the fact that the bottom DRM is formed based on data from various sources. Calculations are performed on a rectangular grid.

The keel shapes of the bottom relief were identified after calculating the profile (vertical) and planned (horizontal) curvature, morphometric values based on second-order derivatives of the DRM function and describing curved and concave relief shapes, i.e. ridge and keel shapes [36]. The profile (vertical) curvature is the curvature of the surface in the direction of the maximum slope (the curvature of the profile line laid along the direction of the stream line), and the horizontal (planned) curvature is the curvature of the line formed by the intersection of the earth's surface with a plane perpendicular to the direction of orientation of the maximum gradient (exposure).

Only the values of negative curvature shapes corresponding to the keel shapes of the relief were plotted on the curvature map. Next, the proposed lineaments were highlighted.

Seismological data

Fig. 1 shows data from long-term seismological observations (pink circles, [40] and data from bottom seismological observations of the Institute of Oceanology of the Russian Academy of Sciences (red circles) [18, 21, 22; 33]. The size of the circle determines the magnitude of the earthquake.

In 2004 and 2006 the Institute of Oceanology of the Russian Academy of Sciences conducted detailed seismological observations with bottom stations near the coast of Dagestan (Middle Caspian). In 2004 bottom stations were installed on the Yalamo-Samur structure to assess the seismic

hazard of the studied area. 10 bottom seismographs of different types of were used, including pop-up [19, 23, 29, 31] and buoy devices [20, 26, 33]. The structure of the seismometric network took the form of two nested squares with a central station in the middle. The duration of registration was 75 days [26]. In 2006 buoy-type devices were installed in the water area of the Middle Caspian Sea on the beam of the Izberbash. The seismic network had the shape of a square with a side of about 50 km and an additional seismograph in the center. Registration lasted 90 days. As a result of these two experiments, records of more than 550 micro- and weak earthquakes with magnitudes M_L = 0.1-4.7 (MLH =-0.7-4.3) were obtained, one fifth of which originated in the upper mantle at depths of 50-200 km. The method of magnitude determination is in the articles [22, 25, 38, 39]. At the same time, for the entire period of instrumental observations since the 1930 last century, regional land-based stations recorded only 10 mantle earthquakes with MLH = 3.5-6.3.

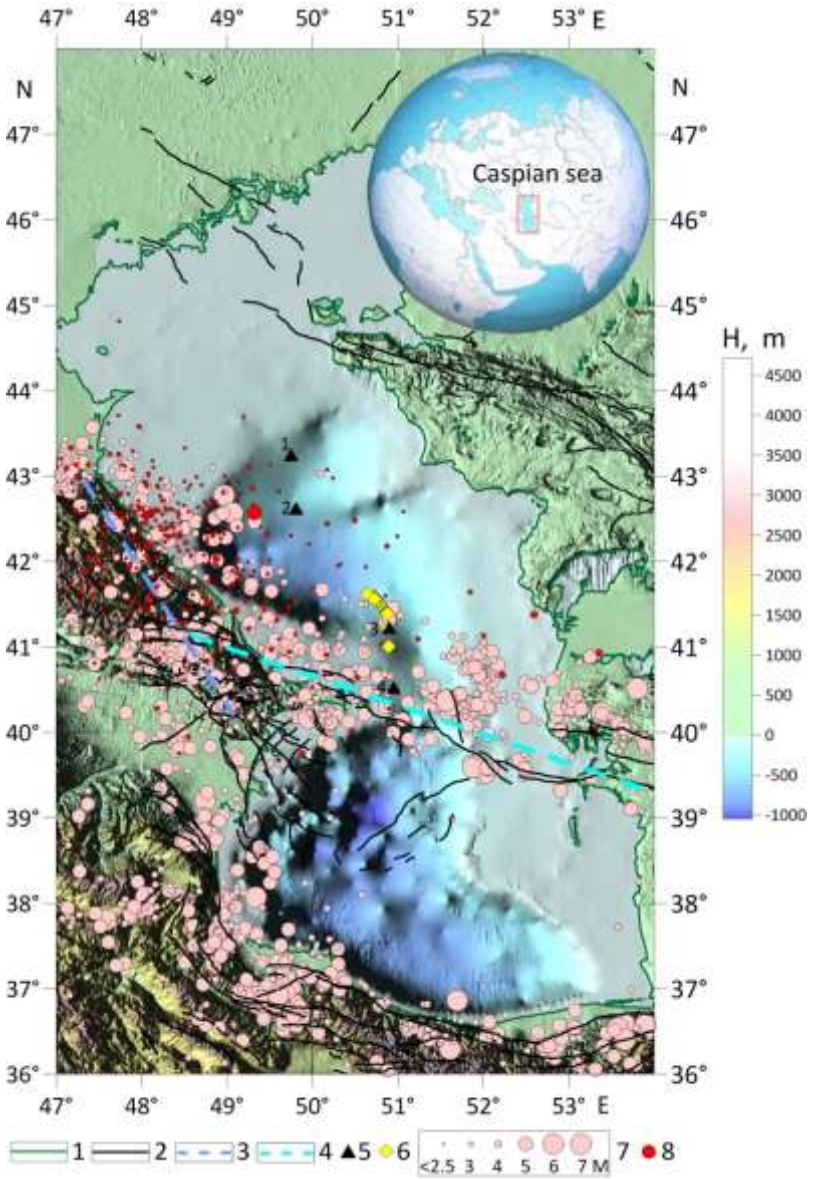


Fig. 1: *Map of the distribution of earthquake epicenters and active fault zones in the Caspian Sea region. 1) The coastline; 2) Active fault zones according to the Active Faults of Eurasia Database (AFEAD) [1]; 3) The West Caspian Fault; 4) The Absheron threshold; 5) The position of the detected faults according to continuous seismic profiling (CSP) data; 6) "pipes" according to the CSP; 7) Earthquake epicenters according to the USGS catalog; 8) epicenters of earthquakes recorded by bottom stations of IO RAS in 2004 – 2006*

Active fault diagram

The Active Faults of Eurasia Database (AFEAD) data for the Caspian region [1] were chosen as the active fault diagram, shown in Fig. 1 with black lines.

Seismic profiling data

Seismo-acoustic data were obtained in expeditions of the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences in the period 2004-2015 using the Geont Shelf single-channel continuous seismo-acoustic profiling system and Sparker source (300 Hz).

The seismic and acoustic data was processed in specialized software packages RadExPro 2012.3, ISE 3.2 and Chirp-II, and the software package Kingdom Suite 2d/3d was used for interpretation.

III. Results and discussion

As a result of the analysis of the shadow maps of the DRM and the calculation of the profile and planned curvature, lineaments of a regional scale were identified, expressed in the relief of the bottom. Presumably, most of them are associated with fault zones. The separation of smaller structures is complicated by the fact that the sedimentary cover smooths out the manifestation of the basement structure on the seabed surface.

Highlighted by grayscale images (shadow maps) DRM bottom lineaments are shown in Fig. 2. There were no lineaments in the coastal part of the DRM. The linear relief elements become clearly distinguishable at different illumination azimuths. Thus, the variation of the illumination azimuths allows us to obtain the most complete picture of the lineament distribution, reflected on the summary map (Fig. 2e).

The results of the lineament selection according to the distribution of the profile and planned curvature of the relief are shown in Fig. 3. The figure shows that the most pronounced and extended lineaments in conditions of slightly gradient relief are highlighted mainly on the planned curvature map, and the profile curvature map for these sections is less informative. In the conditions of sharply rugged relief of mountainous areas of the coastal part of the DRM, the characteristics of planned and profile curvature are equally effective.

Fig. 4 shows a summary diagram showing the lineaments obtained from the DEM analysis, earthquake epicenters from the catalog [40], data from bottom seismological observations of the Institute of Oceanology of the Russian Academy of Sciences [18, 21, 22], the location of the geo-fluido-dynamic structures of the "pipe" [35], locations of faults identified according to the CSP data, active fault zones according to [1].

Judging by Fig.1 and 4, both sets of earthquake epicenters are confined to fault concentration zones identified by data on the curvature of the relief. The epicentral field under consideration is characterized by the presence of lineaments and clusters. The main and densest group of earthquake epicenters stretched from NORTH to SOUTH from about 42.6 to 41.3°n along the Dagestan coast on land (depths of foci 10-40 km) and in the Caspian Sea (depths of foci 10-50 km) along the steeply falling side of the Derbent depression to the northeast.

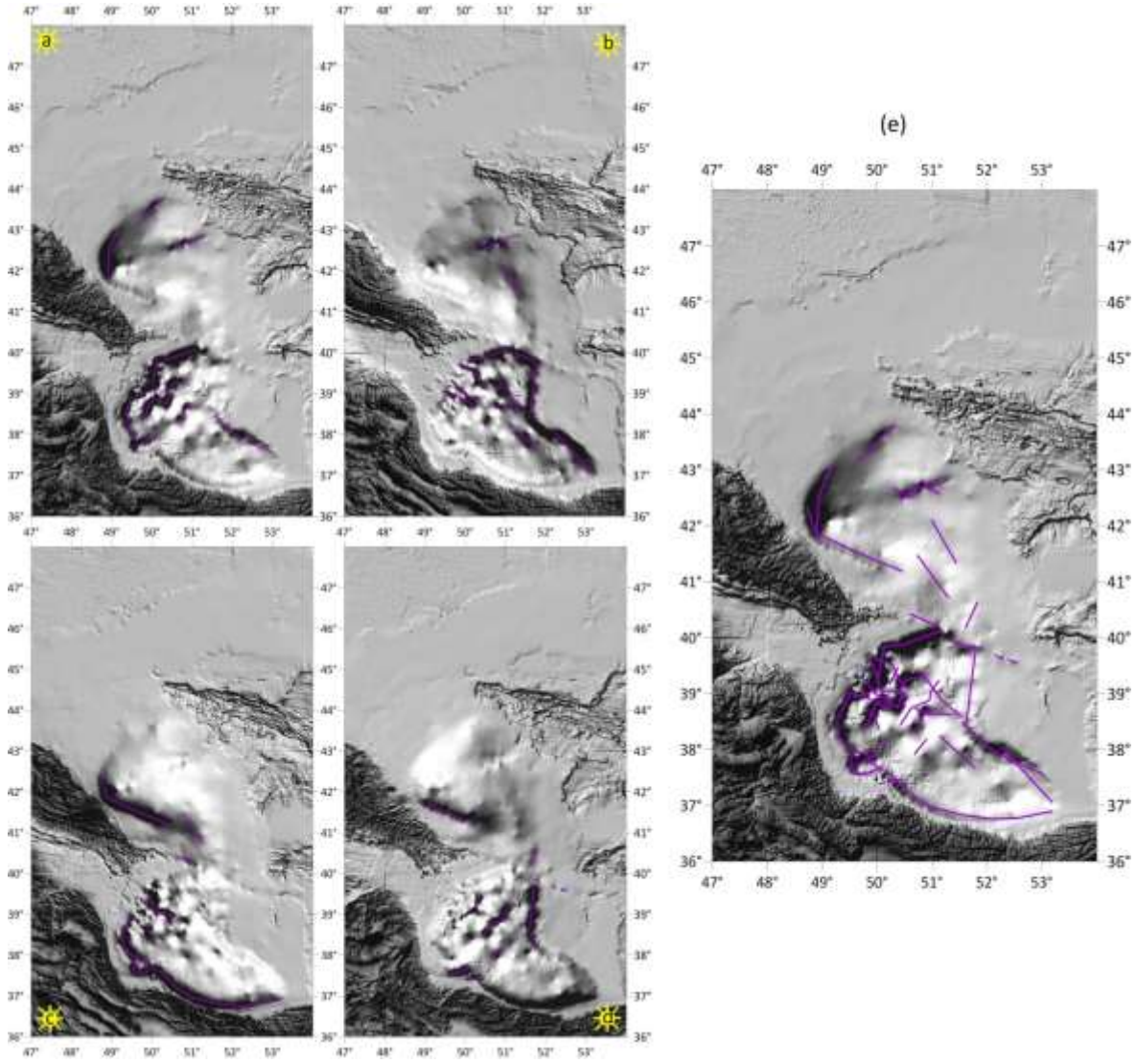


Fig. 2: *Highlighting lineaments in grayscale images (shadow maps) DEM of the bottom of the Caspian Sea at a vertical illumination angle of 45° and various azimuths: (a) 135°; (b) 45°;(c) 225°;(d) 315°;(e) – Summary map. The coastline is shown in black, and the highlighted lineaments are shown in purple color*

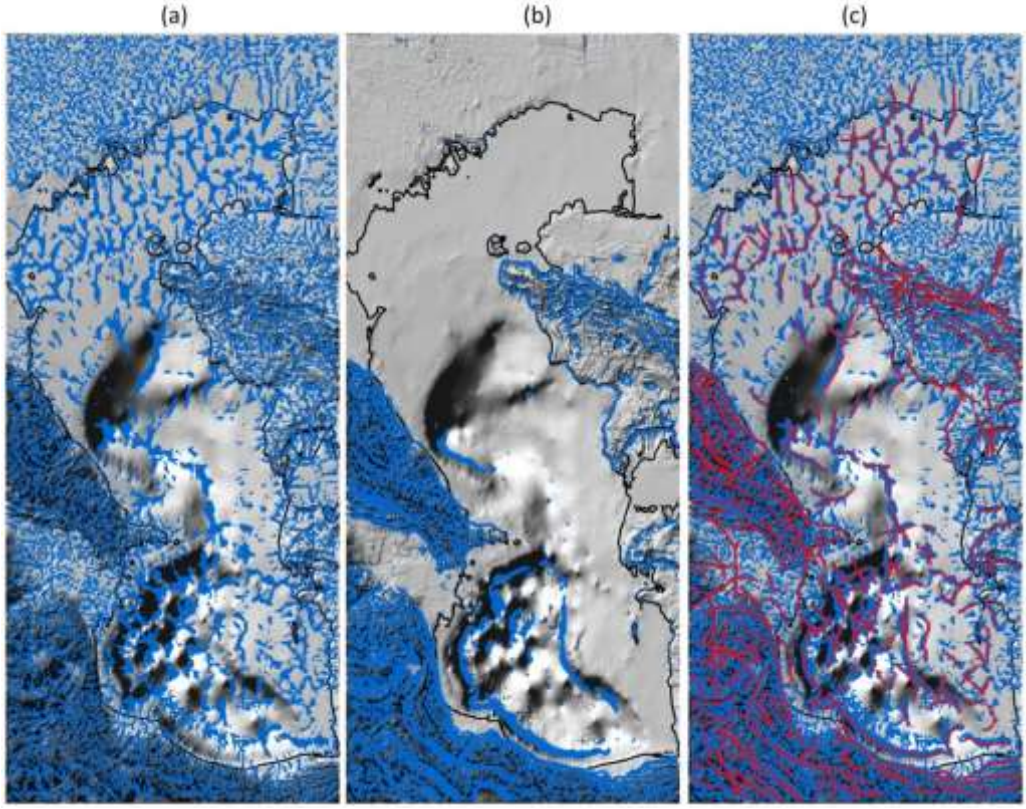


Fig. 3: *Lineament selection based on maps of keel shapes of the curvature of the Caspian Sea bottom relief. The keel shapes are shown on shadow maps plotted in the Mercator projection. a) keel shapes on the map of the planned curvature of the relief; b) keel shapes on the profile curvature map of the relief; c) highlighted lineaments according to keel shapes on the map of the general curvature of the relief*

At the same time, both crustal and mantle earthquakes with foci at depths from 100-150 to 200 km were observed in the latter group. Fig. 1 and 4 show that earthquake epicenters are concentrated mainly along two linear structures: the well–known deep structure – the Absheron threshold and the proposed structure - the deep West Caspian Fault (WCF).

Hypocenters of mantle earthquakes at depths up to 100 km are concentrated at distances up to 170 km from the conventional line of the Absheron threshold and northwest of Makhachkala.

Taking into account the data obtained using bottom seismological observations, it turned out that the area of mantle earthquake propagation is clearly divided into the western (Caucasian) and eastern (Caspian) sectors, separated by the West Caspian system of sub-meridional faults. These faults are characterized by large (several kilometers) vertical displacements with the eastern wing lowered, as well as right-thrust displacements. In the western sector, the continental lithosphere of the Transcaucasian massif is shifting under the folded belt of the Greater Caucasus.

In the eastern sector the dominant process is, apparently, the displacement of the lithosphere of the South Caspian basin under the southern margin of the Scythian platform. The West Caspian fault controls the location of the foci of several deep earthquakes. The fault zone is subvertical or slightly inclined to the west, which excludes the previously assumed displacement of the Caspian structures under the Caucasus [22]. In the process of subduction of the South Caspian lithosphere, the West Caspian fault plays the role of a transform fault.

According to bottom seismological observations, mantle earthquake foci are completely absent in the Western Sector. All of them are located to the east of the WCF.

In the process of the data analysis a spatial comparison of the position of the selected lineaments (faults) with the profiles of the CSP was carried out. This aggregation has shown that the lineaments (faults) identified by us on the CSP profiles are displayed as anomalies of the wave

field, which correspond to disturbances in the fine structure of precipitation. As an example, Fig. 5 shows four temporary sections of the CSP (position in Fig. 1 and 4) located exactly above the fault.

Fig. 4-1 and 4-2 clearly show the undulating anomalies extending to the surface of the bottom in the upper part of the section. In Fig. 4-1, in the enlarged fragment, along with the "creep" type formations identified and described earlier in [35], small-amplitude discontinuous disturbances are visible above. It is also worth noting the seismic and acoustic anomalies of the "bright spot" type, which most often correspond to local manifestations of gas saturation. Fig. 4-2 clearly shows the sediment column, penetrated by thin signal attenuation zones, which are localized in the local undulation of the bottom relief. The enlarged fragment shows small discontinuities directly below the bottom surface.

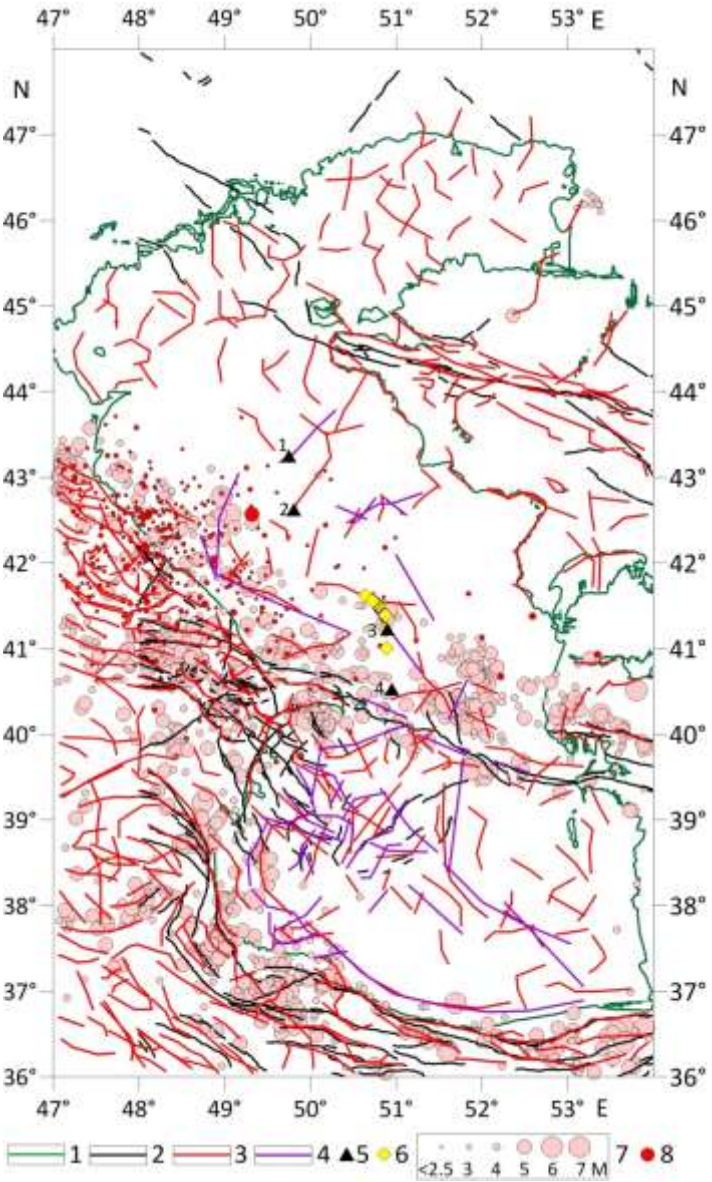


Fig. 4: *Summary diagram of the distribution of lineaments, earthquake epicenters, and active fault zones identified by DRM. 1) the coastline; 2) active fault zones according to GIN RAS data; 3) lineaments identified by analyzing the curvature of the relief; 4) lineaments identified by shadow relief analysis; 5) fault detection points according to CSP data; 6) "pipes"; 7) Earthquake epicenters according to the USGS catalog; 8) epicenters of earthquakes recorded by bottom stations of IO RAS in 2004 – 2006*

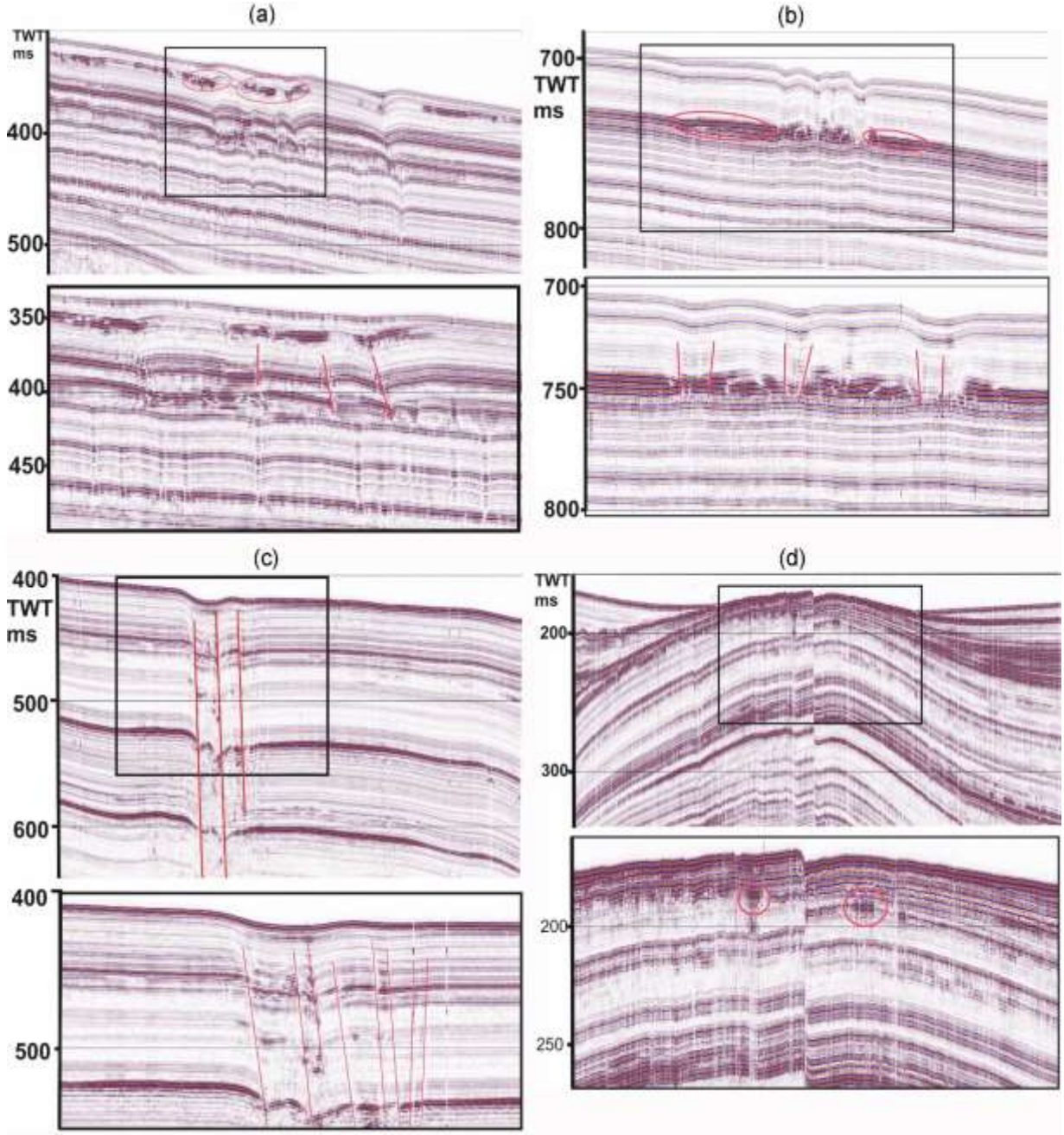


Fig. 5: *Sections of NPS intersecting faults at the points shown in Fig. 4 by triangles. The bottom of the figures shows an enlarged framed section fragment. a) An incision crossing the fault at point 1; b) An incision crossing the fault at point 2; c) An incision crossing the fault at point 3; d) An incision crossing the fault at point 4.*

It should be noted that the sections intersected by the highlighted lineaments shown in Fig. 4-1 and 4-2 are located in the northern part of the Derbent basin near the Tsentralnaya oil and gas structure. In general, the wave pattern is similar to them: parallel stratified strata, which becomes wavy closer to the bottom surface, and wave anomalies are expressed by local small breaks in reflective boundaries and bright spots.

Further south, the wave pattern changes. Wave anomalies and faults become more pronounced and permeate the entire observed precipitation column. Thus, in Fig. 4-3, several subvertical faults with a relatively large amplitude offset and associated wave field anomalies such as "bright spot" and "chaotic recording" are observed. This characteristic pattern corresponds to the "growing" gas pipe identified earlier in the area [9]. The subvertical "Tube" reaches the bottom surface and is clearly marked by a local decrease in relief. Further south, on the Absheron threshold, a vertical fault with

an amplitude of 30 meters is "cut" by the profile of the CSP (Fig. 5-4). The fault is pronounced in the bottom relief and in the entire thickness of the visible sediments and extends beyond the record. The enlarged fragment shows vertical signal attenuation anomalies, which are associated with small areas of the "bright spot" type.

IV. Conclusion

In this paper, using the example of the Caspian region, the use of geomorphometric methods to identify lineaments of a regional scale is demonstrated, in which the bottom DEM (bathymetric model) is used as the initial data. The results of the study showed the effectiveness of using methods of shadow analysis and the allocation of keel shapes by calculating the curvature of the relief to identify large lineaments. The combined use of the results of geomorphometric analysis with data on the distribution of earthquake epicenters makes it possible to identify active fault zones and may prove very promising in assessing seismic hazards on the shelf to identify areas of possible earthquake foci (PES zones).

There are still issues to be resolved: verification of the selected lineaments for compliance with active faults in aseismic areas, determination of the block-hierarchical structure of the studied areas, and determination of the magnitude of block displacement.

The prospects for the development of methods for detecting lineaments based on the DRM of the bottom should be considered to combine with the selection of lineaments based on magnetic and gravitational field anomalies; experiments in the selection of filtration methods and geomorphometric analysis to select the optimal complex.

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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LEGAL REGULATION OF INVESTMENT IN SUSTAINABLE DEVELOPMENT: PROSPECTS AND RISKS IN THE ARCTIC

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Abstract

The Arctic region, characterized by its vast natural resources and strategic importance, has become a focal point for global investments in energy, mining, and infrastructure. This article examines the legal frameworks governing investments in the Arctic, encompassing international treaties, national legislation, and emerging regulatory challenges. Key issues include environmental protection, indigenous rights, and geopolitical tensions. Drawing on case studies from Russia, the United States, and Canada, the analysis highlights the balance between economic development and sustainability. The findings underscore the need for harmonized international standards to mitigate risks and promote equitable investment practices.

Keywords: Arctic investments, legal regulation, international law, environmental protection, indigenous rights, UNCLOS

I. Introduction

The Arctic, encompassing territories of eight Arctic states (Russia, the United States, Canada, Denmark, Norway, Finland, Sweden, and Iceland) and indigenous communities, is undergoing rapid transformation due to climate change and technological advancements. Melting ice caps have opened new opportunities for resource extraction, shipping routes, and tourism, attracting significant investments. However, these activities pose substantial environmental, social, and geopolitical risks, necessitating robust legal regulation.

This article explores the multifaceted legal landscape of Arctic investments, focusing on international and national frameworks. It addresses the interplay between economic interests and protective measures, with a particular emphasis on sustainability and equity. The discussion is structured into sections covering international legal instruments, national regulations, challenges, and future prospects [15].

II. International Legal Frameworks

International law provides the foundational layer for Arctic investments, emphasizing cooperation and environmental stewardship.

United Nations Convention on the Law of the Sea (UNCLOS)

UNCLOS (1982) is pivotal, regulating maritime boundaries, resource exploitation, and environmental protection in the Arctic Ocean. It establishes exclusive economic zones (EEZs) up to

200 nautical miles from coastlines, allowing states to exploit seabed resources. For investments in offshore oil and gas, Article 76 defines continental shelf limits, enabling claims beyond 200 miles if geological evidence supports them [27].

Russia's 2001 submission to the United Nations Commission on the Limits of the Continental Shelf (CLCS) exemplifies this, claiming extended rights over the Arctic seabed. Investments in such areas must comply with UNCLOS's provisions on environmental impact assessments and technology transfer.

The Arctic Council and Related Agreements

The Arctic Council, established in 1996, promotes sustainable development and environmental protection among Arctic states and indigenous peoples. While not legally binding, its agreements influence investments. For instance, the 2013 Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic enhances safety for investment-related activities like shipping and tourism [1].

The Paris Agreement (2015) under the UNFCCC indirectly affects Arctic investments by mandating reductions in greenhouse gas emissions, impacting fossil fuel projects [2].

Other International Instruments

Bilateral agreements, such as the 2010 Norway-Russia Maritime Delimitation Treaty, resolve boundary disputes to facilitate investments. Multilateral efforts, including the International Maritime Organization's (IMO) Polar Code (2017), set standards for shipping in polar waters, crucial for infrastructure investments [18].

III. National Legal Regulations

Arctic states have developed domestic laws to regulate investments, often aligning with international norms while addressing national priorities [16].

Russia

Russia's Arctic Zone of the Russian Federation, defined by Presidential Decree No. 296 (2017), covers 40% of the country's territory and hosts major energy investments. The Federal Law on the Continental Shelf (1995) governs hydrocarbon exploration, requiring licenses and environmental assessments. Investments in the Yamal LNG project demonstrate compliance, with state oversight ensuring revenue sharing and indigenous consultation [13].

The Russian Federation's legal framework for investments in the Arctic is a blend of federal laws, presidential decrees, and international commitments, designed to promote economic development while addressing environmental, social, and geopolitical concerns. As one of the largest Arctic stakeholders, Russia has extensive territories in the region, including the Yamal Peninsula, Chukchi Sea, and Severnaya Zemlya, which are rich in hydrocarbons, minerals, and shipping potential. The legislation emphasizes state control, resource exploitation, and sustainability, often prioritizing national interests. Below, I analyze key pieces of legislation, drawing from the context of the original article on "Legal Regulation of Investments in the Arctic." This analysis highlights their provisions, implementation, strengths, weaknesses, and implications for investors.

1. Federal Law No. 187-FZ "On the Continental Shelf of the Russian Federation" (1995, with Amendments)

This law regulates the exploration, development, and exploitation of natural resources on Russia's continental shelf, including Arctic seabed areas beyond the 200-nautical-mile exclusive economic zone (EEZ). It establishes the legal basis for issuing licenses for hydrocarbon extraction, requiring state approval from the Ministry of Natural Resources and Environment. Provisions mandate environmental impact assessments (EIAs), safety standards, and revenue sharing (e.g.,

royalties and taxes). The law aligns with UNCLOS, allowing Russia to claim extended shelf rights, as in its 2001 CLCS submission [25].

It facilitates investments by providing a clear licensing regime, exemplified by projects like Yamal LNG, where Gazprom received permits after rigorous assessments. Strengths include strong state oversight, ensuring revenue generation (e.g., via the Federal Budget) and technology transfer requirements. However, weaknesses lie in enforcement gaps, as seen in the 2020 Norilsk oil spill, where inadequate compliance led to massive fines and prosecutions [3]. The law's emphasis on economic benefits often overshadows environmental protections, prompting criticisms from international bodies like the Arctic Council for insufficient indigenous consultation. Investors benefit from predictability but must navigate bureaucratic hurdles and liability risks, with amendments in 2018 enhancing digital reporting to improve transparency.

2. Presidential Decree No. 296 "On Determining the Arctic Zone of the Russian Federation" (2017)

This decree defines the Arctic Zone as encompassing 40% of Russia's territory, including Murmansk Oblast, Yamalo-Nenets Autonomous Okrug, and parts of Krasnoyarsk Krai. It designates special economic status for the zone, with incentives like tax breaks, infrastructure subsidies, and priority for state-funded projects in energy, mining, and transportation. The decree also mandates integrated development plans, requiring coordination among federal ministries to balance resource extraction with ecological preservation.

It serves as a strategic tool for attracting investments, reducing red tape for qualifying projects (e.g., via the "Arctic Development" program). Strengths include fostering mega-projects like the Northern Sea Route, boosting GDP through exports. However, it has been criticized for uneven enforcement, with environmental NGOs arguing it prioritizes industrialization over climate resilience, exacerbating permafrost thaw and biodiversity loss. Geopolitical tensions, such as U.S. sanctions post-2022, complicate foreign investments, forcing reliance on domestic or allied partners (e.g., China). For investors, it offers lucrative opportunities but demands compliance with sustainability criteria, as non-compliance can lead to project cancellations, as hinted in the article's discussion of state oversight [8].

3. Federal Law No. 473-FZ "On Territories of Advanced Socio-Economic Development in the Russian Federation" (2014, with Amendments)

This law creates "advanced development territories" (ADT) with favorable tax regimes, simplified customs, and infrastructure support. In the Arctic, ADTs like the "Arctic" ADT (established 2016) target regions such as Arkhangelsk and Nenets Autonomous Okrug, promoting investments in mining, LNG, and logistics. Residents include special economic zones with reduced corporate income tax (down to 5-12.5%) and exemptions from property taxes for up to 10 years.

It accelerates economic growth by de-risking investments through guarantees and subsidies, as seen in the Kolskaya ADT for nickel mining. Strengths include job creation and export diversification, aligning with Russia's Arctic Strategy 2020. Weaknesses include limited environmental safeguards, leading to conflicts with indigenous rights (e.g., Nenets reindeer herders affected by infrastructure). Amendments in 2020 expanded ADT eligibility, but critics note it exacerbates inequality, with benefits skewed toward large corporations like Rosneft. Investors gain fiscal advantages but face reputational risks from environmental incidents, necessitating stakeholder engagement to mitigate legal challenges under international standards like UNDRIP.

4. Federal Law No. 7-FZ "On Environmental Protection" (2002, with Amendments) and Related Norms

This overarching law sets standards for EIAs, pollution control, and biodiversity conservation in the Arctic. It requires permits for resource activities, with penalties for violations, and integrates with the 2017 decree for zone-specific plans. Indigenous protections are addressed via consultations,

though not always mandated.

It provides a framework for sustainable investments, mandating EIAs for projects like oil drilling. Strengths include alignment with UNCLOS and the Paris Agreement, promoting cleaner technologies. However, enforcement is inconsistent, as evidenced by the Norilsk case, where fines were imposed but systemic issues persist. Amendments post-2020 emphasize digital monitoring, but geopolitical isolation limits international cooperation. For investors, compliance is crucial to avoid shutdowns, highlighting the need for proactive environmental strategies to balance profitability with regulatory demands.

Russian legislation on Arctic investments is highly centralized, prioritizing state-led development and resource sovereignty, which has enabled projects contributing billions to the economy (e.g., Arctic oil/gas accounting for 10-15% of exports) [24]. However, it faces challenges like inadequate indigenous inclusion, environmental vulnerabilities exacerbated by climate change, and external pressures (e.g., sanctions hindering technology imports). Compared to Western counterparts, Russia's approach is more permissive economically but less stringent on social equity, leading to tensions with international norms. Investors must conduct thorough due diligence, engage in public consultations, and leverage incentives while preparing for evolving laws, such as potential stricter EU-style regulations if Russia seeks deeper global integration. This framework underscores the article's theme of balancing development with sustainability, urging harmonization for long-term viability [14].

United States

The United States' legal framework for investments in the Arctic primarily focuses on Alaska, which encompasses about 60% of the U.S. Arctic region, including the North Slope, Bering Sea, and Beaufort Sea. This legislation balances economic development, particularly in oil, gas, and mining, with stringent environmental protections, indigenous rights, and national security. Rooted in federal statutes, it emphasizes transparency, public participation, and sustainability, often aligning with international agreements like UNCLOS and the Arctic Council's guidelines. Below, I analyze key pieces of legislation, highlighting their provisions, implementation, strengths, weaknesses, and implications for investors, drawing parallels to the original article on "Legal Regulation of Investments in the Arctic."

1. Outer Continental Shelf Lands Act (OCSLA, 1953, with Amendments)

This law governs the exploration, development, and leasing of offshore resources on the U.S. continental shelf, including Arctic waters like the Chukchi and Beaufort Seas. Administered by the Bureau of Ocean Energy Management (BOEM), it requires competitive leasing auctions, environmental assessments, and royalty payments (e.g., 12.5-18.75% for oil/gas). Amendments like the 2015–2017 updates mandate Arctic-specific plans, including oil spill response and climate impact evaluations.

It enables investments by providing a structured leasing system, as seen in Shell's 2012 Chukchi Sea lease (later withdrawn due to court challenges). Strengths include robust revenue generation (e.g., billions in federal funds) and technological innovation requirements. However, weaknesses include lengthy permitting processes and vulnerability to litigation, as in the 2015 ExxonMobil case where courts blocked drilling over inadequate NEPA reviews. Environmental NGOs often challenge it for insufficient protections against spills in fragile ecosystems. Investors benefit from predictability but must invest heavily in compliance and risk delays from appeals, underscoring the article's emphasis on balancing economic and ecological interests [17].

2. National Environmental Policy Act (NEPA, 1969, with Amendments)

NEPA mandates environmental impact statements (EIS) for major federal actions affecting the environment, including Arctic investments like pipelines or mines. It requires public scoping, alternatives analysis, and mitigation plans, with oversight by agencies like the Environmental

Protection Agency (EPA). In the Arctic, it integrates with OCSLA for projects in Alaska's North Slope.

This law promotes sustainable investments by enforcing comprehensive reviews, exemplified by the 2019 Willow Project EIS for ConocoPhillips' oil development. Strengths include public transparency and indigenous consultation, reducing conflicts with communities like the Inupiat. Weaknesses lie in bureaucratic delays and high litigation costs, as seen in numerous court rulings halting projects (e.g., Pebble Mine in 2020). Critics argue it can stifle innovation, while proponents highlight its role in preventing disasters like the 1989 Exxon Valdez spill. For investors, NEPA demands early stakeholder engagement and robust data, mitigating legal risks but increasing upfront costs, aligning with the article's discussion of regulatory hurdles.

3. Alaska National Interest Lands Conservation Act (ANILCA, 1980)

ANILCA designates vast Alaskan lands, including Arctic areas like the Arctic National Wildlife Refuge (ANWR), as protected wilderness or wildlife refuges. It allows limited resource development (e.g., oil leasing in ANWR's 1002 Area) but prioritizes conservation, subsistence rights for indigenous peoples, and ecological integrity. It includes provisions for co-management with Native corporations under the Alaska Native Claims Settlement Act (ANCSA, 1971).

It facilitates investments in designated zones while safeguarding biodiversity, as in the 2017 ANWR leasing program generating $900 million. Strengths include balancing development with indigenous rights, fostering partnerships like those with the North Slope Borough. However, weaknesses include restrictive land use, leading to ongoing debates over ANWR expansion (e.g., 2020 proposals). Environmental groups view it as insufficient against climate threats, while industry sees it as overly burdensome. Investors must navigate co-management agreements, ensuring benefit-sharing to avoid disputes, which reflects the article's theme of integrating social equity into investment frameworks.

4. Marine Mammal Protection Act (MMPA, 1972, with Amendments) and Related Norms

This law prohibits the "taking" (harassing, hunting, or killing) of marine mammals, with exemptions for subsistence by indigenous groups and incidental takes from commercial activities. In the Arctic, it applies to species like bowhead whales and polar bears, requiring permits from the National Marine Fisheries Service for oil/gas operations [23].

It supports sustainable investments by protecting wildlife, as in mitigation plans for Sakhalin Energy's Bering Sea projects. Strengths include ecosystem preservation and indigenous inclusion. Weaknesses include permit denials or restrictions, impacting operations (e.g., seismic surveys limited to avoid whale disruptions). Amendments in 2016 enhanced protections, but enforcement varies, with occasional violations leading to fines. For investors, compliance involves monitoring and adaptive technologies, highlighting the need for environmental stewardship to secure long-term permits.

U.S. legislation on Arctic investments emphasizes environmental accountability and stakeholder rights, enabling sectors like energy to contribute to national GDP (e.g., Alaska's oil production). However, it faces challenges such as permitting backlogs, climate change accelerating ecosystem degradation, and geopolitical tensions (e.g., Russia-China partnerships). Compared to Russia's more state-centric approach, the U.S. system is decentralized and litigation-prone, promoting innovation but deterring some investors due to costs. To succeed, investors should prioritize partnerships with indigenous groups, invest in green technologies, and anticipate evolving regulations like those under the Biden administration's climate agenda [6].

Canada

1. Canada Petroleum Resources Act (CPRA, 1985, with Amendments)

This federal law governs the exploration, development, and production of petroleum resources on Canada's frontier lands, including Arctic offshore areas like the Beaufort Sea and Baffin Bay.

Administered by Natural Resources Canada, it requires work commitments, environmental assessments, and royalty payments (e.g., 5-30% depending on profitability). Amendments in 2015 introduced stricter safety and spill response standards, including bans on Arctic drilling in certain seasons.

It enables investments by providing a licensing regime, as seen in projects like the Hecla-Kilgok oil field in Nunavut. Strengths include revenue sharing with Indigenous groups and technological mandates for safer operations. However, weaknesses include high regulatory burdens and vulnerability to moratoriums, such as the 2016 federal ban on Arctic offshore drilling, which halted operations and led to legal challenges. Environmental concerns, like oil spills in sensitive ecosystems, have prompted delays. Investors benefit from predictability in permitted zones but must navigate Indigenous consultations and risk cancellations, reflecting the article's focus on balancing economic gains with ecological risks.

2. Impact Assessment Act (IAA, 2019)

Replacing the Canadian Environmental Assessment Act (CEAA 2012), this law mandates comprehensive impact assessments for projects affecting the environment or Indigenous rights, including Arctic mining, pipelines, and shipping routes. It requires public hearings, Indigenous participation, and mitigation plans, with oversight by the Impact Assessment Agency of Canada. In the Arctic, it applies to projects like the Mary River iron ore mine in Baffin Island [4].

It promotes sustainable investments through rigorous reviews, exemplified by the 2021 assessment of the Nunavut Hydro project. Strengths include strong Indigenous engagement, reducing conflicts and ensuring cultural preservation. Weaknesses lie in lengthy timelines (often 2-5 years) and appeals, as seen in the 2019 rejection of the Trans Mountain Pipeline expansion due to inadequate Indigenous consultations [26].Critics argue it can discourage foreign investment, while proponents highlight its role in preventing disasters. For investors, early stakeholder involvement is essential to avoid litigation, aligning with the article's emphasis on transparency and public participation [7].

3. Nunavut Land Claims Agreement (NLCA, 1993) and Related Indigenous Rights Frameworks

This agreement, part of the broader Inuit land claims process, grants Nunavut Inuit ownership of 350,000 km² of land and subsurface rights, with co-management of resources. It includes provisions for benefit-sharing from developments like mining and energy projects, requiring environmental and social impact assessments. Similar frameworks exist in Yukon (Umbrella Final Agreement, 1993) and the Northwest Territories (various treaties) [5].

It facilitates investments by providing clear land tenure, as in the Baffinland Iron Mines project, where Inuit partnerships ensured community benefits. Strengths include fostering reconciliation and equitable development, with royalties funding local economies. However, weaknesses include overlapping jurisdictions causing delays and disputes, such as those in the 2020s over diamond mines in the Northwest Territories. Indigenous groups have successfully challenged projects for insufficient benefits, leading to project modifications. Investors must form partnerships with Inuit organizations to secure approvals, underscoring the article's theme of integrating social equity into investment strategies.

4. Arctic Waters Pollution Prevention Act (AWPPA, 1970, with Amendments)

This law regulates pollution in Arctic waters within 100 nautical miles of Canada's coast, requiring permits for discharges from ships, drilling rigs, and mining operations. It sets strict standards for oil spills, toxic substances, and shipping, with enforcement by the Canadian Coast Guard. Amendments in 2017 expanded protections for vulnerable ecosystems like the Lancaster Sound [20].

It supports environmentally responsible investments, as in the mandatory oil spill contingency plans for Arctic projects. Strengths include proactive pollution control and alignment with

international norms, reducing ecological risks. Weaknesses include enforcement challenges in remote areas and conflicts with shipping interests, exemplified by debates over the Northwest Passage. Climate change has heightened vulnerabilities, prompting stricter rules. For investors, compliance involves advanced monitoring technologies, but it can increase costs, highlighting the need for sustainable practices to mitigate legal and reputational risks [21].

Canadian legislation on Arctic investments prioritizes Indigenous rights and environmental protection, enabling sectors like mining and energy to drive economic growth (e.g., Nunavut's GDP boosted by resource exports). However, challenges include regulatory complexity, reconciliation with Indigenous groups, and climate impacts accelerating permafrost degradation. Compared to Russia's state-led model or the U.S.'s litigation-heavy system, Canada's collaborative approach fosters inclusivity but can lead to slower approvals. Investors should prioritize Indigenous partnerships, invest in clean technologies, and anticipate evolving laws under initiatives like the 2022 Arctic and Northern Policy Framework. Other Arctic States

Norway's Petroleum Act (1996) and Denmark's Greenland policies focus on sustainable mining, with Greenland Home Rule allowing for foreign investments in rare earth minerals (Government of Norway, 1996). Finland, Sweden, and Iceland prioritize tourism and research, with regulations under EU frameworks where applicable [12].

IV. Challenges and Emerging Issues

Despite regulatory frameworks, several challenges impede effective investment regulation:

Environmental Risks: Investments in oil and gas threaten fragile ecosystems. The 2020 Norilsk oil spill in Russia highlighted enforcement gaps, prompting calls for stricter liability under UNCLOS [3].

Indigenous Rights: The United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP, 2007) requires free, prior, and informed consent for projects affecting indigenous lands. Disputes in Canada's Nunavut illustrate tensions between economic gains and cultural preservation [27].

Geopolitical Tensions: Sanctions against Russia (e.g., post-2022 Ukraine invasion) restrict Western investments, while China's Belt and Road Initiative introduces new players, complicating sovereignty [8].

Climate Change Adaptation: Rising sea levels and permafrost thaw necessitate adaptive regulations, such as mandatory carbon offset programs.

Arctic Sunrise Case (Netherlands v. Russia, 2013–2016)

In September 2013, Russian authorities seized the Greenpeace ship Arctic Sunrise and arrested its crew after they protested against Shell's oil drilling operations in the Pechora Sea, part of Russia's Arctic zone. The activists boarded an oil platform to highlight environmental risks.

This case involved the application of UNCLOS Article 87 (freedom of navigation) and the International Convention for the Safety of Life at Sea (SOLAS). Russia claimed the protest violated its sovereignty, while the Netherlands (as the ship's flag state) argued it was a peaceful environmental action.

The International Tribunal for the Law of the Sea (ITLOS) ordered Russia to release the ship and crew in 2013. A subsequent arbitration under the United Nations Convention on the Law of the Sea (Annex VII) ruled in 2016 that Russia had violated the freedom of navigation. This case underscores the tension between state sovereignty and international environmental activism, influencing regulations for protest activities near Arctic oil rigs and emphasizing the need for investor compliance with maritime laws to avoid legal disputes [30].

Beaufort Sea Maritime Boundary Dispute (Canada v. United States, Ongoing)

This dispute concerns the delimitation of the maritime boundary in the Beaufort Sea, a resource-rich area with potential for oil and gas investments. Canada and the U.S. have overlapping claims to the continental shelf beyond 200 nautical miles.

Governed by UNCLOS Articles 74 and 76, which require equitable delimitation of EEZs and continental shelves. The case involves submissions to the CLCS and principles of international equity, with environmental assessments under the Arctic Council's guidelines.

Ongoing negotiations and a 1988 agreement on hydrocarbon exploration in the disputed zone have allowed joint management. A potential adjudication could clarify boundaries, impacting investments like those in Alaska's North Slope. It highlights the role of bilateral cooperation in resolving sovereignty issues to de-risk investments [29].

Hans Island Sovereignty Dispute (Canada v. Denmark, Resolved 2022)

Hans Island, located in the Kennedy Channel between Greenland (Denmark) and Ellesmere Island (Canada), has been a flashpoint for territorial claims since the 1970s, with symbolic "occupations" by both sides. The dispute affects shipping routes and potential resource investments.

Based on international law principles of uti possidetis (respect for historical boundaries) and UNCLOS for maritime zones. Indigenous perspectives from Inuit communities were considered in negotiations [19].

In June 2022, Canada and Denmark agreed to divide Hans Island along the meridian, granting equal access. This resolution facilitates Arctic investments, such as in tourism and mining, by reducing geopolitical uncertainties and promoting transboundary cooperation.

ExxonMobil v. Environmental Groups (U.S. Courts, 2015–Ongoing)

In 2015, U.S. federal courts blocked Shell's Arctic drilling plans in the Chukchi Sea off Alaska due to environmental concerns raised by groups like the Center for Biological Diversity. The case challenged the adequacy of environmental impact statements under the National Environmental Policy Act (NEPA).

NEPA requires comprehensive assessments for federal permits, aligning with UNCLOS's environmental provisions. Indigenous rights under the Alaska Native Claims Settlement Act (ANCA, 1971) were invoked regarding impacts on subsistence hunting.

Courts ruled that the Bureau of Ocean Energy Management (BOEM) failed to adequately assess risks like oil spills. Shell abandoned its Arctic drilling program in 2015. This precedent strengthens environmental scrutiny for investments, requiring investors to incorporate climate change and indigenous consultations, influencing global standards for Arctic resource projects.

Norilsk Nickel Oil Spill Litigation (Russia, 2020–Ongoing)

In May 2020, a fuel tank at Norilsk Nickel’s power plant ruptured, releasing over 21,000 tons of diesel into the Arctic tundra and rivers, devastating ecosystems and affecting indigenous communities.

Russian environmental law (Federal Law on Environmental Protection, 2002) and UNCLOS were invoked for liability. The case involved corporate negligence and inadequate spill response, with parallels to international treaties like the London Convention on marine pollution.

Norilsk Nickel faced fines exceeding $2 billion, and executives were prosecuted. The incident led to stricter Russian regulations on Arctic infrastructure. It serves as a cautionary example for investors, emphasizing the need for robust liability frameworks and emergency preparedness to mitigate reputational and financial risks.

Indigenous Land Claims: Nunavut Tunngavik Inc. v. Canada (Canadian Courts, 2010s)

This series of cases stems from the Nunavut Land Claims Agreement (NLCA, 1993), where Inuit organizations challenged federal decisions on resource development, such as mining projects, for failing to provide adequate compensation and consultation [10].

Rooted in Canadian constitutional law (Section 35, recognizing indigenous rights) and

UNDRIP. Cases address "duty to consult" and benefit-sharing in investments affecting traditional lands [9].

Courts have upheld Inuit rights, mandating renegotiations for projects like the Mary River iron ore mine. These rulings promote equitable investments, requiring investors to engage indigenous stakeholders early, reducing litigation risks and fostering sustainable development [11].

V. Conclusion

The legal regulation of investments in the Arctic navigates a complex terrain of international cooperation, national sovereignty, and sustainability imperatives. While frameworks like UNCLOS and national laws provide structure, gaps in enforcement and harmonization persist. Future developments should prioritize integrated approaches, incorporating indigenous perspectives and technological innovations for climate-resilient investments [22].

Strengthening the Arctic Council's role and enhancing multilateral agreements could foster equitable growth. Policymakers must balance short-term economic benefits with long-term ecological and social stability to ensure the Arctic's sustainable future.

CONFLICT OF INTEREST.

Author declare that they do not have any conflict of interest.

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ASSESSMENT OF THERMOMECHANICAL BEHAVIOUR OF SOFC EXECUTIVE DESIGN ELEMENTS

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Abstract

The thermo-mechanical analytical model proposed for different solid oxide fuel cell (SOFC) designs addresses the deformation behavior and mechanical stability of SOFCs at various thermal stresses, specifically the creep resistance and the long-term endurance beyond the elastic limit. The model considers the deformation of multi-layer SOFC in the temperature range of 600–800°C and presents the combination of the correlated parameters for SOFC performance evaluation, stability and long-term endurance under realistic operating conditions and temperature gradients. The numerical analysis of the thermo-mechanical properties of the SOFC materials is presented in terms of mechanical behavior at failure conditions and the influence of rheological and structural properties on SOFC long-term endurance. The SOFC thermal behavior, creep parameters of the SOFC materials and long-term stability are analyzed in terms of stresses, deformations and displacements.

Keywords: modelling, materials, performances, operating temperature, design of compatibility, thermal strain stresses

I. Introduction

Conventional energy sources such as gasoline (diesel), coal and hydro source are the main sources for power generation. However, these conventional energy sources are being depleted, and are also unfriendly to the environment. Alternative energy sources such as renewable energy (RE) systems are becoming more popular in power generation applications. RE sources include solar energy, wind energy, photovoltaic (PV) cell energy, fuel cell etc. which are very effective in reducing the green house gas emissions. In the near future, large portions of increase in electrical energy demand will be met through widespread installation of distributed generation (DG). Many advantages are considered for application of DG, i.e., increased service reliability, reduction of the need for grid reinforcement, generation expansion and power factor correction. Furthermore, it is possible to improve voltage regulation and local power quality more precisely using DGs in comparison to conventional centralized generators. DG sources comprise of direct energy conversion sources producing DC voltages or currents such as fuel cells and photovoltaic sources, high-frequency sources such as micro turbines, and variable frequency sources such as wind energy. Power generation from solar energy sources and wind energy sources is unpredictable, because solar power depends on the availability of sun light and wind energy system depends on the wind. Since fuel cells have no geographical limitations, they are preferred for small scale power generation. Power generation in fuel cells depends on the hydrogen input which is available in abundance. Further, fuel cells are known for their low to zero emissions, high efficiency (35-60%) and high reliability because of the absence of moving parts. Fuel cells are static energy conversion

devices that partially convert the chemical energy of fuels directly into electrical energy and produces water as its byproduct.

The successful utilization of materials requires that they satisfy a set of properties. These properties can be classified into thermal, optical, mechanical, physical, chemical, and nuclear, and they are intimately connected to the structure of materials. The structure, in its turn, is the result of synthesis and processing. A schematic framework that explains the complex relationships in the field of the mechanical behavior of materials, shown in Fig. 1, is Thomas's iterative tetrahedron, which contains four principal elements: mechanical properties, characterization, theory, and processing. Interrelationships among structure, properties, and processing methods, the most important theoretical approaches, and the most-used characterization techniques in materials science today.

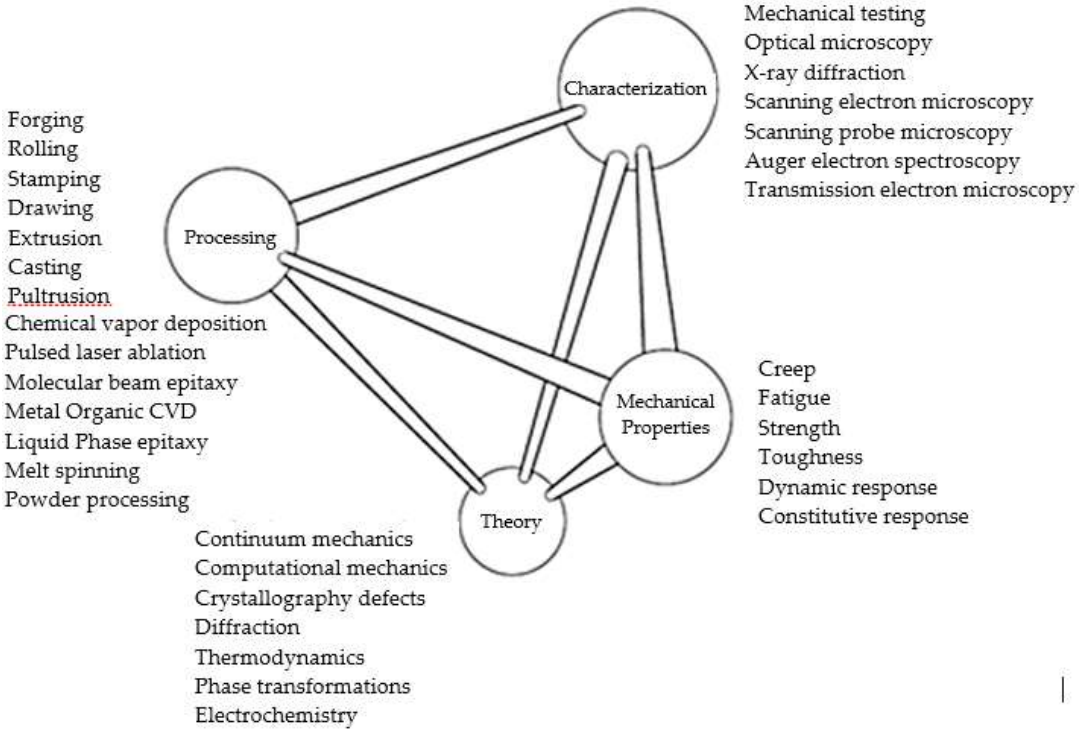


Fig. 1: *Tetrahedron, which contains four principle elements*

This entry will endeavor to answer the question whether SOFC technology is now ready for the market or perhaps put in another way: Is the market ready for SOFC technology and which challenges still need to be addressed?

The entry will describe how SOFC technology can contribute to solving the energy challenges in the future. The current status of the SOFC technology and industry will be briefly discussed and the possible markets described. Three main challenges on the road to competiveness – **life- time, reliability, and cost – are addressed.** Technoeconomic studies of the different market segments are used to define the threshold for market entry. The entry ends by looking ahead and concluding that the SOFC technology is ready for the market with respect to the projected cost and lifetimes, but that reliability under real-life conditions still remains to be demonstrated. The learning investments needed, however, do not appear to be prohibitive considering the benefits which this game - changing technology has to offer.

There are six main types of fuel cell: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), polymer electrolyte membrane fuel cell (PEMFC) and direct methanol fuel cell (DMFC), solid oxide fuel cell (SOFC).

Among different types and scale power generation systems, fuel cells have received more attention, because they can provide also both heat and power.

Advantages of SOFC Fuel Cells are:

- Higher electrical efficiency. The SOFC technology will be able to provide an electrical efficiency of up to 60%. This efficiency is very high compared to worldwide power plants operating at average electric efficiencies of 30–35% and to existing decentralized, smaller power generation equipment (engines and generators) operating at as low as 5–10% for engines and 15–25% for generators. Application of SOFC units with higher electrical efficiency will result in substantial savings in fuel and money, and for operation on fossil fuels also in a proportional reduction in CO_2 emissions.

- High efficiency for all capacities. The SOFC technology is scalable and can cover the complete range from 1 kW to 1 MW, or even higher, with almost no loss of efficiency. The technology offers a very competitive output per weight or volume compared to power plants. Because of this, the SOFC technology addresses a wide range of applications and finds use both in urban and remote areas and both for stationary and mobile purposes.

- Fuel flexibility. The SOFC technology is (together with MCFC) the only technology among the different fuel cell technologies which is able to effectively generate power directly based on the fossil fuels in use today, and at the same time, the technology has a clear path to renewables and CO2-neutral energy systems. This is due to the higher operating temperatures and the superior ability of the SOFC to convert hydrocarbon in the fuel cell stack.

- Lower maintenance cost. The SOFC system provides a highly effective and direct electrochemical conversion of fuel to power. The only rotating parts in the system are a fuel pump and a small air blower. Accordingly, maintenance costs are expected to be substantially lower, and operating periods between overhauls are substantially longer than conventional technologies (see Fig. 2).

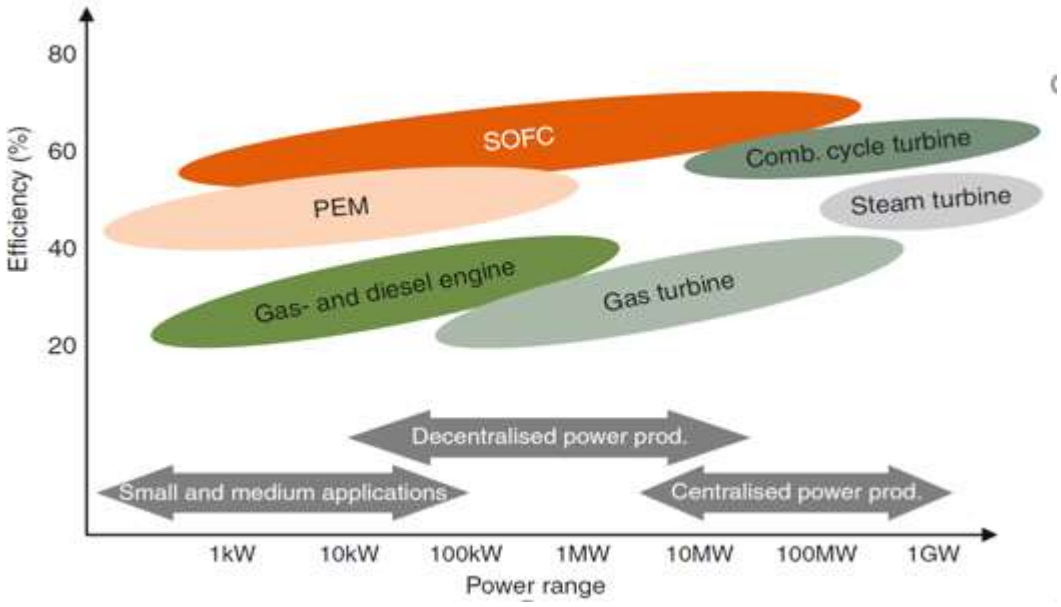


Fig. 2: *SOFC compared with other power production technologies (illustrative figures)*

II. New approach to risk forecasting

The increasing penetration of renewable energy sources (RES) and distributed generation (DG) technologies introduces significant uncertainties related to reliability, lifetime, and structural endurance of energy systems. Traditional risk forecasting methods, which primarily rely on statistical performance data of conventional power plants, are insufficient for technologies such as Solid Oxide Fuel Cells (SOFCs), photovoltaic systems, or wind turbines. These systems operate under highly dynamic loading conditions, where thermal, mechanical, and rheological properties of materials play a decisive role.

The proposed new approach to risk forecasting integrates thermomechanical modeling, rheomechanical behavior analysis, and structural endurance assessment. Unlike conventional reliability analysis, this methodology explicitly accounts for:

- Coupled stress–strain–temperature interactions in multilayer SOFC structures;
- Creep and plastic deformation effects under prolonged operation at elevated temperatures;
- Anisotropy and nonlinearity of material properties**, including imperfections and manufacturing deviations;
- Dynamic operational risks arising from fluctuating loads in renewable energy integration.

By applying the developed energy theory of deformation and incorporating experimental creep-core parameters, the model enables quantitative estimation of critical operational thresholds, such as the onset of plastic deformation, buckling time, and long-term endurance limits. This predictive framework allows for risk-informed design of SOFC systems, providing more accurate forecasts of reliability and lifetime under real operating conditions.

Such a forecasting methodology forms the foundation for technoeconomic risk evaluation, ensuring that decisions on large-scale deployment of SOFCs and other advanced energy technologies consider both their mechanical stability and economic feasibility. Ultimately, this new approach supports the safe and efficient integration of next-generation power generation systems into modern energy infrastructures.

III. Engage experts

Structural strength of materials – a set of mechanical properties that ensure reliable and long-term operation of the material under operating conditions depend on a number of factors (see Fig.3)

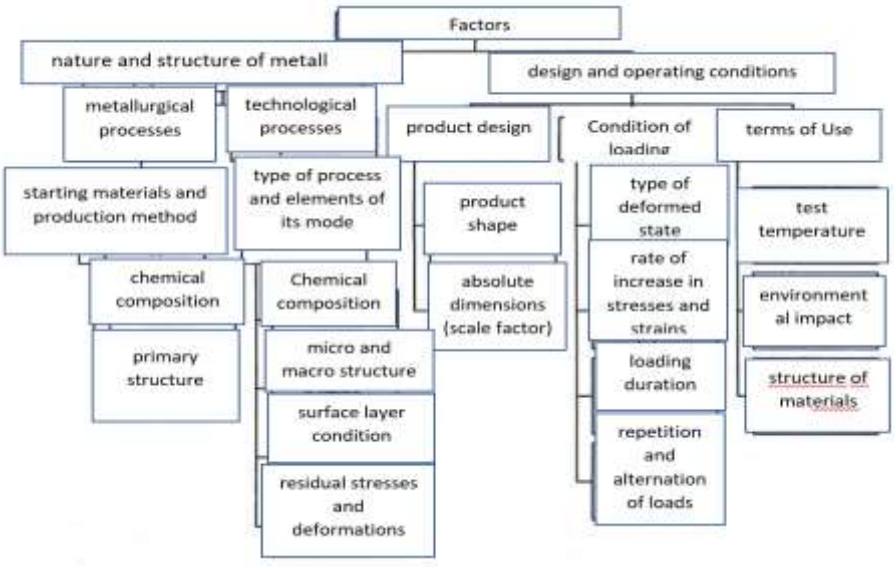


Fig. 3: *Factors define reliable and long-term operation of the material*

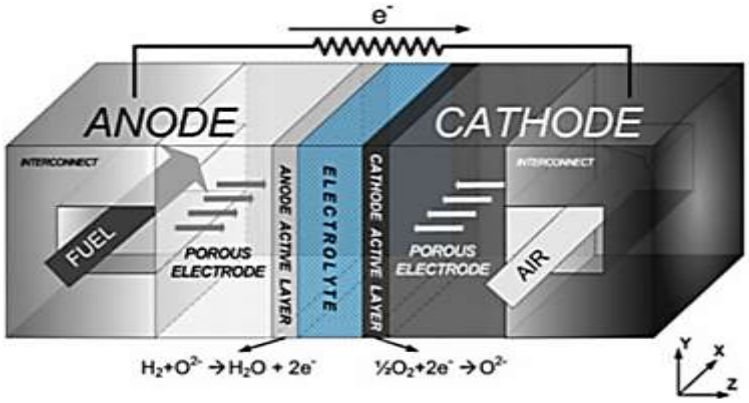


Fig. 4: *Schematic of the basic operation principles of a SOFC (I. Bonis 2012)*

Depending on the location of the loading path to the yield surface, as well as on the radius of the yield surface and the location of its center, different deformation behaviors can occur. This behavior depends on various parameters, the clarification of which will make it possible to determine the degree of correlation between the elastic and plastic parts of the total deformation (see Fig. 5 and 6).

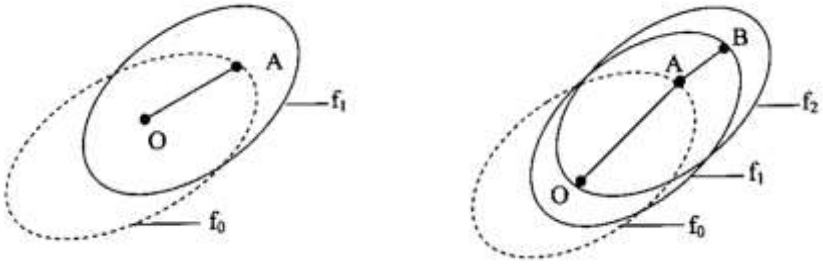


Fig. 5: *Elastic deformation behavior:*
f_1 - yield surface under repeated loading; f_2 - is the limit state yield surface corresponding to destruction;
OAB - trajectory of the path of active loading; Point "O" - a geometric place with zero stresses

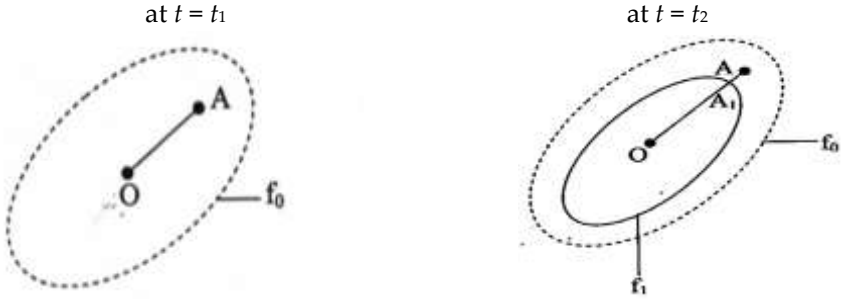


Fig. 6: *Creep deformations ($t_1 < t_2$)*

Therefore, a brief review of recent studies confirms the fact that the simplifications adopted in the preparation of mechanical and theoretical models for the rheomechanical properties of materials and their changes, loading modes and deformation state significantly affect attempts to determine and evaluate SOFC performance and quality indicators, taking into account operational conditions. Therefore, in our opinion, in order to fill this void, it was necessary to develop a theory and an appropriate research methodology that would allow modeling deformation behavior and creating strength conditions for real structures, taking into account real operating conditions.

Such a theory, called energy theory, was developed, which was based on a hypothesis that characterizes both physically and mathematically the deformation processes under repeated loading and has the following content.

The work of the total elastic deformation in the stress space for the case of any static loading in opposite directions is a constant value. Mathematically, this means that: If the point with coordinates "σ_{ij}" in the stress space is on the yield surface, then the point with coordinates - $\sqrt{\frac{\sigma_{1T}^2+\sigma_{2T}^2}{J_1+2(1+V)J_2}-1}\cdot\sigma_{ij}$ is also on the yield surface. Graphic representation of the mathematical value of the proposed theory (see Fig. 7):

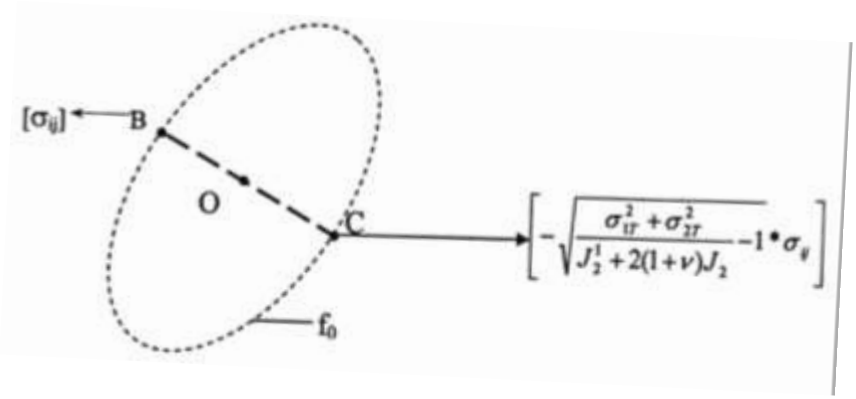


Fig. 7: *Graphical representation of the mathematical significance of the proposed energy theory*

From this, the yield surface equation is obtained in the for

$$\bar{J}_1^2+2(1+\nu)\bar{J}_2=\bar{\sigma}_T^2,$$

where σ_{1T} and σ_{2T} – respectively, the tensile yield strength and compression; J_1 and J_2 - respectively, the first and second invariants of the tensor stresses; σ_{ij} (i, j = 1,3) – stress tensor components; ν – коэффициент Пуассона; $\bar{J}_1$ и $\bar{J}_2$ – respectively, the first and second invariants of the tensor stress differences $\left(\sigma_{ij}-\sigma_{ij}^1\right)$; σ_{ij}^1 – coordinates of the yield surface center; J_1^0 and J_2^0 – respectively, the first and second invariants of the tensor stresses at the end of the active loading path;

$$\bar{\sigma}_T^2=\left(J_1^{02}+2(1+\nu)J_2^0\right)\left(\frac{K_0+1}{2}\right)^2;$$

$$K_0=\sqrt{\frac{\sigma_{1T}^2+\sigma_{2T}^2}{J_1^{02}+2(1+\nu)J_2^0}-1};$$

$$\sigma_{ij}^1=\frac{1-K_0}{2}\sigma_{ij}^0$$

The implementation of these phenomena makes it possible, on the basis of appropriate strength conditions, to evaluate and calculate the bearing capacity of structural elements of the SOFC type, taking into account the structural and rheomechanical properties and changes in their material support under operating conditions, loading modes, deformation anisotropy, geometric nonlinearity (finiteness of deformations during buckling) and etc. for the following deformation states:

- elastic state with stable and changing physical and mechanical properties of materials;
- elastic-plastic state, taking into account changes in the physical and mechanical properties of materials and deformation anisotropy;

- elastic-viscous-plastic state, when changes in the mechanical properties of materials contribute to the occurrence of creep deformation.

A method has been developed for studying the stress-strain state of structural elements, taking into account geometric nonlinearity in the absence (presence) of initial imperfections (manufacturing errors). Here, the subjects of study are the time of onset of plastic deformation, the critical time of onset of buckling, the critical load of buckling, etc. In this case, the rheological properties of materials are characterized by the corresponding model of the creep core and its parameters (to determine them, it is necessary to conduct appropriate experimental studies).

The thermomechanical analytical model is assumed for studying the deformation behavior of SOFC at various operational temperatures, in particular, provide the resistance of creep and long-term endurance outside the elastic limit.

The model takes into account the deformation of the multilayer SOFC in the temperature range of 600-800°C and is a decision on long-term endurance in the process of real operating conditions.

The numerical analysis of thermo physical properties of SOFC materials and their changes, depending on the mechanical behavior their destruction are estimated taking into account the rheological and structural properties of materials for the long-term endurance of SOFC.

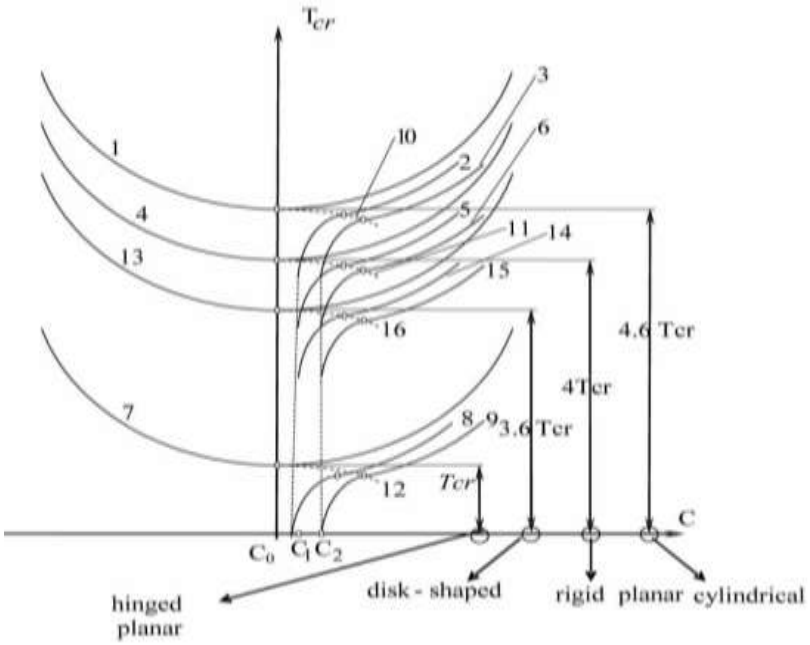


Fig. 8: *Critical temperature (T_{cr}) changes vs. surface irregularity for different SOFT design: C_0, C_1, C_2 – Initial surface irregularities; Tier - critical temperature for rigid planar design; $3.6T_{cr}$ – critical temperature for disc shaped design; $4T_{cr}$ – critical temperature for hinged planar design; $4.6T_{cr}$ – critical temperature for cylindrical design; 1 – SOFC cylindrical design with zero initial surface irregularity C=0; 2 – SOFC cylindrical design with initial surface irregularity C_1; 3 – SOFC cylindrical design with initial surface irregularity C_2; 4 – SOFC rigid planar design at initial surface irregularity C=0; 5 – SOFC rigid planar design at initial surface irregularity C_1; 6 – SOFC rigid planar design at initial surface irregularity C_2; 7 – SOEC hinged planar design at initial surface irregularity C=0; 8 – SOC hinged planar design at initial surface irregularity C_1; 9 – SOFC hinged planar design at initial surface irregularity C2; 13 – SOFC disc shaped design with zero initial surface irregularity C=0; 14 – SOFC disc shaped design with initial surface irregularity C_1; 15 – SOFC disc shaped design with initial surface irregularity C_2; 10, 11, 12, 16 – accordingly, surface irregularity characterizing the decrease of T_{cr} with approaching irregularity*

The results of modeling thermomechanical deformation behavior of SOFC allowed to develop an algorithm for a decision on synthesis of the materials properties and their characteristics outside the elasticity limit, which is significant for long - term operation of SOFC at elevated temperatures.

In the end, a technique has been developed for the synthesis of desired materials taking into account the operating temperature, topology surfaces, form, metric characteristics and thermo-physical properties.

The influence of the surfaces state on the deformation behavior of the device the constructive performance are considered for the irregularities range from C_0 to C_2 ($C_0 < C_2$). These results of poses have to make decisions according to the constructive characteristics and material support of the developed anode substrates - 1 - direction (see Fig. 8).

The application of the form, metric characteristics and material execution of dense elements are considered for various operational temperatures and are presented in the logarithmic coordinates (see Fig. 9).

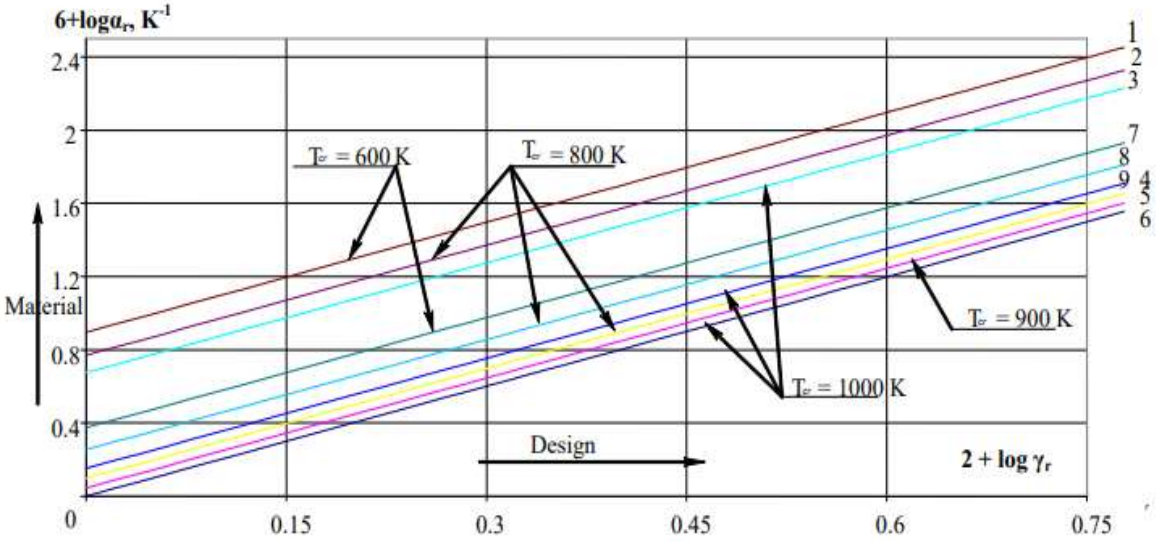


Fig. 9: *Application of shape, metric characteristics and material design of dense elements for different operating temperatures represented in logarithmic coordinates: 1,2,3 – cylindrical; 4,5,6 – planar; 7,8,9 – disk-shaped SOFC designs*

The results obtained allow you to make decisions for the design of devices from dense materials with a different metric characteristic, form of execution and properties of material support. Thus compatible combinations of these indicators for various operating temperatures might be determined.

The third direction of work – to study of porous materials for use in the practice of designing a device as a whole and their elements. This issue has been discussed many times with project partners. With his great support and faith in the possibility of application in the practice of creating devices, the following task has been set and solved:

Development goal – the study of the deformation behavior of porous structure and the determination of an adequate deformation model for this behavior, taking into account mass transfer processes in a dynamic model for planning and effective implementation of various measures aimed at designing devices using of a similar material structure.

Task content:

1. The problem of determining a mathematical model of deformation behavior and studying, on this basis, the stress-strain state of porous structure under quasi-static and dynamic loading is being solved.

2. The presence of mass transfer during loading, etc. the dynamism of porous structure distinguishes and is decisive for choosing their equations of state.

In all models the most commonly used materials were studied to analyze the distribution of thermal stress. The mechanic properties of materials were listed in Table 1 taken from Refs. properties of materials were listed in Table 1 taken from Refs [8, 23]. It should be noted that the material was assumed as linear elastic and isotropic. Fig. 10 showed the anode's coefficient of thermal expansion, which was a function of its porosity [30]. Moreover, the Young's modulus (GPa) and shear modulus (GPa) was a function of porosity, which was the main point all of investigations and could be calculated from the used for that experimentally obtained equations.

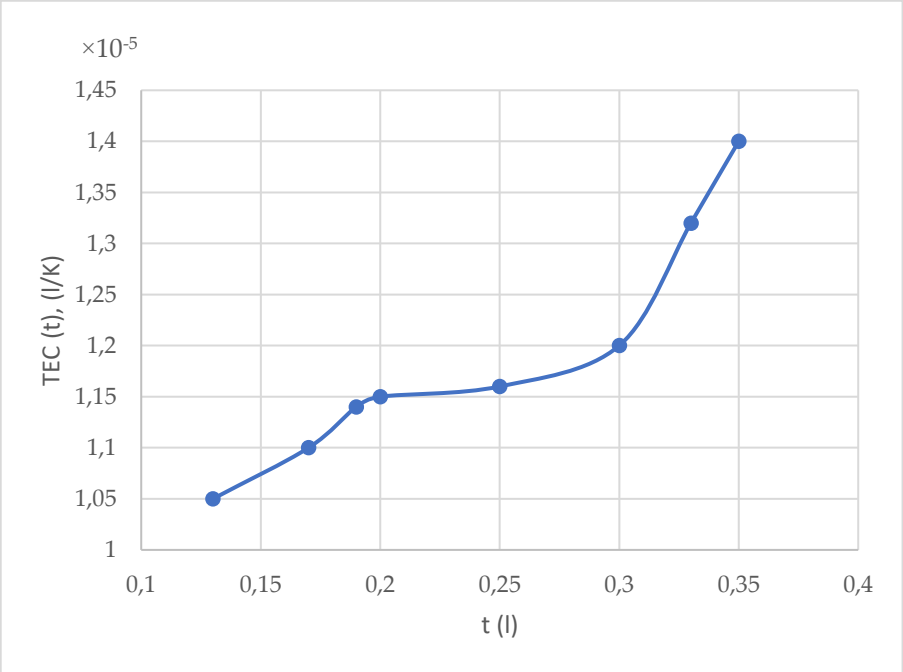


Fig. 10: *The relationship between porosity and TEC*

The thermal strain stress was enhanced when the temperature increased, which resulted in a thermal expansion, which was different for each material (Table 1). The thermal stress was proportional to the coefficient of thermal expansion (a) and the difference of the temperature distribution (T) and the reference temperature (Tref). The reference temperature was the sintered temperature for the cell's materials and it was set as 800 C, i.e., the thermal strain stress only emerged when the temperature was higher than 800 C.

Table 1: *The key stress factors for the modeling SOFC*

Layer	Young's Modulus [GPa]	Poisson's ratio	Coefficiant thermal expantion (CTE), [$10^{-6}K^{-1}$]
Anod	220	0.3	12.5
Cathod	160	0.3	11.4
Electrolyte	205	0.3	10.3
Interconnect	205	0.28	12.3

V. Conclusion

1. A classifier has been compiled of factors that determine the load-bearing capacity and quality indicators of technological machines, and in general their effectiveness, having different material design in terms of structural, physical-mechanical and chemical-thermal properties, causing of vary deformation behavior in structural materials under various operating conditions and loads.
2. Isotropic and kinematic Mises plasticity curing rules are available, is confirming existing of isotropic and kinematic curing linear combination in the process of exploration under operating modes.
3. This allows for the existence of two systems of forces that contribute to changes in both the volume and shape of the structural material and causing mainly plastic deformation behavior.
4. Changing in both the volume and shape of the structural material contribute to changes in the radius, coordinates of the yield surface center, as well as the location of the active loading path in relation to its position.
5. A new method for determining coefficients of statical and dynamical plasticity (SCP and DCP) for various groups of materials is presented.
6. To determine the estimate of plasticity coefficients , the linear law of Hencky-Mises for materials hardening was used and for determining the static and dynamic hardening coefficients corresponding analytical expressions are obtained.
7. The obtained dependences of the plasticity coefficients make it possible to evaluate the properties of the plastic deformation behavior of structural materials individually and in combination with others, which have unequal plastic and structural-mechanical properties i.e. meaning of flat - shaped hybrid structure.
8. An algorithm has been developed for the synthesis of dense structure materials based on zirconium with properties that are compatible combinations with the operating temperature, shape and metric characteristics of devices from these materials.
9. It has been proven that porous structures are characterized by nonlinear elastic behavior under quasi-static loadings developing in time.
10. The equations of state are obtained and a mathematical model of the deformation behavior of porous structures is formulated to study their stress-strain state, taking into account the corresponding loading modes.
11. It has been established that when Hooke's law is used as an equation of state to describe the deformation behavior of porous structures under quasi-static, i.e. loads distributed in time can contribute to 80% distortion of their stress-strain state.
12. The expansion in Taylor series of the original functional dependence was used, which determines the physical and geometric relationships in deformation behavior and, as a result, equations of state were obtained in general form for structure with elastic, elastic-plastic and nonlinear-elastic deformation character rustics.
13. The obtained dependences allow us to investigate various problems of studying the stress-strain state of porous structures under various loadings, determined taking into account the implemented technological measures in the process of generating electricity by fuel cells on an anode substrate.

ACKNOWLEDGMENT

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CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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KINETIC ANALYSIS OF THE THERMAL DEGRADATION OF POLYVINYL CHLORIDE STABILIZED WITH SUNFLOWER OIL-BASED METAL SOAPS

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Abstract

One of the major challenges encountered during the processing of polyvinyl chloride (PVC) is its susceptibility to thermal degradation. Although a variety of thermal stabilizers are currently employed in industry to mitigate this problem, the development of a universal and highly effective stabilizer remains an urgent research priority. In this context, the influence of metal soaps synthesized from sunflower oil on the thermal degradation of PVC was investigated using thermogravimetric analysis (TGA). The degradation kinetics were further evaluated by applying the Coats–Redfern method, based on different kinetic models, as well as the model-free Broido integral method. The TGA results demonstrated that the incorporation of metal soaps effectively delayed the onset of thermal degradation, with decomposition occurring at higher temperatures compared to pure PVC. Specifically, the temperatures corresponding to 5, 10, 20, and 50% mass loss for pure PVC were 256.56, 270.71, 279.25, and 313.14 °C, respectively. For PVC stabilized with calcium soap, these values increased to 267.60, 276.51, 291.41, and 323.73 °C, while for PVC stabilized with aluminum soap, the corresponding values were 270.01, 284.96, 301.46, and 335.19 °C. These findings were further corroborated by the higher activation energy values obtained from the Coats–Redfern analysis and the Broido method, indicating an improvement in thermal stability. Overall, the results suggest that sunflower-oil–based metal soaps enhance the thermal stability of PVC and may serve as promising alternatives for long-term stabilization applications.

Keywords: polyvinyl chloride, thermal stabilization, thermal degradation, sunflower oil, metal soaps

I. Introduction

The polymer industry has undergone rapid development since the previous century, and polymer-based compositions have become some of the most widely utilized materials in modern society. Global polymer production now exceeds 400 million tons annually, with forecasts indicating that this upward trend will continue in the near future. Among the most extensively produced polymers are polyethylene, polypropylene, and polyvinyl chloride (PVC), which serve as the basis for a broad range of consumer and industrial products used in virtually every aspect of daily life [1]. PVC is particularly versatile, as it can be processed into both plasticized (flexible) and unplasticized (rigid) composites. Common applications include pipes, profiles, cable insulation, fittings, and packaging materials for food and industrial goods [2]. While PVC exhibits favorable chemical and mechanical stability, its major drawback is its susceptibility to thermal degradation [3].

During processing and service, exposure to elevated temperatures initiates degradation processes. Beginning near the glass transition temperature, the release of hydrogen chloride (HCl) occurs due to structural defects in the polymer backbone. At approximately 140 °C, this process accelerates, with the evolved HCl exerting an autocatalytic effect that further promotes chain scission within the polymer matrix [4–6]. Continued heating leads to mass loss as HCl evolution progresses. Concurrently, chlorine elimination gives rise to double bonds along the polymer chain, which extend to form conjugated polyene sequences. As the population of these polyenes increases, progressive discoloration of the PVC composition occurs. Once the conjugated segments reach a length of approximately 5–7 double bonds—corresponding to an overall mass loss of around 1%—visible darkening of the polymer becomes evident [7–9].

Although PVC undergoes thermal degradation at relatively moderate temperatures, its processing typically requires exposure to much higher temperatures, in some cases exceeding 200 °C [10]. To prevent such degradation under processing conditions, thermal stabilizers are commonly employed. A wide range of stabilizers with different origins and chemical compositions are used in industry, including lead compounds [11], organotin compounds [12], calcium–zinc systems and metal soaps [13], organic stabilizers [14], and hydrotalcite-based additives [15].

Despite their effectiveness, the use of lead-based stabilizers has been progressively restricted due to growing evidence of their adverse effects on human health. Numerous toxicological studies have demonstrated that lead (Pb) is one of the most hazardous heavy metals, with widespread environmental distribution in water, soil, food, and plastic materials [16,17]. Once absorbed, lead accumulates in the body and is eliminated only very slowly, thereby amplifying its toxicological impact [18]. Clinical findings indicate that lead primarily affects the nervous system, hematopoietic system, kidneys, and reproductive functions [19]. In children, lead exposure is strongly associated with reduced cognitive ability, attention deficits, and intellectual disability, whereas in adults it is linked to hypertension, renal failure, and impaired calcium metabolism in bone tissue [20,21]. Consequently, the use of lead stabilizers has been banned in the European Union, although they are still employed in parts of Asia.

Tin-based stabilizers represent another widely used class of additives for the preparation of PVC-based composites. Organotin compounds, in particular, have been shown to play a crucial role in enhancing the thermal stability of PVC. These stabilizers suppress dehydrochlorination, elevate the decomposition temperature, and additionally offer benefits in terms of color retention and transparency [22]. For example, pentaerythritol stearate ester-based tin(II) alkoxides have been demonstrated to exert a particularly strong stabilizing effect, while dioctyltin maleate stabilizers have also been reported to significantly improve the thermal resistance of PVC [23,24]. Nevertheless, tin-based stabilizers also exhibit several disadvantages. Foremost among these is their high production and application cost, which restricts large-scale industrial use. Furthermore, ecotoxic effects and the bioaccumulation potential of certain organotin derivatives have been reported, raising significant concerns for both environmental and human health [25].

Calcium and zinc soaps, regarded as more environmentally benign alternatives, remain less effective compared with lead- and tin-based stabilizers. A major limitation is that $ZnCl_2$, generated during PVC degradation, acts as a catalyst that accelerates dehydrochlorination. This phenomenon, commonly referred to as "zinc burning," compromises the long-term stability of the polymer mass [26]. In addition, emerging evidence regarding the adverse health effects of excessive zinc exposure has cast further doubt on its ecological safety [27].

Hydrotalcites have also been explored as stabilizers, although their industrial application remains limited. Despite their effectiveness in small concentrations, their relatively high cost and their tendency to increase polymer viscosity—thereby impairing processability—hinder their widespread adoption [28].

In recent years, considerable attention has shifted toward bio-based stabilizers derived from renewable raw materials. Such additives include metal soaps synthesized from vegetable oils, epoxy compounds, and various metal chelates. For instance, calcium and zinc soaps prepared from free fatty acids, a by-product of palm oil refining, have been evaluated as PVC stabilizers. The results indicated that these compounds can serve as promising alternatives to conventional synthetic metal soaps [29]. Similarly, tannin–metal complexes, particularly tannin–calcium systems, have demonstrated multifunctional stabilizing effects in PVC formulations [30].

Although Ca–Zn-based plant-derived soaps have been extensively studied, stabilizers derived from other metals remain comparatively underexplored. Importantly, the ongoing challenge lies in identifying stabilizers that are simultaneously eco-friendly, cost-effective, and efficient. Toward this aim, recent studies have investigated the effect of calcium and aluminum soaps synthesized from sunflower oil on the thermal stability of PVC. In these studies, the kinetics of PVC thermal degradation were analyzed, and the activation energy was determined using Coats–Redfern and Broido integral methods, providing deeper insight into the stabilizing efficiency of these bio-based compounds.

II. Experimental part

For the synthesis of metal soaps derived from sunflower oil, Final brand commercial sunflower oil was selected as the raw material. The oil was subjected to saponification in an ethanol–water medium in the presence of alkali. Following the synthesis of the water-soluble soap, the product was diluted with water to obtain a homogeneous solution. The excess alkali that did not participate in the reaction was subsequently neutralized using a standard hydrochloric acid solution. The physicochemical properties of the sunflower oil employed in the synthesis are presented in Table 1 [31].

Table 1. Properties of sunflower oil

Saturated fatty acids, %	Oleic acid, %	Linoleic acid, %	Linolenic acid, %	Free fatty acids, %	Iodine value, g/100g	Saponification value, mg/g	Moisture, %
10.7	20.7	67.6	≤ 1	0.062	136	191	0.05%

To obtain aluminum and calcium soaps, aqueous 20% solutions of $CaCl_2$ and $Al_2(SO_4)_3 \cdot 18H_2O$ salts were prepared in slightly more than the stoichiometric amount and added to the previously synthesized soap solution. The corresponding metal soaps were precipitated, collected by filtration through filter paper, thoroughly washed several times with distilled water, and subsequently dried. The dried precipitates were ground in a mortar and applied as stabilizers to the polymer matrix.

For the preparation of polymer samples, Rusvinyl PVC-S grade poly(vinyl chloride) was used as the base polymer. The synthesized calcium and aluminum soaps were separately incorporated into the PVC at a concentration of 5 phr (parts per hundred resin) and mechanically blended. To fabricate test specimens of both the mixtures and neat PVC, the blends were pressed using an Ecopress 102 (Turkey) heating press at 180 °C under a pressure of 150 bar.

Thermal degradation studies of the prepared samples were carried out using a NETZSCH STA449F3 Jupiter (Germany) thermogravimetric analyzer. Thermogravimetric analysis (TGA) was performed under a nitrogen atmosphere up to 900 °C with a constant heating rate of 30 °C/min. The activation energies corresponding to the dehydrochlorination and initial decomposition stages of PVC were determined from the thermogravimetric data using the Coats–Redfern and Broido integral methods [32,33]. Both approaches are based on the Arrhenius equation, which describes the temperature dependence of reaction rate constants. In the Broido method, the activation energy is evaluated according to the Broido equation (Eq. 2.1):

$$ln\left(ln\left(\frac{1}{1-\alpha}\right)\right) = -\frac{E_a}{R}\frac{1}{T} + constant \quad (2.1)$$

- α – degree of conversion for the selected reaction stage

$$\alpha = \frac{w_0 - w_t}{w_0 - w_f} \quad (2.2)$$

- w_t – residual fraction (%) at a selected temperature
- w_f – residual fraction (%) at the end of the selected temperature interval
- w_0 – initial fraction (%) at the beginning of the selected temperature interval
- E_a – activation energy (J/mol)
- R – universal gas constant (8.314 J·mol^{-1}·K^{-1})
- T – absolute temperature (K)

For the kinetic calculations, the Coats–Redfern equation, derived from the Arrhenius law, was applied (Eq. 2.3).

$$ln\left[\frac{g(\alpha)}{T^2}\right] = ln\left[\frac{AR}{\beta E_a}\left(1 - \frac{2RT}{E_a}\right)\right] - \frac{E_a}{RT} \quad (2.3)$$

- α – degree of conversion for the Coats–Redfern method

$$\alpha = \frac{w_0 - w_t}{w_0 - w_f} \quad (2.4)$$

- $g(\alpha)$ – integral form of the reaction model
- A – characteristic coefficient (pre-exponential factor) (min^{-1} or s^{-1})

At high activation energy values, the Coats–Redfern method can be expressed as follows:

$$ln\left[\frac{g(\alpha)}{T^2}\right] = ln\left(\frac{AR}{\beta E_a}\right) - \frac{E_a}{RT} \quad (2.5)$$

($ln\left(\frac{AR}{\beta E_a}\right)$ – characterizes the intersection point

The most commonly used kinetic models for the dehydrochlorination stage are presented in Table 2.

Table 2: Kinetic models for dehydrochlorination stage

Model	Mechanism	$g(\alpha)$
F1	First-order reaction	$-ln(1-\alpha)$
D3	Three-dimensional diffusion	$\left[1-(1-\alpha)^{1/3}\right]^2$
A2	Avrami–Erofeev (n = 1/2)	$[-ln(1-\alpha)]^{1/2}$
R3	Contracting sphere	$1-(1-\alpha)^{1/3}$

For the determination of activation energy, linear regression analysis is employed. In the Coats–Redfern method, the regression is constructed using $Y = ln\left(\frac{g(\alpha)}{T^2}\right), X = \frac{1}{T}$. In the Broido method, linear regression is performed using $Y = ln\left(ln\left(\frac{1}{y}\right)\right), X = \frac{1}{T}$. Based on the constructed regression plots, the activation energy and the determination coefficient are obtained.

III. Results and discussion

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) of PVC samples demonstrated that bio-based metal soaps markedly enhance the thermal stability of the polymer. For the unstabilized PVC sample, a rapid decrease in mass was observed beginning at approximately 220 °C, whereas in PVC samples stabilized with metal soaps, significant weight loss did not occur until after 240 °C.

During the initial degradation stage, namely dehydrochlorination, the polymer lost nearly 60% of its mass. In neat PVC, this process proceeded within a narrower temperature range. Specifically, a 5% mass loss was recorded at 256.56 °C. With increasing temperature, mass loss accelerated: 10% and 20% mass losses occurred at 270.71 °C and 279.25 °C, respectively. A 50% mass loss and a 60% mass loss—marking the completion of dehydrochlorination and the end of the initial decomposition

stage—were observed at 313.14 °C and 341.77 °C, respectively. The TGA–DTA–DDTA curves of pure PVC are presented in Fig.1.

As evident from the DDTA curve, energy absorption increased sharply within the temperature interval corresponding to dehydrochlorination. The abrupt mass loss at this stage is attributable to the autocatalytic effect of hydrogen chloride (HCl) released during degradation. Moreover, the lower energy absorption recorded in the DTA curve during the initial decomposition stage, compared with that in the subsequent stages of secondary organic mass decomposition and charring, further corroborates the autocatalytic role of HCl.

For the PVC sample stabilized with aluminum soap synthesized from sunflower oil, a 5% mass loss was recorded at 270.01 °C. As in the case of pure PVC, degradation intensified with rising temperature, leading to rapid weight reduction; however, compared with neat PVC, the onset of degradation was delayed and the rate of mass loss was lower. Specifically, 10%, 20%, and 50% mass losses occurred at 284.96 °C, 301.46 °C, and 335.19 °C, respectively. Completion of the dehydrochlorination stage, corresponding to a 60% mass loss, was observed at 357.72 °C. The observed increase in decomposition temperatures confirms the thermal stabilizing effect of aluminum soap. The TGA–DTA–DDTA curves of PVC stabilized with aluminum soap are presented in Fig.2.

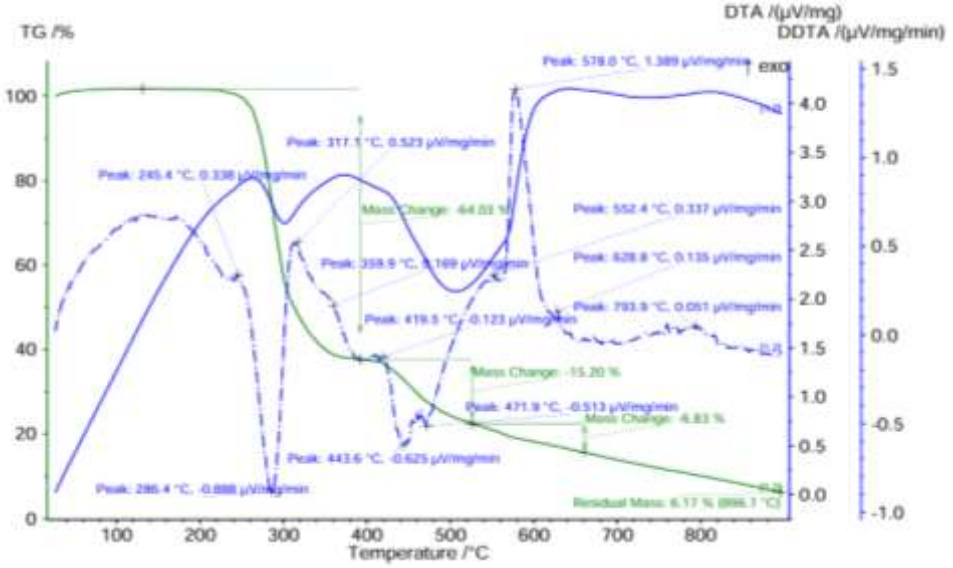


Fig.1. *TGA-DTA-DDTA curves of pure PVC*

As observed from the DDTA curves, energy absorption in the temperature interval corresponding to the dehydrochlorination stage was lower than that of pure PVC. This behavior can be attributed to the exothermic reaction occurring when the hydrogen chloride (HCl) released during degradation is neutralized by the metal soap stabilizer. The reduced energy uptake indicates that HCl was effectively scavenged by the aluminum soap.

Furthermore, the hydrophobic gel-like structure of the sunflower oil–based aluminum soap likely hindered the diffusion of HCl into the polymer phase. This suggests that the aluminum soap reduced the autocatalytic effect of HCl by providing a barrier effect. A comparison of the DDTA and DTA curves further revealed that energy absorption in the second decomposition stage was generally higher. The lower energy absorption observed in the pyrolysis region, relative to pure PVC, may be explained by the formation of $AlCl_3$ during dehydrochlorination, arising from the interaction of HCl with aluminum soap, and by the catalytic role of this salt in subsequent degradation reactions [34].

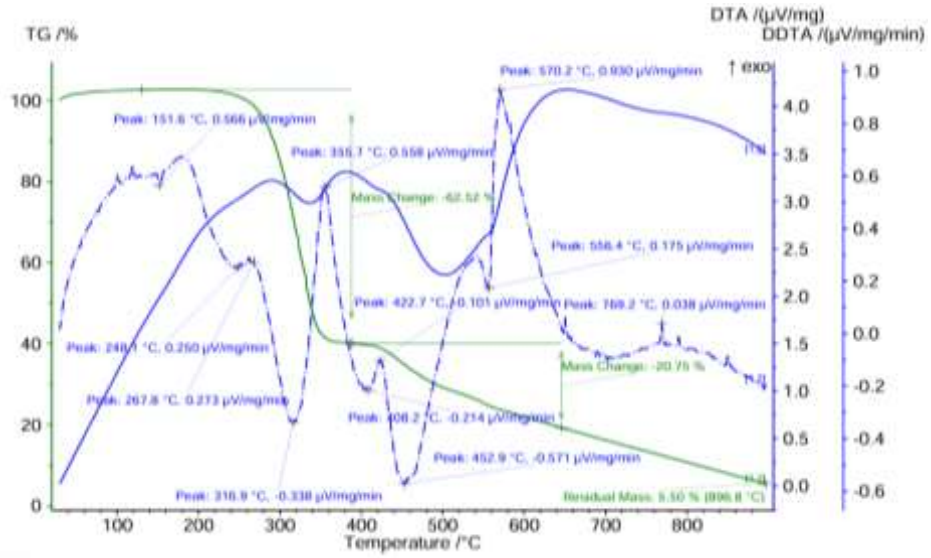


Fig.2. *TGA-DTA-DDTA curves of stabilized PVC with aluminum soap*

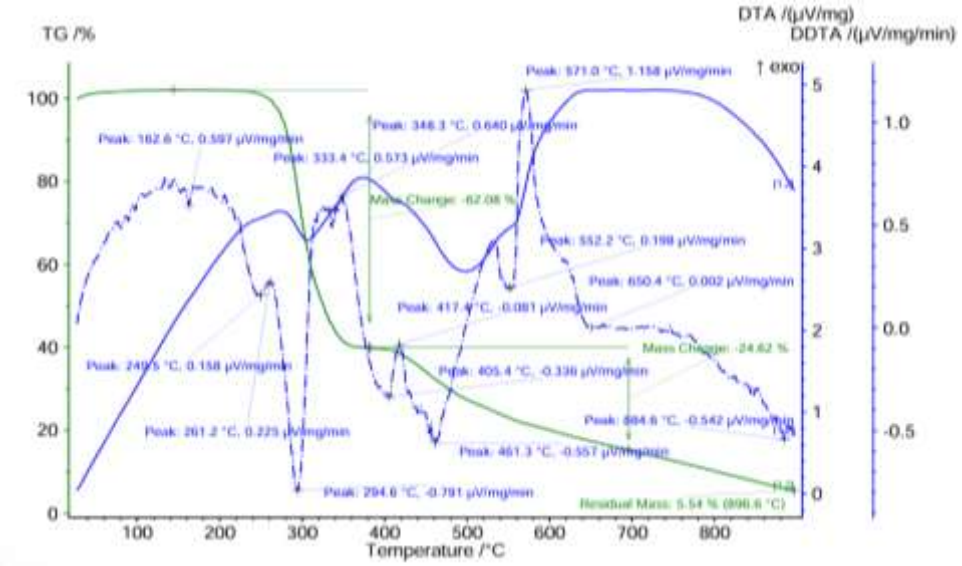


Fig.3. *TGA-DTA-DDTA curves of stabilized PVC with calcium soap*

The TGA results of the calcium soap–stabilized PVC sample indicated that a 5% mass loss occurred at 267.60 °C, a 10% loss at 276.51 °C, and a 20% loss at 291.41 °C. These findings demonstrate that calcium soap contributed to improved thermal stability of PVC. A 50% mass loss was observed at 323.73 °C, while a 60% mass loss—marking the completion of the dehydrochlorination stage—was recorded at 353.27 °C. In contrast to the aluminum soap–stabilized system, no significant variation in energy absorption was observed in the DDTA and DTA curves (Fig.3).

The percentage mass loss of PVC samples at 250, 300, 350, 400, and 450 °C is summarized in Table 3. As can be seen, the incorporation of thermal stabilizers exerted little influence on the second decomposition stage, with stabilization being primarily evident during the dehydrochlorination stage.

Table 3. Mass losses of PVC samples at 250, 300, 350, 400 and 450° C

Sample	Temperature, ° C				
	250	300	350	400	450
	Mass loss, %				
PVC-pure	3.05	41.57	61.35	64.29	69.98
PVC-Aluminum soap	2.03	18.90	57.94	62.89	67.32
PVC-Calcium soap	1.49	29.66	59.44	62.57	67.84

The calculation of activation energies for the degradation reactions in the presence of thermal stabilizers was primarily focused on the dehydrochlorination stage. In this study, the Coats–Redfern and Broido integral methods were applied to evaluate the activation energies of PVC samples. The calculations were performed using thermogravimetric data, with linear regression established for four kinetic models of the Coats–Redfern method, as well as the Broido method. The corresponding regression plots are presented in Fig. 4, 5, and 6 for pure PVC, PVC–aluminum soap, and PVC–calcium soap, respectively.

As illustrated in all three graphs, the first-order reaction model (F1) of the Coats–Redfern approach exhibited the closest correlation with the linear regression derived from the Broido method. Although the F1 model is most frequently employed to describe the dehydrochlorination process, other kinetic models were also evaluated. These include the three-dimensional diffusion model (D3), which accounts for gas diffusion through the polymer matrix; the Avrami–Erofeev model (A2), which describes the reaction in terms of nucleation and crystal growth; and the three-dimensional shrinking-core model (R3), which characterizes the process as spherical nucleation.

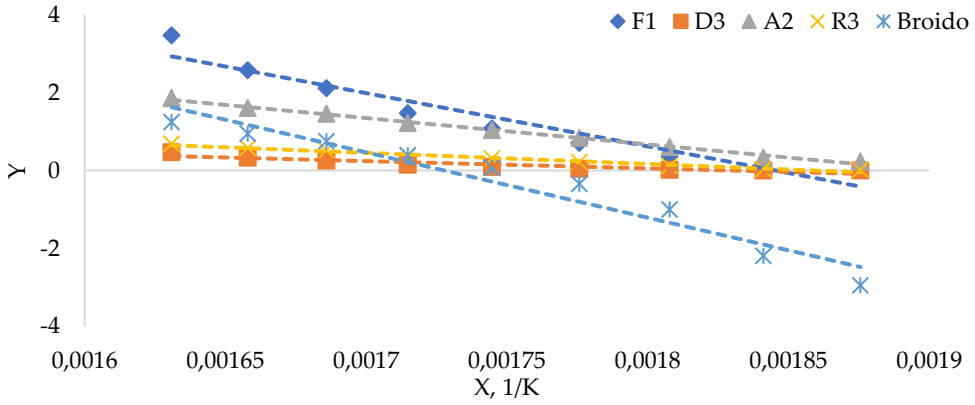


Fig.4. *Linear regression plot of PVC-pure constructed according to the Coats–Redfern and Broido method*

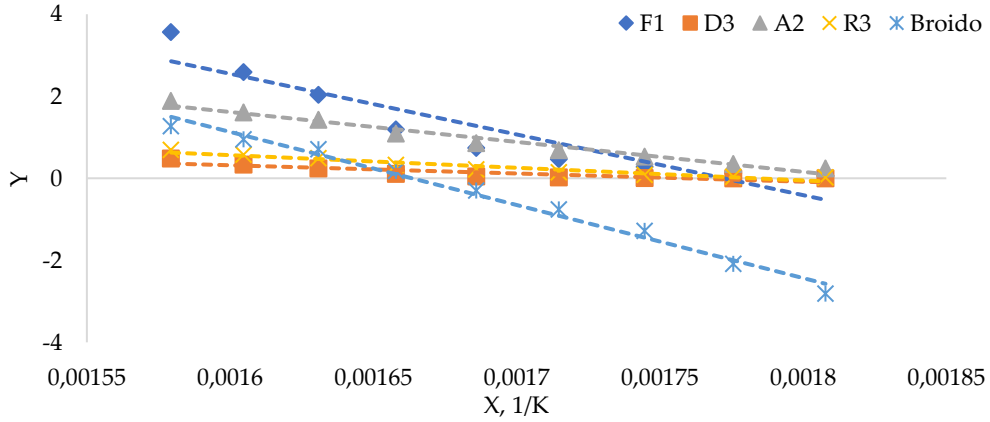


Fig.5. *Linear regression plot of PVC-pure constructed according to the Coats–Redfern and Broido method*

The results of the kinetic calculations demonstrated that the activation energy values obtained using the F1 model of the Coats–Redfern method and the model-free Broido method are consistent with values reported in the scientific literature. Although the activation energies derived from the alternative models were comparatively lower, they nevertheless provide useful insights into the degradation mechanism. The calculated results are summarized in Table 4.

As shown in the table, the incorporation of aluminum and calcium soaps led to an increase in the thermal stability of PVC. Furthermore, the observed increase in the pre-exponential factor indicates that, while the stabilizers enhance the decomposition onset temperature, the degradation process ultimately accelerates at higher temperatures. This suggests that thermal stabilizers play a more significant role in delaying the onset of dehydrochlorination rather than influencing the subsequent stage of degradation, which involves main-chain scission and charring.

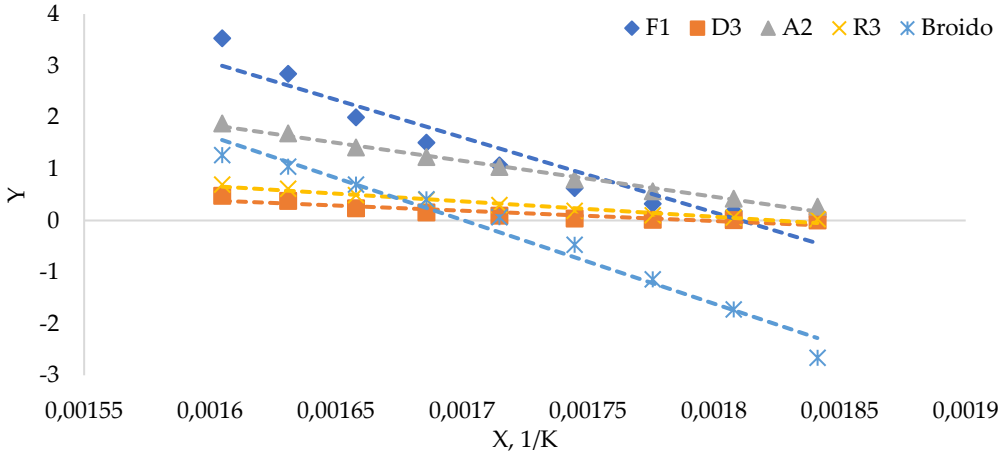


Fig.6. *Linear regression plot of PVC-pure constructed according to the Coats–Redfern and Broido method*

Table 4. Activation energies, determination coefficients, and pre-exponential factors of PVC samples

Mothod	Model	Activation energy (Ea), Determination coefficient (R^2), Pre-exponential factor (A)	PVC-pure	PVC-Aluminum soap	PVC-Calcium soap
Coats-Redfern	F1	Ea, kJ/mol	113.74	123.02	120.97
		R^2	0.93	0.87	0.92
		ln(A), s^{-1}	34.08	35.13	35.24
	D3	Ea, kJ/mol	15.47	16.65	16.62
		R^2	0.86	0.79	0.85
		ln(A), s^{-1}	10.24	10.43	10.50
	A2	Ea, kJ/mol	56.29	60.63	57.95
		R^2	0.99	0.97	0.99
		ln(A), s^{-1}	20.98	21.48	21.16
	R3	Ea, kJ/mol	23.72	25.56	24.81
		R^2	0.98	0.94	0.97
		ln(A), s^{-1}	12.57	12.82	12.75
Broido		Ea, kJ/mol	139.52	148.13	134.99
		R^2	0.94	0.99	0.97
		ln(A), s^{-1}	38.03	38.73	36.62

IV. Conclusion

The effect of calcium and aluminum soaps synthesized from vegetable oil on the thermal stability of polyvinyl chloride was investigated. Thermogravimetric results demonstrated that these metal soaps enhanced the thermal stability of the polymer. To more precisely evaluate their influence, the activation energies of thermally stabilized and unstabilized PVC samples were calculated using the multi-model Coats–Redfern method and the Broido integral method. The results indicated that the incorporation of metal soaps increased the activation energy of the dehydrochlorination stage, confirming their stabilizing effect. Conversely, it was observed that the stabilizers exerted little to no influence on the subsequent decomposition of the organic residue following dehydrochlorination.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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MULTI-CRITERIA RISK-ORIENTED SELECTION OF A SITE AND TECHNOLOGY FOR BUILDING A DATA CENTER IN ENERGY-LIMITED REGIONS

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Abstract

The article presents a multi-criteria risk-oriented approach to selecting a site and technology for building data centers (DCs) in energy-constrained regions. The methodology takes into account construction technology, logistical accessibility, climatic and geotechnical risks, readiness for power supply and connectivity of utility systems. Particular attention is paid to the integration of digital tools (GIS–BIM, MCDM) and risk analysis related to power supply, logistics and water supply. Examples of comparative analysis of traditional and modular construction are given, and the advantages of industrialized solutions for accelerating deadlines and reducing risks are shown. The proposed approach allows for the formation of a formalized risk profile and making informed decisions taking into account the specifics of the region.

Keywords: risk-based approach, multi-criteria choice, energy-constrained regions, construction of data processing centers

I. Introduction

The development of the digital economy and the exponential growth of data volumes lead to increased demand for data processing centers (DPCs) even outside the capital regions [1]. However, in remote and energy-limited regions, the construction of data centers is associated with particular difficulties. Southern regions, for example, experience a shortage of available energy capacity due to climatic conditions, although the business need for local data centers for storing and processing data is high. [2]. The correct choice of site for the data center in such conditions is critically important: a good location lays the foundation for reliable operation, while the wrong choice leads to constant problems and financial losses. [3][4]. Moreover, problems caused by incorrect site selection usually only become apparent at the final stages of construction and commissioning of the facility, when it is already too late or extremely expensive to correct anything.

Research related to the subject of this work is gradually shifting the focus from "pure" energy efficiency to the risks of construction feasibility and availability of energy resources. At the level of pre-project preparation, it is indicative to use multi-factor models of geographic information systems (GIS models) for preliminary ranking of sites taking into account geotechnical factors, hydrological hazards, and transport restrictions. Work on integrating geotechnical, environmental,

geophysical, and transport factors into site selection demonstrates a measurable effect on reducing construction risks [5]. A similar approach is the integration geographic information systems with an object-oriented model of a construction site or complex of construction sites (GIS–BIM) for constructing geotechnical models and "safe construction zones", which allows for the early identification of areas with unfavorable soils, risks of flooding/landslides and the adjustment of the layout of engineering infrastructure facilities of the data center [6].

Construction deadlines and logistics are a separate block. Comparisons of "classical" and automated planning show that 4D-BIM increases the predictability of deadlines due to the link between the calendar, model and real availability of resources, which is especially critical for remote sites and cramped construction zones [7].

II. Risk analysis of data center project

A separate area is risks, as a determining critical path of a data center project. Empirical reviews of intersystem queues for connection to networks record median expectations from ~ 4 to 5 years from application to commissioning for projects in recent years. Power supply and network reinforcements often take longer than the actual construction cycle [8]. Industry analysts supplement this with practical assessments: long lead times for transformers/busbars and complete switchgear (CSG) (up to several years), as well as protracted technical connection procedures, increase the uncertainty of the schedule and financial risks associated with capital expenditures (CAPEX risks) [9]. For energy-deficient regions, this means the need to include network risks in multi-criteria construction decisions, for example, consider phased capacity expansion and modular substations.

A related class of risks is disruption of construction supply chains. Surveys of risk management in construction supply chains highlight the growing vulnerabilities at the intersection of procurement, heavy-duty logistics, special equipment and personnel. Formed recommendations in the form of risk matrices for process management [10].

Industrialized construction is considered as a means of reducing calendar and logistical risks: prefabrication of modules, engineering solutions, power units and modular machine rooms. Reviews of modular construction show that optimization of production and installation schedules provides benefits in terms of duration and variability of deadlines [11], and studies of prefabricated objects record the influence of the selected technology and delivery system on the actual duration of work [12]. In the context of data centers, this directly translates into a reduction in work in unfavorable climates and on narrow sites, as well as the ability to accelerate the introduction of queues with restrictions on network connections [9, 11 - 12].

Construction solutions for heat removal also have a risk dimension: ensuring water supply and drainage, placing cooling towers and dry coolers, and complying with noise standards. Studies on data center water consumption demonstrate significant data uncertainty and a high share of potable water in a number of scenarios - this increases permitting and infrastructure risks in water-deficient basins [13]. On the technology side, a number of recent studies and tests record a shift towards liquid cooling, which structurally reduces dependence on water, simplifies placement in cramped areas, increases the temperature of the coolant and opens the way to heat recovery [14 – 17]. For builders, this means a shift in the layout of engineering systems (collectors, heat exchangers and pumps) and in the requirements for installation and commissioning, as well as new supply risks [18].

For cold regions, research focuses on geocryological risks: frost heave, thawing, subsidence, impact on foundations and linear networks. Research [19] summarizes risk assessment methods

and emphasizes the need to adapt foundation and drainage designs to changing permafrost. Current guidelines for Arctic construction systematize design solutions and construction practices - seasonality, winter downtime, roads, insulation and thermal stabilization of soils [20]. Russian research assesses the socio-economic consequences of permafrost degradation and brings legal and organizational aspects to the management of construction risks in the North [20, 22]. For data centers, this translates into requirements for the choice of foundation type (pile systems, grillages with thermal stabilization), site drainage, winter concreting technologies and logistics of heavy modules.

Finally, in terms of risk-oriented multi-criteria choice methods in construction, hybrid multi-criteria decision-making methods are used to rank risks, select technologies, and structure alternatives under high uncertainty [10 – 12, 21]. These tools combine well with GIS–BIM [5 – 8] and allow for the integration of construction and technological risks (geotechnics, seasonality, logistics, supplies, water infrastructure) into a single model, along with cost, timing, and sustainability criteria.

The task of choosing the optimal site for a data center generally requires taking into account a wide range of criteria, since there are no standardized methods for all cases. In the practice of data center construction, each new project is forced to form its own list of requirements and criteria, based on open sources, expert advice and previous experience.

Within the framework of the risk-oriented approach, the following procedure is proposed:

1. Identify all key factors that influence the success of the project;
2. For each factor, assess the risks associated with it (probability and potential damage);
3. Assign a “weight” or priority to criteria based on the significance of the risks involved;
4. Conduct a comparative assessment of alternative sites and construction technologies based on a set of criteria.

III. Criteria for assessing the risks of a data center project

A weighted assessment can be used to quantitatively integrate different factors. Based on the algorithm described above, as well as an analysis of studies on the topic, the following criteria were formulated:

1) Erection technology (industrialization). Research on modular and industrialized construction shows that increased factory readiness, standardization of units, and parallelization of work reduce the duration and variability of deadlines. A systematic review of production planning in modular construction confirms these advantages and the maturity of optimization methods.

2) Construction and logistics accessibility of the site. Large-scale equipment logistics, access road restrictions, crane zones and construction site layout are drivers of delays and cost overruns; reviews show a direct link between the quality of the logistics organization and productivity and safety.

3) Climatic and geotechnical exposure of construction processes. In cold and difficult natural conditions (permafrost, floods, seismicity) the risk of special events and "weather windows" increases, which affects the timing and cost of work; these effects are confirmed by review studies.

4) Readiness of power connection (time - to - power). For energy-deficient regions, the timing and reliability of technological connection are a critical path of the project; reports and roadmaps record long queues and delays.

5) Connectivity of utility systems (water, sewerage, heat, communications). Water capacity and water use limits limit the choice of cooling technologies, waste heat utilization and the presence of heating networks can reduce the overall risk and improve the project economy,

telecom infrastructure factors are also important.

IV. Multi-criteria risk-oriented principle

Based on these criteria, the proposed multi-criteria risk-oriented principle was formed. The alternative is considered as a combination of the site S and the technological solution for construction, cooling τ: a=(s,τ). The integrated assessment is based on five criteria reflecting the contribution of the construction industry to the feasibility of the project:

U_1 — construction manufacturability;

U_2 — construction and logistics accessibility;

U_3 — climatic and geotechnical exposure;

U_4 — readiness of power connection;

U_5 — connectivity of engineering systems.

Standardization of indicators: let Cjk(a) — the measured indicator k within the criterion j. Min – max -norming is applied:

"More is better":

$$c_{jk}(a) = \frac{x_{jk}(a) - \min x_{jk}}{\max x_{jk} - \min x_{jk}}$$

"Less is more":

$$c_{jk}(a) = \frac{\max x_{jk} - x_{jk}(a)}{\max x_{jk} - \min x_{jk}}$$

Aggregation indicators in the criterion:

$$U_j(a) = \sum_k v_{jk} c_{jk}(a),\ v_{jk} \geq 0,\ \sum_k v_{jk} = 1$$

Risk assessment according to criteria:

- An expert-analytical approach (FMEA):

$$R_j(a) = \frac{1}{125 N_j} \sum_{r=1}^{N_j} P_{jr} I_{jr} D_{jr}$$

- Scenario approach (if statistics are available):

$$R_j(a) = \frac{\mathrm{CVaR}_\alpha [L_j(a, \omega)]}{\max\limits_a \mathrm{CVaR}_\alpha [L_j(a, \omega)]}$$

Final integrated assessment of the alternative:

$$S(a) = \sum_{j=1}^{5} w_j (U_j(a) - \gamma_j R_j(a))$$

where Uj are the normalized indicators according to the criteria, Rj are their risk indices, wj are the importance weights, γj are the risk aversion coefficients

The higher the S(a), the more preferable the project. Before ranking, strict cutoffs are applied according to regulatory and resource restrictions (zoning, sanitary requirements, water limits, deadlines for technological connection).

V. Results and discussion

The application of the described approach in real projects allows to significantly improve the validity of decisions on the localization of the data center and the choice of technology for its implementation. Each potential site option is assessed comprehensively: not only by capital costs or proximity to customers, but also by the total risk of failures and losses over the operational horizon. Risk-oriented choice means that preference is given to the option that minimizes the likelihood of major negative events (accidents, interruptions, business downtime) with acceptable costs for preventive measures.

Let's consider a hypothetical scenario: a commercial data center is planned to be built in the south of Russia, where demand for services is high, but the region is characterized by a hot climate and a shortage of available electric power capacity. Using a multi-criteria approach, several alternative regions or specific sites can be compared. For example, Option A is a site in the most energy-deficient southern region, and Option B is a site in a more northern region with better power supply. Option A may have the advantage of being closer to the customer base (less latency and higher commercial potential), but is accompanied by high risks: the need for an expensive cooling system with cooling towers due to the hot climate, investments in new energy infrastructure (lines from a remote substation), possible power outages during peak summer months. Option B, on the contrary, can offer stable power supply from hydropower and natural cooling for most of the year (low energy efficiency rating), but is located further from consumers, and the infrastructure (roads, communications) is weaker. The decision in this case is made based on the total risk scores: if the risk of failure and the cost of insuring it (redundancy, diesel generators, excess cooling capacity) outweigh the benefits of the location, then Option A is considered inappropriate. Thus, the multi-criteria approach allows for a transparent justification of the choice: either to build a data center where reliability is higher, or to take clearly planned measures to neutralize the risks of an unfavorable location.

As for the construction technology, the approach is similar - alternatives are assessed (for example, traditional capital construction versus a modular data center from factory-made products) in terms of their impact on project risks. Experience in data center construction in regional conditions shows a significant difference between these approaches. For example, the Key Point Group of Companies tested both options when implementing projects in Vladivostok and Novosibirsk. In Vladivostok, the classic approach was used: all work was performed on site, a capital building for the data center was erected from scratch. In Novosibirsk, on the contrary, they decided to speed up construction and improve the quality of the facility due to modular technology using ready-made factory units. Already assembled modules were delivered to the site, quickly installed and connected to the system. The results were impressive: the Novosibirsk Tier III data center was built in a short time (the first stage of 440 racks was commissioned in 12 months, and the expansion by another 440 racks will take only ~5 months). The quality of execution has improved, and the number of human errors has decreased due to the high factory readiness of solutions. In addition, the modular data center is easier to maintain - access to systems is simplified due to the block structure, which also reduces operational risks.

The choice of modern construction technology, such as modular, can be considered as a risk management tool: reducing the risks of failure to meet deadlines, exceeding the budget and the occurrence of defects. Of course, the modular approach may require developed logistics for the delivery of large modules, but in most cases, the benefits in speed and reliability outweigh these. In general, the influence of the construction industry is clearly visible: the use of advanced

engineering solutions and cooperation with experienced contractors allows us to mitigate many risks that are typical for projects in remote and infrastructure-weak regions.

By applying the proposed multifactorial approach, it is possible to form a formalized risk profile for each project option under consideration. This allows for a reasonable choice of the option with the lowest acceptable risk instead of relying only on cost and assumptions. In energy-constrained regions, this is especially important, since the environment itself increases the likelihood of adverse incidents. Risk-oriented planning allows for the adaptation of the project to these conditions: to provide for additional power sources, enhanced cooling, a remote monitoring and control system to minimize personnel visits to a remote facility. The selected site and construction technology will ensure the required level of reliability (SLA) and data security, despite external restrictions.

VI. Conclusion

Building a data center in an energy-deficient region is a complex multifaceted task, the success of which depends on the right strategic decisions at the start. The analysis showed that a comprehensive risk-oriented approach to choosing a location and technology for implementing a data center is needed. Firstly, relying only on generally accepted standards and typical practices is not enough - it is necessary to develop an individual list of criteria and requirements for the site, taking into account the specifics of the project. Secondly, even before the start of construction, it is necessary to form your own set of rules and a methodology for evaluating options, including using recommendations and "elements" from the experience of previous projects. Thirdly, it is necessary to distribute priorities between criteria in proportion to the degree of risk: factors critical to reliability should receive maximum attention. Compliance with these principles can significantly reduce the likelihood of errors in choosing a site and, as a result, avoid serious consequences during the operation of the data center. The result of applying the methodology is a reasonable choice of the optimal region, a specific site and a format for building a data center, which achieves a balance between costs and the level of risk.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INTELLIGENT MODELLING OF CONTROL SYSTEMS IN FLEXIBLE MANUFACTURING AREAS AT TECHNOPARK

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Abstract

The methods and tools of intellectual modeling of the control system at the design stage of the mechanical processing area of the flexible manufacturing system (FMS) of the technological park, selected as the object of research, were analyzed. The purpose of the work is to create expert knowledge of the control system of the mechanical processing area of the technological park and its information-measuring functions using the method of graphically determined modeling. A generalized architecture of an automated tool for modeling and studying the control of the mechanical processing area of the FMS was developed. Computer experiments were conducted to model the study of the control of the mechanical processing area of the FMS using a Petri net. The algorithm of complex coordinated and synchronized actions of the mechanical processing area of the FMS was described with a knowledge base.

Keywords: Agile manufacturing system, mechanical processing area, modeling, technopark, management system, Petri net, intelligent system, expert knowledge

I. Introduction

Based on the purpose of the work, referring to the literature sources and experience used to analyze the current state of the problem [1-6], the following three main directions have been identified for the description of control activities of the FMS with knowledge: classification of special formalisms of knowledge description models in computers; application of knowledge description models in computers in modeling technical systems; analysis of the current state of application of technical systems with Petri nets at the stage of system-technical design.

Based on the analysis of the results of research in the indicated areas, the current status and level of scientific research work carried out to solve the problem were determined, and the advantages and disadvantages were summarized through a comparative analysis, and the following main conclusions were formulated [7-11]:

- knowledge representation models in the computer, which is the basic element of intellectual systems, are formed by knowledge in the form of neural, semantic, Petri nets, expert-type production rules, logical and Frame models;

- by application area, it constitutes knowledge aimed at solving production management and economic problems, formalized by logical modeling methods and used in systems intended for decision-making;

- knowledge formalized with logical modeling and fuzzy network models in systems that advise, test, predict, and diagnose intelligent systems for solving problems.

The current state of intellectual models that provide for the design of the control system of the FMS of a technopark, which is considered a complex technical system, shows that the most common representation schemes and tools [12, 13] that describe human knowledge are the following: goal tree, "and", "or" tree (output tree), semantic network, neural network, etc. The knowledge base management system created on the basis of these models consists of software tools and performs the main functions - automated management of the goal tree, result, semantic and neural network trees, their definition, modification, sending requests to the knowledge base and receiving responses.

The selected search strategy uses not all the information in the knowledge base (KB) at all stages of solving the problem, but only the part that is relevant to it. For this purpose, the activation of knowledge by associative search with queries appropriate to the situation of the object by the expert and in dynamic expert systems is relevant. The current state of the evolution of production systems, the level of artificial intelligence of the fourth industrial revolution, the restructuring of industrial enterprises to ensure the release of high-quality products to the world market, the design of complex systems, their modeling, research and evaluation of the feasibility of their creation through computer experiments with various methods based on knowledge of specific purposes, are relevant.

[14-16] it is shown that in the process of developing of FMS control system, unlike the design of simple technical systems, it is required to solve issues such as the analysis of their functional work, the study of their properties, the determination of the operating modes of technological equipment (selection and design of mechatronic devices, layout schemes, selection and design of standard and non-standard elements, development of control and monitoring systems, organization of synchronized and coordinated activity). At the stages of design, production, testing, application and operation of FMS, the following modeling devices are widely used: finite automata; asynchronous processes with parallel operation; logical, frame and production models, semantic and Petri nets, etc. It is shown that each of the mentioned modeling devices has its own advantages and disadvantages and effective areas of application, and the properties of these devices should be taken into account in the process of designing of FMS control system.

An analysis of the current state of application of modeling tools at the stages of system-technical design (technical task, sketch and technical design) has shown that the Petri net tool is a more universal tool compared to other methods [17, 18]. This is explained by the fact that the Petri net allows you to evaluate the feasibility of creating an object without direct physical contact with it, as a result of analyzing the main properties of the network. At the same time, it is shown that Petri nets are not considered effective in modeling and studying relatively simple processes, and it is more efficient to use other modeling tools for their intended purpose.

It was noted that currently there are many extensions of Petri nets, and they have been developed into efficient software complexes for modeling and studying FMS and are widely used in design procedures, especially in studying the management, control, forecasting and other activities of FMS [19, 20]. In practice, in the study of FMS control with Petri nets, the problem of describing the FMS at three main levels - subject, mathematical and program, creation and object level with simple modeling devices, and in the subsequent stages, the transformation into a Petri net model with various purposeful transformation algorithms and the analysis of the main properties of the network at the mathematical level of FMS, and the assessment of the feasibility of the operation of the FMS control algorithm, has been solved.

II. Architecture of the automated design tool for the control system of FMS in the technopark

The modern level of development of computer technology, the use of effective modeling methods, the need to study the feasibility of designing and creating these areas at the initial design stages using computer experiments arises. In this work, a generalized structure of the interaction of the mathematical, algorithmic, software, technical, information-search support subsystems of the automated design tool, the activities of which are described by various modeling methods, in a complex manner - in the interaction of the constructive and control system, is created. From the analysis of the generalized structure of the interaction of the subsystems of the automated design tool (ADT) of the control system of the FMS, it can be seen that the complex automated design of the control system of the FMS should be carried out in two main directions: the creation of bases of non-standard mechatronic devices created on the basis of standard and constructive design; It requires the creation and study of computer model databases by modeling mechatronic devices, as well as the creation of knowledge bases of control models and algorithms for their management [21-24].

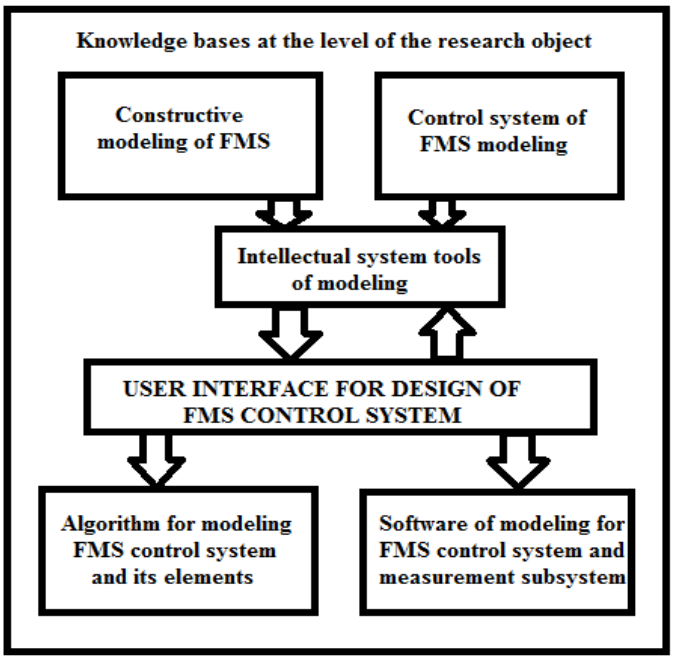


Fig. 1. *Architecture of ALA for modeling a complex study of the management system of the MIS*

The structural modeling tool of the FMS control system is formed from a set of knowledge bases at the research object and mathematical level. The knowledge base at the research object level includes: computer models of FMS in the form of layout schemes; computer models of standard and non-standard mechatronic devices; computer models of transport and storage systems; computer models of various processing equipment of FMS; technical and other characteristics of equipment and mechatronic devices of MIS; databases of the FMS control system.

At the mathematical level, the knowledge base includes computer models of the components of the control system of the FMS under study in two or three-dimensional spaces, separately, and computer models of the control system of the FMS in two or three-dimensional spaces [25].

When performing computer experiments, the computer model being studied is transferred to the working area and its control is studied through experiments.

The proposed generalized architecture of the ADT management design tool for modeling the complex study of the FMS management system is given in Figure 1. As can be seen from the architecture, the knowledge of the ADT of FMS control system is described at four main levels: semantic information; subject; mathematical and software tools [26, 27].

As is known, design procedures are carried out at different stages by specialists (teams) with different qualifications, and the technical and conceptual errors of each are propagated to the next stages and ultimately detected at the testing stage of the physical model of the object. At the stages of design procedures, the selected properties of the object are described with various signs (symbols) in accordance with the technical task. The analysis shows that communication between the design organizations and the customer organization is mainly carried out in languages corresponding to the professional level of the latter. In this case, the customer can also use mathematical and logical formulas proven on empirical and scientific grounds, confirmed by various experiments.

III. Modeling the operation of the control system of the FMS in technopark

The DB of a FMS control system is created by including the types, characteristics, technical specifications, and parameters of all its components.

$$DBc \rightarrow \{DB_{ae1}, DB_{ae2}, \ldots, DB_{aen}\}$$

At the next stage, the issues of creating knewledge base (KB) and KB management system (M)S for building algorithms of the operation of the FMS of the mechanical processing flexible manufacture module (FMM) in different situations and depending on the processing of various designs are considered. At both stages, the technological operations performed by the crane manipulator (CM) are accompanied by the differentiation of only the movement routes of the CM, that is, only the sequence of loading the FMM of the mechanical processing FMM is determined. Taking into account the diversity of the designs being processed mechanically, the issues of creating KB and KBMS of the software of the program-controlled machines should be considered.

In the dissertation work, in order to analyze the dynamics of the technological process of the TDM using the example of the TDM, the sequence of events (technological operations) P_i occurring in it and the calculation of the logical predicates tj for the occurrence of events are considered.

$[(P_1 = \text{operation 1}) \vee (P_2 = \text{operation 2}) \vee$
$\vee (P_n = \text{operation n})] \wedge [((\text{end(operation 1)} < \text{start(operation 2)}) \wedge$
active element of the FMM
(For example, crane manipulator (CM) (operation 1) = $x_1 \wedge$
CM(operation 1)=$x_2 \wedge$CM(operation 2)= x_3]
$\wedge$(type(operation 1)= layout is positioned on machine (lathe))
$\wedge$(type(operation 2)= CM's handle holds the layout)
$\wedge$[((end(operation 2) < start (operation 3)) $\wedge$.

Here x_1 - crane manipulator (CM), x_2 - layout (Machine), x_3 - lathe (Machine).

P_i occurring in the CHIS events occur in time t_i. This dependence can be described in logical language as follows:

$(\forall P_i \in$ technological operations of the crane manipulator in the FMM)
[Positioning of T in Machine(P_1) $\rightarrow$(start(P_1) + t_1 =end(P_1)]$\wedge$
[Tn in CM's capture by the holder (P_2)$\rightarrow$
(start(P_2) + t_2 = end(P_2)] $\wedge$[Selecting the type of movement of the CM (P_3, P_{3+1} ,....)$\rightarrow$
(head(P_3) + t_3 =end(P_3)] $\wedge$[Processing of T to machine (P_m) $\rightarrow$(head(P_m) + t_2 =end(P_{m+1})].

Here t_i is the positioning time of the layout in machine, t_2 is the closing and opening time of the KM handle, t_3 is the duration of the movement trajectory of the CM arm.

Production rules are used in the design of the control system of the FMS. Thus, a knowledge

base and a control algorithm are developed based on the production model to design the software of the control system. The main active elements in the control system of the agile production module are the transmitters and execution mechanisms of the machines. The movements of the active elements of the FMS, their transmitters and execution mechanisms are formally described in tables 1 and 2.

Table 1. Assignments of the transmitters of the CHIs's MQ

Transmitters	**Technological of operations types**
Positioned r ici block (MB) data	
S^1_1	Positioning the layout in the TD MB
S^2_1	Positioning the layout in the FD MB
S^3_1	Positioning the layout in the RD's MB
S^4_1	Positioning the layout in the DB of the AD
Crane manipulator (CM) transmitters	
S^1_2, $\overline{S}^1_2$	Positioning the CM handle in the closed or open position
S^2_2	Positioning the CM in the low position
S^3_2	Positioning the CM in the upper position
S^4_2	Positioning of the forward movement of the CM
S^5_2	Positioning of the CM reverse movement
Lathe (Machine) data	
S^1_3	Positioning the start of a technological operation in TD
S^2_3	Positioning the end of the technological operation in TD
Milling machine (FD) data	
S^1_4	Positioning the start of a technological operation in FD
S^2_4	Positioning the end of the technological operation in FD
Radial bending machine (RBD) specifications	
S^1_5	Positioning the start of a technological operation in RBD
S^2_5	Positioning the end of the technological operation in RBD
S^1_6	Positioning the start of a technological operation in the OB
S^2_6	Positioning the end of a technological operation in the machine tool

A control algorithm is built based on the selected transmitters and execution mechanisms of the active elements of the FMS. The control algorithm built with the help of the production model consists of the elements of the application conditions (P_i) of the production core :

$$P_i=\{P_1, P_i, \ldots.., P_n\}, \quad (4)$$

where n denotes the number of conditions.

The control algorithm for the process of loading and processing the workpiece onto the lathe using a crane manipulator along the technological trajectory of the lathe can be described by the following production algorithm:

1. Algorithm for loading TD FMM with CM

P1: ***if*** TD does not have T in MB, ***then*** CM is moving down;

P2: ***if*** the CM has moved down and the CM's grip is open, ***then*** the KM's grip is holding T;

P3: ***if*** If the CM's grip is on T, ***then*** CM is moving up;

P4: ***if*** the CM has moved up, ***then*** the CM is moving forward;

P5: ***if*** the CM arm has moved back and is in the TD working zone, ***then*** The handle of the CM should be opened and positioned at the MB of the T TD;

P6: ***if*** T is positioned at the MB of TD, ***then*** CM should move back and start processing T at TD;

P7: ***if*** the processing operation of T has been started in TD, ***then*** the processing operation of T in TD should be executed and completed within time t_i.

Workpiece along the technological trajectory of the lathe using a crane manipulator and loading it onto the lathe and processing it can be described by the following production algorithm:

1. Algorithm for loading TD FMM with CM

P1: ***if*** TD does not have T in MB, ***then*** CM is moving down;

P2: ***if*** the CM has moved down and the CM's grip is open, ***then*** the CM's grip is holding T;

P3: ***if*** If the CM's grip is on T, ***then*** KM is moving up;

P4: ***if*** the CM has moved up, ***then*** the KM is moving forward;

P5: ***if*** the CM arm has moved back and is in the TD working zone, ***then*** The handle of the CM should be opened and positioned at the MB of the T TD;

P6: ***if*** T is positioned at the MB of TD, ***then*** CM should move back and start processing T at TD;

P7: ***if*** the processing operation of T has been started in TD, ***then*** the processing operation of T in TD should be executed and completed within time t_i.

Table 2. The IM of the CHI appointments

Execution mechanisms	**Technological of operations types**
Positioned on the machines block (MB) execution mechanisms	
EM^1_1	Implementation of TD's positioning in the MB
EM^2_1	Execution of FD's positioning in the MB
EM^3_1	In the MB of RBD positioned r loop execution
EM^4_1	Implementation of the positioning of the BD in the MB
Crane manipulator operating mechanisms	
EM^1_2, $\neg EM^1_2$	Execution of positioning of the CM handle in the closed or open position
EM^2_2, $\neg EM^2_2$	Performing the positioning of the CM in the up or down position
EM^3_2, $\neg EM^3_2$	Execution of positioning of the forward or backward movement of the CM
Machine tools execution mechanisms	
EM^1_3, $\neg EM^1_3$	Execution of positioning of the initial or final states of the technological operation of the TD
EM^2_3, $\neg EM^2_3$	Execution of positioning of the initial or final states of the technological operation of the FD
EM^3_3, $\neg EM^3_3$	Execution of positioning of the starting or final states of the technological operation of the RBD
EM^3_4, $\neg EM^3_4$	Execution of positioning of the initial or final state of the technological operation of the machine tool

A control algorithm is constructed using logical symbols in accordance with the production conditions shown above:

$(P_1) \neg S^1_1 \Rightarrow \neg EM^2_2$;

$(P_2)\ S^2_2 \,\&\, \neg S^1_2 \Rightarrow EM^1_2$;

$(P_3)\ S^1_2 \Rightarrow EM^2_2$;

$(P_4)\ S^3_2 \Rightarrow EM^3_2$;

$(P_5)\ S^5_2 \Rightarrow \neg EM^1_2 \,\&\, EM^1_1$;

$(P_6)\ S^1_1 \Rightarrow EM^3_2 \,\&\, EM^1_3$;

$(P_7)\ S^1_3 \Rightarrow \neg EM^1_3$.

The dissertation presents a block diagram of the control algorithm for loading the lathe's MF with CM. As can be seen, production rules were used as an efficient modeling apparatus for studying the activities of all MFs of the mechanical processing FMS, and a finite automaton was used for the automatic transport manipulator. Therefore, algorithms for converting the modeling methods shown in the dissertation into a Petri net model were developed.

In the example of TD, the sequence of transition from production rules to Petri nets and the development of the FM action algorithm as a result of the analysis of the properties of the Petri net are considered.

Table 3. Predicates appropriate to the situations of CM activity

Predicates	Definition of predicates
P_1	The CM handle is open;
P_2	the presence of the layout in the layout positioning zone;
P_3	moving the CM down to the layout positioning zone;
P_4	Capture of the design by the CM holder;
$P5$	CM moving upwards;
P_6	CM moving forward;
P_7	Placing and positioning the layout on the positioning block of the TD by the CM;
P_8	CM moves back and starts processing in TD;
P_9	Completion of the design processing operation in TD;

The following active actions-transitions correspond to predicates t_j ($j = \overline{1,9}$) :

t_1	The CM's handle is not working (open);
t_2	the layout positioning zone is active (there is a layout);
t_3	CM is working (moving down);
t_4	The CM's handle is working (closing);
t_5	CM is working (moving up);
t_6	CM is working (moving forward);
t_7	The positioning block of the TD is working;
t_8	TD is running (processing operation is starting);
t_9	TD is running (processing operation is ending).

In this case, the productions in the form of "condition - action" are expressed as follows.

$$P_1 \to t_1;\ P_2 \to t_2;\ P_3 \to t_3;\ P_4 \to t_4;\ P_5 \to t_5;\ P_6 \to t_6;\ P_7 \to t_1 \& t_7;\ P_8 \to t_8;\ P_9 \to t_9.$$

The numbers of predicates and transitions are equal to each other (P_i=9, t_i=9), the invariants P and T of the incidence matrix, whose number of rows and columns is equal to each other, are determined by the well-known Gauss method based on the input and output matrices, and a graph-scheme of the action algorithm in the form of a Petri net with a Petri net of the lathe FMM control system is constructed (Figure 2).

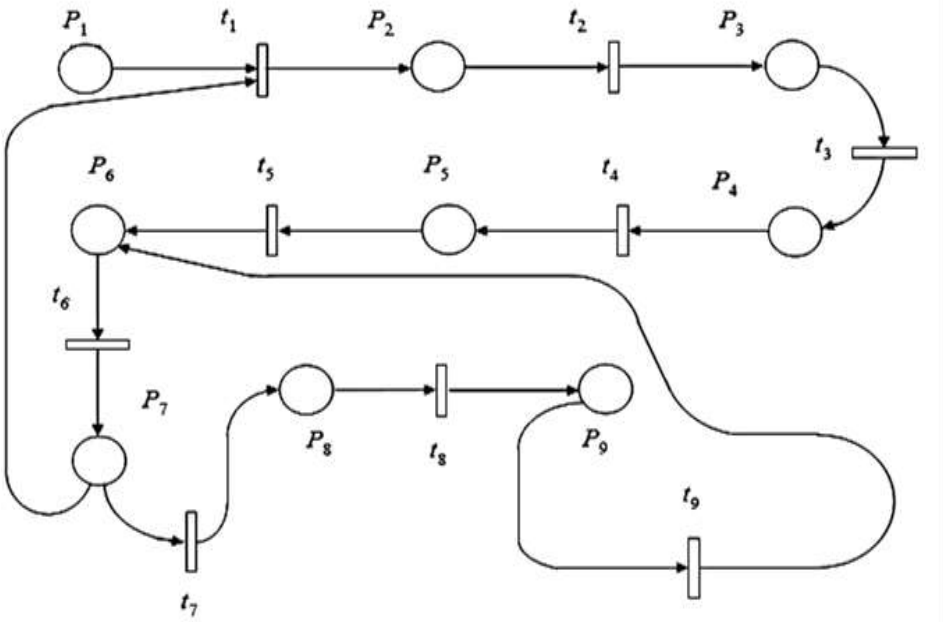


Fig. 2. *Petri net graph diagram of the activity algorithm of the FMM control system with Petri net*

Conclusion

As can be seen from the architecture of the ADT of the mechanical processing FMS control system, taking into account the sequence of the FMS's activities, the control algorithm of each of its components is selected from the subject-level KB and converted into a Petri net using the appropriate Petri net transformation algorithm, and a KB is created at the mathematical level. This sequence can be shown as follows.

Algorithm

First stage

Step 1. Transform the finite automaton control algorithm of the automatic transport manipulator into a Petri net model and store it in the KB at the mathematical level (N_1).

Step 2. Converting the production rules algorithm of the loading of FMM1 (TDM) by the CM into a Petri net model and storing it in the KB at the mathematical level (N_2).

Step 3. Converting the production rules algorithm of the FMM2 (FDM) loading by the CM into a Petri net model and storing it in the KB at the mathematical level (N_3).

Step 4. Converting the production rules algorithm of the FMM3 (RBD) loading by the CM into a Petri net model and storing it in the KB at the mathematical level (N_4).

Step 5. Converting the production rules algorithm of the FMM4 (EDM) loading by the CM into a Petri net model and storing it in the KB at the mathematical level (N_5).

Step 6. Converting the production rules algorithm for automatic loading of finished products into a Petri net model by the CM and storing it in the KB at the mathematical level (N_6).

Second stage

Step 7. Evaluation of the feasibility of applying control algorithms by studying them with computer experiments as a result of analyzing the properties of each Petri net separately (N_1, N_2, N_3, N_4, N_5, N_6) sequentially

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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BASEFLOW AS THE UNDERGROUND ORGANIZER AND REGULATOR OF A SİNGLE RİVER SYSTEM

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Abstract

Rivers have two nutrition sources: surface runoff and subsurface feeding. Rain and snow water constitute their surface runoff and underground feeding of rivers constitutes baseflow (subsurface runoff). Rivers are fed by surface flow during rainfall cases, and by subsurface ways during dry periods. The surface runoff fraction can be determined by measurements of water discharge at existing hydrological observation stations. Determining the share of groundwater recharge is one of the most difficult areas in hydrological studies, and this process is usually carried out indirectly (hydrograph separation, subtraction of the sum of surface runoff and evaporation from precipitation, etc.). However, studying baseflow is of great importance in terms of assessing the water resources of rivers, regulating and managing the river runoff. The article is devoted to the issue of determining the baseflow share of the rivers, and for this purpose a new formula was proposed. The rivers groundwater feeding of the southern slope of the Great Caucasus mountains, which are the study area, were estimated using the new method, and there was very little error between the actual values and the results obtained with the offered formula. The assessment mechanism with new formula allows for highly accurate estimation of the baseflow of rivers basins under any natural conditions, even in the absence of observational data and without spatial-temporal limitations.

Keywords: Surface runoff, baseflow (subsurface runoff), hydrologic soil groups, hydrograph separation, initial abstraction

I. Introduction

The Republic of Azerbaijan is located in an arid and sub-arid region, so there is a serious water shortage. On the other hand, under the influence of global climate change and human activity, there is a tendency for water resources to decrease. River waters account for more than 80% of Azerbaijan's water resources. Against the backdrop of arid climate, the formation capabilities of river waters are weakening and their gradual depletion is observed. The increase of human activities and the population's demand for drinking water also puts additional pressure on the reduction of water resources. According to estimates, over the past 30 years, the republic's water resources have decreased by 15-25% in various rivers. In such conditions, there is a need for continuous assessment of river water resources. The water resources of rivers consist of their surface and underground flow parts. The formation of natural components, including river flow, in any area depends on the temperature and humidity conditions of the area. Previously, assessments of the humidity of the

area and water balance elements were carried out mainly with precipitation and temperature quantities, but now the direction of scientific approaches has changed significantly. Modern science requires the solution of water-related issues not only in a multi-year period, but also within a more specific time and space. While hydrometeorological indicators can play the role of basic data for assessment in the medium-long term, they lose their importance within a specific time-space framework. In such situations, the level of humidity of the area and the moisture content of the soil become the main factors. That is, when we assess the water balance of the area at any given moment, the precipitation and temperature quantities lose their role as the main factor in that specific situation. Therefore, currently, in order to increase the flexibility and accuracy of hydrological scientific research, there is a tendency to assess the humidity conditions of the area on a multifactorial basis. Research that is inclined to the multifactorial principle gives impetus to a deeper analysis of the humidity conditions of the area and to solve the problem [3, 10].

Thus, in the process of assessing the water resources of rivers, multifactorial and complex analysis of the water balance of river basins is an important detail. The surface runoff of rivers can usually be measured by various methods at hydrometeorological stations. However, the process of groundwater inflow into rivers, determining its share in its nutrition and participation in the study of water balance remains a poorly studied area of hydrology. For this purpose, in the presented article, we have put forward a new scientific approach to calculating the shares of underground feeding of rivers (baseflow). The role of groundwater in the water balance of the territory and in the nutrition of rivers is characterized by the following three important aspects:

1) Baseflow as an integral part of a single river system, along with surface runoff.
2) As a participant in the water balance of the area and a soil moisturizer.
3) As an underground organizer and regulator of rivers runoff.

II. Methods and materials

Satellite images, digital elevation models (DEM) and hydrometeorological observation data from 2000-2024 were used as input research materials. Fragments of Landsat-7 ETM+ and Landsat-8 OLI/TIRS multispectral satellite images were applied to obtain landscape types (LULC) and regions moisture condition. Considering the content of the study, priority was given to indices for vegetation (NDVI, SAVI), bare soil (BSI), build-up (NDBI), urban (UI), water (NDWI) and moisture (NDMI).

The hypsometric indicators of the area (elevation, slope degree, aspects, etc.) were studied using a digital elevation model (DEM-Digital Elevation Model). Surface, Density and Hydrology and other software were applied in ArcGIS to collect morphometric indicators (determination of river basins, flow directions, horizontal and vertical surface fragmentation, density of the river network, etc.).

In areas where observations were not made, the restoration of climatic data was carried out using modern Interpolation and Analogue terrains methods, Counter-approach technology [17].

The Rational method was used to study surface runoff, the NRCS-CN method was used to study the infiltration capacity, the Penman-Monteith method was estimated to research evapotranspiration, the Ponce-Shetty and Lvovich methods were used to study the theoretical foundations of water balance. [4, 12, 14, 15, 21].

When studying the soil-water mechanism with NRCS-CN methods, the following water balance elements are usually assessed:

1) Hydrological abstract (or hydrological water losses) ─ the part of precipitation that does not turn into surface runoff. In other words, the entire part of precipitation that does not turn into surface runoff is considered abstract losses. Its content reflects the part of precipitation spent on soil moistening, infiltration and evapotranspiration. Hydrological abstract is denoted by L and is calculated by this formula.

$$L=P-Qs \quad (1)$$

Here, P ─ is atmospheric precipitation, Qs ─ is surface runoff.

2) Maximum soil water retention ─ indicates the maximum water retention capacity of the soil of the area under specific physical-geographical conditions and is denoted by S. The functional relationship between the maximum retention (S), precipitation (P) and surface runoff (Qs) is calculated by the following formula:

$$S = 5 \times [\ P+2Qs - (4Qs^2 + 5PQs)^{½}\ ] \quad (2)$$

3) Initial abstraction ─ is the fraction of precipitation that is spent on various areas before surface runoff is formed and is denoted by Ia. Initial abstraction plays the role of a preparatory stage for surface runoff, that is, it shows the share of it spent on losses (filtration, accumulation in depressions, transpiration by the plant surface, initial evaporation from the soil, etc.) after the onset of precipitation until the runoff occurs. The Ia=λS relationship reflects the state of precipitation transformation into runoff under various natural conditions. Here λ is the initial abstraction coefficient. Ia=0.2S is assumed for average (normal) humidification conditions, Ia=0.3S for arid areas, and Ia=0.1S for extreme moisture conditions. [1, 11, 26, 28].

4) Factual soil moisture ─ indicates the actual humidity content of the soil at the time of observation, that is, the amount of water in it. Factual soil moisture is indicated by F and is expressed as follows:

$$F=P-Qs-Ia \quad (3)$$

5) Antecedent Moisture Condition (AMC) ─ reflects the moisture content of the area on the eve of precipitation. The word "antecedent" ("antecedent") indicates how the weather conditions were in terms of humidity (dry, hot, humid, rainy) in the days before the onset of precipitation. The territories are divided into 3 AMC conditions according to the moisture conditions. In the USDA classification, the amount of precipitation (P) in the last 5 days is usually taken as the main criterion when assessing AMC conditions. If the precipitation in the last 5 days is 12-28 mm, it is considered normal moisture (AMC II). When precipitation is less than 12 mm, AMC I (dry) conditions are accepted, and when it is more than 28 mm, AMC III (moist) conditions are accepted [5, 19, 20].

III. Results and discussion

The role of groundwater in river flow is mainly manifested in its regulatory function, in its role as a source of nutrition for the river during dry periods without precipitation. This has also been proven by monitoring changes in precipitation and water discharge in several areas of Azerbaijan with different natural conditions. Comparison of data from hydrometeorological stations in the same area has shown that in most cases, maximum water discharge is not observed in rivers in the first days of precipitation. This is explained by the fact that precipitation is used for soil moistening and initial abstraction in these first days. On rainy days, flow occurs mainly through the surface, while groundwater recharge is more pronounced in the dry period, especially 5-10 days after precipitation. Although groundwater recharge manifests itself gradually and evenly, since infiltration increases after relatively heavy precipitation, the activity in groundwater recharge is relatively high during the first 5-10 days after precipitation, and gradually weakens in the subsequent period, which in turn results in a decrease in soil moisture.

Depending on the physical and geographical conditions of the area, baseflow share is at different levels, sometimes even higher than the surface nutrient part. So far, in scientific studies, the share of the underground feeding of the rivers and its role in the formation of the river runoff have been assessed in three ways:

1) By comparing river basins with similar morphometric indicators, but sharply differing in geological structure and water discharge.

2) By separating the hydrographs of rivers according to their nutrient sources.

3) By applying the remaining part to the underground nutrition after calculating the surface runoff and evaporation quantities in the water balance.

The method of finding the share of the underground feeding of rivers by hydrograph separation is the most widespread method in hydrology. This method has been widely used both in the former post-Soviet space and in hydrological studies in the USA and the West European countries. With some exceptions, in this method, the river's baseflow shares are usually calculated by the volume of water covered by the lowest levels of water discharge in the hydrographs [7, 9, 16, 27].

One of the difficulties in studying baseflow is that in most cases its share is determined by quantitative indicators of the remaining part after calculating other water balance elements. It is known that precipitation falling on river basins in the multi-annual term is found by separating it into 3 components: [8, 23].

$$P = Q+U+E \quad (4)$$

where: P – atmospheric precipitation, Q – surface runoff, U – baseflow (underground feeding of rivers), E – actual evapotranspiration.

Observations are usually made on the water discharge of surface runoff on the elements of the river water balance. Observations on infiltration (baseflow) and actual evaporation data are a minority. In the former post-Soviet space, including Azerbaijan, when assessing water balance elements, surface runoff was usually determined by data from observation stations, and groundwater flow was determined by hydrograph separation . The remaining part of the precipitation was considered to be spent on actual evapotranspiraration.

As can be seen, very serious calculation errors were observed when assessing the water balance of the area. Thus, at least two of the three components of precipitation (infiltration and evaporation), and sometimes all three, including surface runoff, were calculated without relying on measurement data.

The baseflow of rivers is a parameter that depends largely on the geological-lithological structure of river basins and the rocks permeability capacity. The concept of “Hydrologic Soil Group" (HSGs) is a very important parameter in the study of soil-water relations, especially in the field of assessing the infiltration level of the area. HSGs are classified based on the granulometric composition of soils, reflecting the infiltration capabilities of soils and the potential to create surface runoff. According to the NRCS classification, 4 HSGs (A, B, C, D) are distinguished and 12 soil codes are defined within them according to their mechanical composition.

Table 1: *Infiltration rate changes depending on soils granular texture*

Soil texture types	Percent of slope				
	0-4%	5-8%	8-12%	12-16%	Over 16%
	Infiltration rate, ınches/hour				
Coarse Sand	1.25	1.00	0.75	0.50	0.31
Medium Sand	1.06	0.85	0.64	0.42	0.27
Fine Sand	0.94	0.75	0.56	0.38	0.24
Loamy Sand	0.88	0.70	0.53	0.35	0.22
Sandy Loam	0.75	0.60	0.45	0.30	0.19
Fine Sandy Loam	0.63	0.50	0.38	0.25	0.16
Loam	0.54	0.43	0.33	0.22	0.14
Silt Loam	0.50	0.40	0.30	0.20	0.13
Silt	0.44	0.35	0.26	0.18	0.11
Sandy Clay	0.31	0.25	0.19	0.12	0.08
Clay Loam	0.25	0.20	0.15	0.10	0.06
Silty Clay	0.19	0.15	0.11	0.08	0.05
Clay	0.13	0.10	0.08	0.05	0.03

From group A to D, a tendency for infiltration to weaken and runoff to increase is observed in soils. Hydrological soil groups are distinguished from each other by taking into account the

predominance of a mixture of sand (S), silt (Si), loam (L) and clay (C) in the soil composition. Since the sand-clay composition plays a major role in water filtration, the amount of sand and clay plays the main transitional quantity between soil types. For type A soils, the amount of sand is more than 50%, the amount of clay is 0-10%, in group B, sand is 20-50% and clay is 10-20%, in group C, sand is 40-60%, clay is 20-40%, and in type D, sand is 20-30%, and clay is more than 40-60% [13].

The changes in permeability capacity depending on the granular composition of soils are reflected in Table 1 [22].

The basic methods mentioned above play a leading role in the world in the field of assessment of various components of water balance elements (surface runoff, infiltration, evaporation). Currently, it has become possible to obtain most of the information about the components that affect the water balance elements from satellite space information. On the other hand, there are GIS and other multifunctional software that allow studying the impact of components on water balance elements. For this reason, perfect methodologies are created based on the internal modification of the existing water balance methods themselves and their synthesis. Such methods, in addition to incorporating the advantages of the basic methods, serve to eliminate the shortcomings existing in them and have more advanced features [2, 6, 18, 24, 25].

In our research, we have proposed a new method to calculate the share of baseflow by combining the advantages of hydrological methods that play a leading role in the world. As mentioned, the atmospheric precipitation (P) falling on the basin is spent on surface runoff, baseflow and evapotranspiration over a multi-year period. In the NRCS-CN method, the part of precipitation spent on surface runoff (Q) is found through CN numbers reflecting the existing natural conditions. The remaining part of precipitation (L) that does not turn into surface runoff goes to actual soil moisture (F) and evapotranspiration (E): L=F+E. According to the NRCS-CN method, actual soil moisture is expressed as F=P-Q-Ia equation. On the other hand, according to the method, the ratio of the actual soil moisture (F) to the maximum soil water retention (S) is equal to the ratio of hydrological losses to precipitation: F:S=L:P.

As can be seen, as the fraction of surface runoff (Q) in precipitation decreases, the share of infiltration and evaporation in the remaining hydrological losses (L) increases. Also, as Q decreases and S increases, the share of evaporation (E) in maximum retention (S) is risen compared to the infiltration (F) indicator.



Fig. 1: *River basins of the southern slopes of the Greater Caucasus Mountains*

Thus, the F:S ratio expresses the share of infiltration in the maximum water retention conditions of soils. However, the maximum water retention quantity includes all other losses that are not included in the initial abstraction, evaporation and surface runoff. Since the water balance

elements, in turn, are determined by atmospheric precipitation, we have proposed to calculate the baseflow share of rivers as the F:S ratio of the quantity

$$U = (L \times \frac{F}{S}) \quad (5)$$

here, U – is the share of groundwater feeding of rivers (in mm), L – is hydrological losses (mm), F – is the factual soil moisture (mm), S – is the maximum water soil retention (mm).

In order to study the groundwater flow in the river's feeding, the southern slope of the Greater Caucasus Mountains located within the Republic of Azerbaijan was selected as the study area (Fig.1).

Table 2 shows the main water balance elements of the rivers of the southern slopes of the Greater Caucasus.

Table 2: *Main water balance elements of the Greater Caucasus rivers: P-precipitation, Qs-surface runoff, L-hydrological losses, S-maximum retention, Ia-initial abstraction, F-factual soil moisture.*

River	P mm	Q_s mm	L mm	S mm	Ia mm	F mm
Mazym	735	222.7	512.3	860.2	172.1	340.2
Balaken	843	236.4	606.6	1056.4	211.3	395.3
Katekh	893	266.8	626.2	1058.5	211.7	414.5
Tala	798	244.3	553.7	925.1	185.0	368.7
Mukhakh	827	262.7	564.3	926.0	185.2	379.1
Qapychay	632	202.5	429.5	701.9	140.4	289.1
Kurmukh	865	331.2	532.8	794.7	158.9	373.9
Kashkachay	641	167.7	473.3	850.9	170.2	303.1
Shin	655	206.5	448.5	738.7	147.8	300.7
Kish	728	225.3	502.7	835.5	167.1	335.6
Dashagıl	822	292.6	529.4	821.0	164.2	365.2
Kungut	789	252.9	536.1	876.0	175.2	360.9
Eyrichay	670	158.7	511.3	960.9	192.2	319.1
Alijan	618	63.5	554.5	1421	284.2	270.3
Turyanchay	822	122.4	699.9	1583	316.6	383.3
Goychay	742	118.4	623.6	1375	412.5	211.1
Girdiman	936	187.4	748.6	1511	453.3	295.3
Aksu	648	102.9	545.1	1204	421.4	123.7
Pirsaat	314	66.3	247.7	488.9	171.1	76.6
Jeyrankechmez	238	17.7	220.3	620.1	217.0	3.3
Sumqayıt	229	20.7	208.3	554.9	194.2	14.1

The groundwater feeding rates of the Greater Caucasus rivers have previously been estimated by various authors based on observational data and by hydrographs separation. A comparison the actual parameters and values obtained by new formula is given in Table 3.

Table 3: *Comparison of the actual and new calculated values of the groundwater nutrition share of the rivers of the southern slope of the Greater Caucasus*

Rivers	Underground feeding of the rivers		
	Factual, mm	Calculated with new method, mm	Difference , %
Mazym	183.2	202.6	+9.57
Balaken	198.2	226.9	+12.6
Katekh	261.3	245.2	–6.16
Tala	238.2	220.7	–7.35
Mukhakh	210.4	231.0	+8.92
Kapychay	165.7	176.9	+6.33
Kurmukh	254.1	250.4	–1.46
Kashkachay	143.1	168.6	+15.1
Dashagıl	262.4	235.5	–10.3
Eyrichay	181.3	169.8	–6.34
Alijan	98.6	105.4	+6.45
Turyanchay	187.7	169.4	–9.74
Goychay	90.8	95.7	+5.12
Girdiman	129.4	146.3	+11.6
Aksu	60.7	56.0	–7.74
Pirsaat	36.2	38.8	+6.70
Jeyrankechmez	0.81	1.07	+24.3
Sumqayıt	19.6	5.29	+3.45

IV. Conclusion

In our study, the baseflow (subsurface flow share) of the rivers of the southern slope of the Greater Caucasus Mountains located in the Republic of Azerbaijan was assessed. The baseflow of the river estimated by the formula we proposed were also compared with the traditional hydrograph separation method, which is the most popular in this field so far. At the same time, they were also compared with the subsurface flow shares measured at several gauged points. The application of the most modern scientific methods and studies conducted in the GIS environment allowed us to obtain very reliable results. It was found that there was a very slight difference between the quantities of the baseflow of the river obtained by the new approach we proposed and the results obtained by the actual and hydrograph separation of the rivers. Thus, in 73 cases this difference did not exceed ±10%, and in only 27 cases the error was slightly higher than 10%. These provide grounds for using this method to determine the baseflow of rivers located in any physical-geographical conditions where there is no hydrometeorological data or insufficient observation input.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ANALYTICAL MODEL OF SOIL LAYER VIBRATIONS UNDER SEISMIC LOADING: RESONANCE EFFECTS AND ENGINEERING APPLICATIONS

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Abstract

Seismic impacts cause low-frequency vibrations of structures, leading to the development of inertial forces and significant mechanical stresses in structural elements. These stresses may exceed the strength limits of materials, resulting in damage or collapse. Therefore, in seismically active regions, buildings are designed with consideration of seismic reinforcement. This paper proposes an original model for analyzing vibrations of a soil layer, which for the first time accounts for the relationship between vibration frequency, standing wave length, and the physical–mechanical properties of the foundation. The scientific novelty lies in treating the elastic layer as an independent oscillatory system, separate from global Earth vibrations, and in refining the method for determining resonance frequencies. A two-dimensional model is used, based on equations of motion derived from Lamé constants and boundary conditions that reflect real soil–structure interaction. The obtained analytical expressions make it possible to evaluate the natural frequencies of vibrations depending on the layer thickness and its elastic properties. The modeling results are consistent with the observed ranges of seismic waves typical for most buildings. It is established that the coincidence of the soil and structure frequencies leads to resonant amplification, increasing foundation stresses and the risk of failure. The practical significance of this work lies in the possibility of applying the model to assess seismic resistance, optimize design solutions, and develop effective seismic protection technologies. Future research perspectives include accounting for anisotropy, base friction, nonlinear effects, and applying numerical modeling methods to improve the accuracy of engineering calculations.

Keywords: seismic impact, resonant frequencies, elastic soil layer, standing wave, dynamic stability, Lamé parameter

I. Introduction

Earthquakes are among the most destructive natural phenomena, exerting a significant impact on the safety of buildings and structures. In seismology, special attention is given to studying the interaction between the soil layer and structures, since this interaction determines the magnitude of the resulting stresses and the likelihood of structural failure. The present study is the first to describe the vibration of the soil layer under seismic loading as a distinct dynamic phenomenon and to investigate the characteristics of standing wave propagation in an elastic medium.

The seismic wave spectrum contains vibrations with frequencies close to the natural frequencies of many structures, which for various modes typically range from fractions of a hertz to a few hertz (characteristic periods from 0.2 to 2 s). At resonance, stresses increase at the soil–foundation interface as well as within the structure itself, leading to a higher probability of failure. Resonant amplification of pendulum-like oscillations is particularly dangerous when the center of gravity of the structure is located far from its point of support — a situation typical for bridge piers, chimneys, and high-rise buildings.

II. Methods

A two-dimensional analytical formulation of an elastic soil layer was developed. The equations of motion were derived using Lamé constants, with boundary conditions: zero stresses at the surface and free horizontal sliding at the base. The method of separation of variables was applied, assuming harmonic solutions. This analytical approach allows, for the first time, to express the vibration frequency of the soil layer explicitly through the wave length and elastic parameters, revealing the resonance conditions with structural systems.

The seismic effect is characterized by three parameters: amplitude level, predominant period, and duration of vibrations. The duration can be crucial for structural stability, as short-term loads with high acceleration may be harmless for many structures.

The longest period of Earth's free oscillations is about 1.5 hours, while the periods of soil layer oscillations during earthquakes are on the order of fractions of a second. Therefore, earthquakes can be considered independent of the Earth's global oscillations. In this study, the soil layer is analyzed independently of the Earth's vibrations. A soil layer of thickness y_0 is considered. On the surface, stresses are absent, i.e. $\sigma_{xy} = 0$ and $\sigma_{yy} = 0$; at the base $v = 0$ and $\sigma_{xy} = 0$, which means there is no vertical displacement and the soil is free to slide horizontally (Fig. 1).

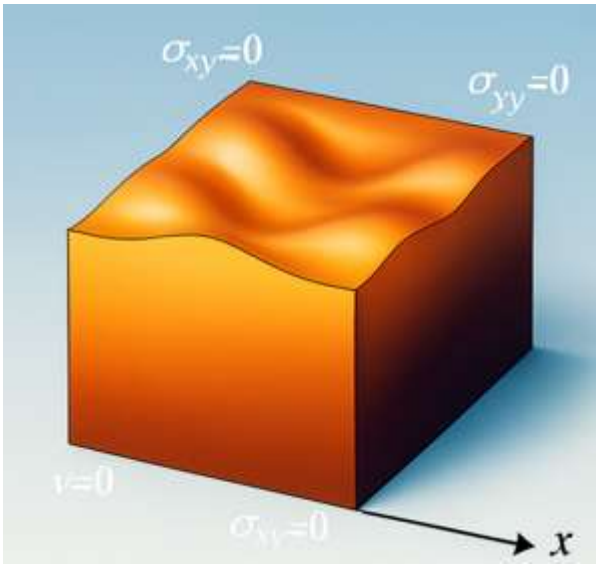


Fig. 1: *Horizontal sliding of the soil*

To simplify the analysis, a two-dimensional formulation is adopted for the elastic soil medium. The equations of motion are expressed as follows:

$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu)\nabla^2 u \quad (1)$$

$$\rho \frac{\partial^2 v}{\partial t^2} = (\lambda + 2\mu)\nabla^2 v \quad (2)$$

где ρ – is the density of the soil,, λ, μ – are the Lamé parameters, t - time, u, v – are displacements in the horizontal and vertical directions.

$\nabla^2 = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}$, λ *and* μ assumed to be constant.

Under the assumption of oscillatory motion characterized by angular frequency $\boldsymbol{\omega}$ and standing wave length $\boldsymbol{l}$ (Fig.2), the following formulation applies:

$$u = Usin\omega t cos\frac{2\pi}{l}x \quad (3)$$

$$v = Vsin\omega t sin\frac{2\pi}{l}x \quad (4)$$

where $\boldsymbol{u}$ and v are functions of the vertical coordinate y.

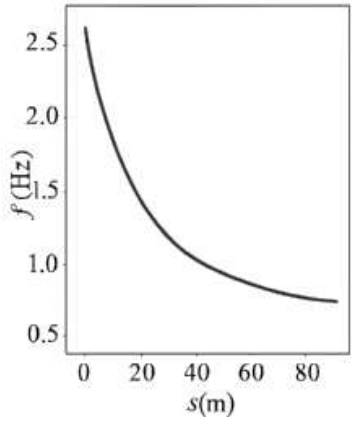


Fig.2: *Frequency dependence on resonant standing wave length*

By substituting expressions (3) and (4) into equations (1) and (2), we obtain

$$-\rho\omega^2 U = (\lambda + 2\mu)\left[-\left(\frac{2\pi}{l}\right)^2 U + U^{\parallel}\right] \quad (5)$$

$$-\rho\omega^2 V = (\lambda + 2\mu)\left[-\left(\frac{2\pi}{l}\right)^2 V + V^{\parallel}\right] \quad (6)$$

Solving equations (5) and (6) with respect to u and v, we obtain

$$u = c_1 sin\Omega y + c_2 cos\Omega y \quad (7)$$

$$V = D_1 sin\Omega y + D_2 cos\Omega y \quad (8)$$

where $$\Omega\sqrt{\frac{\rho\omega^2}{\lambda+2\mu} - \left(\frac{2\pi}{l}\right)^2} \quad (9)$$

For the shear stress, we obtain the following expression:

$$\sigma_{xy} = \mu\varepsilon_{xy} = \mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) = \mu\left(\frac{2\pi}{l}V + u'\right) sin\omega t cos\frac{2\pi}{l}x \quad (10)$$

Applying the boundary conditions at: $y = 0, v = 0, \sigma_{xy} = 0$, the resulting formulation is:

$$D_2 = 0; \quad c_1 = 0 \quad (11)$$

At the upper boundary $y = y_0, \sigma_{xy} = 0, \sigma_{yy} = 0$, the resulting expressions are:

$$\sigma_{xy}\big|_{y=y_0} = \mu(D_1 \sin\Omega y_0 - \Omega c_2 sin\Omega y_0) sin\omega t cos\frac{2\pi}{l}x = 0$$

or

$$\frac{2\pi}{l}D_1 - \Omega C_2 = 0 \quad (12)$$

From equations (7) and (11), it follows that

$$U = c_2 cos\Omega y_0$$

$$V = D_1 sin\Omega y_0 \quad (13)$$

Subsequently, we derive the expression

$$\sigma_{yy} = \lambda\Delta + 2\mu\varepsilon_{yy} = \lambda\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + 2\mu\frac{\partial v}{\partial y} = \left[\lambda\left(-\frac{2\pi}{l}U + V'\right) + 2\mu V'\right] sin\omega t cos\frac{2\pi}{e}x =$$

$$= \left[-\frac{2\pi}{l}\lambda c_2 cos\Omega y_0 + (\lambda + 2\mu)\Omega D_1 cos\Omega y_0\right] sin\omega t cos\frac{2\pi}{e}x - \frac{2\pi}{l}\lambda c_2 + (\lambda + 2\mu)\Omega D_1$$

$$= 0 \quad (14)$$

From equations (12) and (14), it follows that

$$\omega^2 = \frac{2(\lambda + \mu)}{\rho} \quad (15)$$

where ν denotes the oscillation frequency.

$$\nu = \frac{\omega}{2\pi}$$

III. Model Formulation

The frequency of an earthquake provides a basis for estimating the wavelength of standing soil vibrations. The following materials present various phenomena that may occur during seismic events. In particular, assuming that the Lamé parameters of the soil remain constant, the wavelength l of the standing wave can be approximated analytically as:

$$l = \frac{2\pi}{\omega}\sqrt{\frac{2(\lambda+\mu)}{\rho}}$$

This relation reflects the fundamental coupling between soil stiffness and wave propagation characteristics under seismic loading.

The frequency of an earthquake provides a basis for estimating the wavelength of standing soil vibrations.

The following materials present various phenomena that may occur during seismic events. In particular, assuming that the Lamé parameters of the soil remain constant

$$\lambda = 1 \cdot 10^9 Pa, \qquad \mu = 0{,}8 \cdot 10^9 Pa,$$

According to equation (15), we obtain

$\omega = 2\pi\nu;\ E = 2 \cdot 10^9$; $\rho = 2 \cdot 10^3$ кг/м^3; $\nu -$ frequency.

1) $l = 100m;\ \nu = 27{,}6\ 1/sec$
2) $l = 300m;\ \nu = 9{,}2\ 1/sec$

IV. Results

The analysis revealed that the oscillation frequency of the soil layer is strongly influenced by its thickness and elastic properties. The computed resonance frequencies are consistent with the observed ranges of seismic wave periods typically affecting civil structures (0.2–2 s). It was found that when the natural frequency of the soil coincides with the excitation frequency, a resonance amplification effect occurs (Fig.3), resulting in elevated stress levels at the foundation and a significant increase in the risk of structural failure. These findings underscore the critical importance of incorporating site-specific soil characteristics into the seismic design of buildings and infrastructure. In particular, the resonance behavior highlights the need for accurate estimation of soil stiffness and stratification in order to mitigate amplification effects. The results also support the use of analytical models for predicting wave–structure interaction and provide a basis for refining seismic safety criteria in engineering practice.

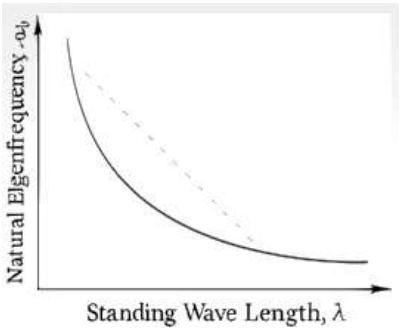


Fig.3: *Soil Resonance Curve*

A structure modeled as a free body in space possesses six degrees of freedom, corresponding to distinct spatial vibration modes: three translational displacements (vertical and two horizontal) and three rotational motions. These include rocking about the longitudinal axis (lateral sway), pitching about the transverse axis (longitudinal tilt), and torsional rotation about the vertical axis.

The dynamic response of a structure with a foundation represents a superposition of these vibration modes, each characterized by its own natural frequency. Under seismic excitation, the

interaction between soil and structure leads to complex modal behavior, which must be accounted for in dynamic analysis.

In the subsequent formulation, the Lamé parameters $\lambda\ (\lambda = 1 \cdot 10^9 Pa)\ and\ \mu\ (\mu = 0{,}8 \cdot 10^9 Pa)$ are considered depth-dependent. Where applicable, basal friction at the bottom of the soil layer is also incorporated to refine the boundary conditions and improve the accuracy of the vibration model.

V. Discussion

A comparative analysis between the obtained results and previously established data confirms the validity and reliability of the proposed analytical model. The observed agreement with known seismic behavior patterns supports the adequacy of the theoretical framework and its applicability to real-world scenarios.

The scientific novelty of this study lies in the conceptual treatment of the soil layer as an autonomous dynamic system, decoupled from the global oscillatory modes of the Earth. Unlike conventional approaches that often assume uniform or externally constrained soil behavior, this model emphasizes the intrinsic vibrational characteristics of the soil mass itself. Such a perspective enables a more precise identification of resonance frequencies and facilitates the prediction of hazardous operational regimes for structures subjected to seismic loading.

From a practical standpoint, the developed methodology offers a robust tool for assessing the seismic resilience of buildings and infrastructure. By incorporating depth-dependent elastic parameters and accounting for localized soil–structure interaction effects, the model enhances the accuracy of seismic risk evaluation. Furthermore, it provides a theoretical basis for the design of targeted anti-seismic measures, including foundation optimization, vibration isolation strategies, and site-specific engineering solutions.

Overall, the findings contribute to the advancement of analytical techniques in earthquake engineering and underscore the importance of soil dynamics in the formulation of reliable seismic protection systems.

VI. Conclusion

This study presents an advanced analytical model for evaluating soil layer vibrations induced by seismic activity. Unlike conventional approaches that often simplify the soil–structure interaction, the proposed model treats the soil layer as an independent dynamic system with its own vibrational characteristics. This allows for a more accurate representation of energy transfer from seismic waves to the foundation.

The analysis establishes a functional relationship between the natural frequency of soil vibrations, the wavelength of standing waves, and the elastic properties of the underlying medium. It is shown that resonance effects—arising when the excitation frequency matches the system's natural frequency—can significantly amplify vibration amplitudes. This leads to increased stress concentrations in the foundation and elevates the risk of structural damage.

The results highlight the necessity of incorporating detailed geotechnical parameters into the design of earthquake-resistant foundations. Neglecting these factors may result in underestimating seismic hazards, particularly in regions with high seismic activity.

Future research directions include extending the model to account for soil anisotropy, depth-dependent variations in elastic parameters, and basal friction at the bottom of the soil layer. Additional emphasis will be placed on integrating numerical simulation techniques, such as finite element analysis, to validate analytical predictions and explore complex soil–structure interaction scenarios.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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CASCADE RISK MODELING IN MOUNTAINOUS REGIONS: THE CASE OF THE 2023 SHOVI TRAGEDY IN GEORGIA

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Abstract

Mountainous regions are highly susceptible to natural hazards due to the interplay of geological instability, extreme climatic events, and infrastructural vulnerability. Such hazards often evolve into cascading risks, where an initial event triggers a sequence of secondary processes with far-reaching social, economic, and environmental consequences. This study examines the 2023 Shovi landslide in Georgia as a case of cascading risk development, integrating meteorological, glaciological, and geological data through hybrid forecasting models and semantic network analysis. Multi-level risk assessment is employed to map the progression from initial triggers, through direct and indirect impacts, to systemic disruptions affecting tourism, transport, and local communities. Expert-based evaluations supplement data gaps, enhancing model accuracy and reliability. The study further demonstrates how hybrid modeling and semantic network approaches can inform decision-making frameworks, enabling early warning protocols, infrastructure planning, and community preparedness. Findings underscore the importance of integrating diverse data sources and analytical approaches to improve disaster resilience, offering insights applicable to other mountainous regions with high variability in precipitation and glacial activity.

Keywords: cascading risks, landslide, hybrid forecasting, semantic networks, multi-level risk assessment, Shovi, disaster resilience, mountainous regions.

I. Introduction

Mountainous regions are among the most disaster-prone environments globally, where the interplay of geological instability, climatic extremes, and infrastructural vulnerability generates elevated risks of catastrophic events. Such regions frequently experience natural hazards including landslides, debris flows, avalanches, and floods, often resulting in substantial human and economic losses. These hazards are particularly dangerous due to their potential to develop into cascading risks, in which a single triggering event initiates a sequence of secondary processes, producing profound impacts across multiple systems. Understanding and modeling these cascading dynamics has thus become a critical task in disaster risk research and management.

Cascading risks are defined as those risks that, once initiated, lead to the emergence of other interconnected risks, functioning according to a "chain reaction" principle. That is, a single hazard or failure can set off a series of events that propagate across different systems or sectors. Key characteristics of cascading risks include:

- Chain effect: One event acts as a triggering factor for other risks.
- Interdisciplinary impact: Effects may extend across social, economic, technological, and ecological domains.
- Unforeseen consequences: An initially minor risk can escalate into a global or systemic crisis.

On August 3, 2023, a devastating disaster struck the Shovi mountain resort in Georgia's Racha region. Massive landslides and debris flows, triggered by a combination of geomorphological and hydrometeorological factors, destroyed infrastructure and claimed dozens of lives. This tragedy shocked the nation and attracted international attention, not only due to the scale of destruction but also because it illustrated the complex nature of cascading processes in fragile mountainous environments.

The objective of this study is to examine the Shovi tragedy as a case of cascading risk development and to propose a conceptual framework for its analysis. The research employs systemic and semantic network approaches to reconstruct event sequences and highlight the interactions between natural and anthropogenic factors. By doing so, the study contributes to a deeper understanding of how cascading risks originate, propagate, and culminate in large-scale disasters. This paper presents a theoretical framework applied to the Shovi tragedy, encompassing hybrid forecasting models, semantic and network-based approaches, multi-level risk assessment, and integration with decision-making systems.

II. Theoretical Framework: The Shovi Landslide Case Study

A. Hybrid Forecasting Models in the Shovi Context

Hybrid forecasting models integrate statistical techniques, machine learning, and expert-based approaches to improve predictive accuracy in complex systems. In the case of the Shovi landslide, a hybrid model could combine meteorological data (e.g., precipitation intensity), glaciological observations (e.g., glacier melt rates), and geological assessments (e.g., slope stability) to provide a comprehensive risk evaluation. For instance, integrating deep learning techniques with physical models has shown promising results in enhancing flood prediction accuracy [1].

B. Semantic and Network-Based Approaches

Semantic networks represent relationships among concepts, enabling the modeling of complex systems through interconnected nodes and edges. Applied to disaster risk assessment, semantic modeling can identify causal chains and feedback loops. In Shovi, semantic modeling could clarify interactions among climatic factors, glacier dynamics, and human activity, providing insights into disaster progression. Research has demonstrated the utility of semantic approaches in vulnerability modeling and disaster management [2].

C. Multi-Level Risk Assessment and Modeling

Multi-level modeling in risk assessment accounts for factors across different spatial and temporal scales. In Shovi, a comprehensive understanding of risk required integrating micro-level factors (e.g., local soil saturation) with macro-level patterns (e.g., regional climate trends). A proposed three-tier framework for multi-level risk assessment considers interactions among hazards and their complex effects [3].

D. Lessons Learned from Shovi

The Shovi landslide exemplifies the challenges of disaster forecasting. Despite data availability, the absence of an integrated forecasting system contributed to the tragedy. A comprehensive hybrid model, incorporating semantic networks and multi-level risk assessment, could have supported earlier warnings and informed mitigation strategies. This study highlights the importance of integrating diverse data sources and analytical approaches to enhance disaster preparedness [4].

E. Decision-Making Implications

Effective disaster risk reduction requires translating predictive models into actionable strategies. In the Shovi context, integrating forecasting models into decision-making systems could facilitate timely evacuations and infrastructure planning. Enhancing disaster resilience necessitates a unified framework combining hybrid forecasting, semantic modeling, and multi-level risk assessment.

III. Analysis of the Shovi Tragedy

A. Risk Assessment and Multi-Factor Modeling

The Shovi case has been previously discussed in [5] as an example of multi-factor forecasting. However, it can also be analyzed in the context of cascading risks, as the sequence of events clearly illustrates the propagation of hazards:

- Initial Event: Collapse of a cliff mass.
- Direct Impact: Landslide and debris flow.
- Indirect Impact: River blockage, infrastructure destruction, and subsequent environmental destabilization.
- Cascading Consequences: Human fatalities, economic losses, and social and psychological crises.

Thus, the tragic event in Shovi exemplifies the mechanism of cascading risk escalation. The initial cliff collapse triggered direct consequences in the form of landslides and debris flows. Simultaneously, it generated indirect effects by obstructing the river flow and damaging local infrastructure. Both pathways led to systemic disruption, significantly affecting tourism, transportation, and the local economy. Ultimately, these disruptions culminated in cascading outcomes, including substantial human losses, social destabilization, and long-term economic challenges for the region.

This case (see Figure 1) demonstrates how a localized geophysical hazard can propagate through interconnected systems, amplify overall impacts, and create a chain reaction of risks.

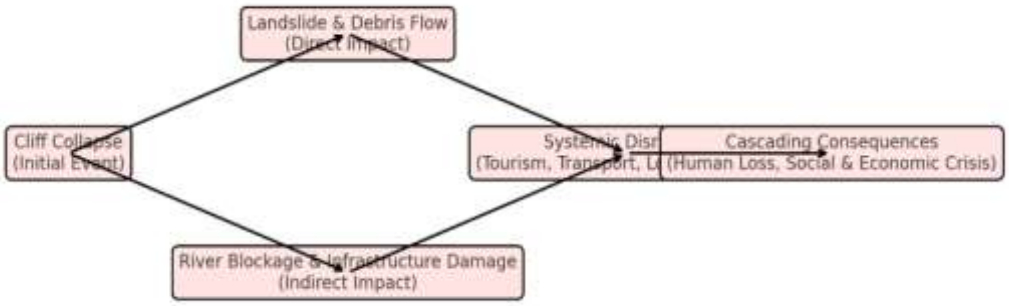


Figure 1: *Cascading Risk Scheme Based on the Shovi Tragedy.*

- Cliff Collapse (Initial Event) – collapse of cliff mass.
- Landslide & Debris Flow (Direct Impact) – landslide and debris flow.
- River Blockage & Infrastructure Damage (Indirect Impact) – river blockage and infrastructure damage.
- Systemic Disruption (Tourism, Transport, Local Economy) – systemic disruption in tourism, transport, and local economy.
- Cascading Consequences (Human Loss, Social & Economic Crisis) – final outcomes: human loss, social and economic crisis.

B. *Risk Assessment and Multi-Level Modeling*

Multi-level modeling for risk assessment has been proposed by the authors in [6,7]. This approach presents a three-tier semantic model that establishes causal relationships among events at different levels. A typical three-tier semantic model (see Figure 2):

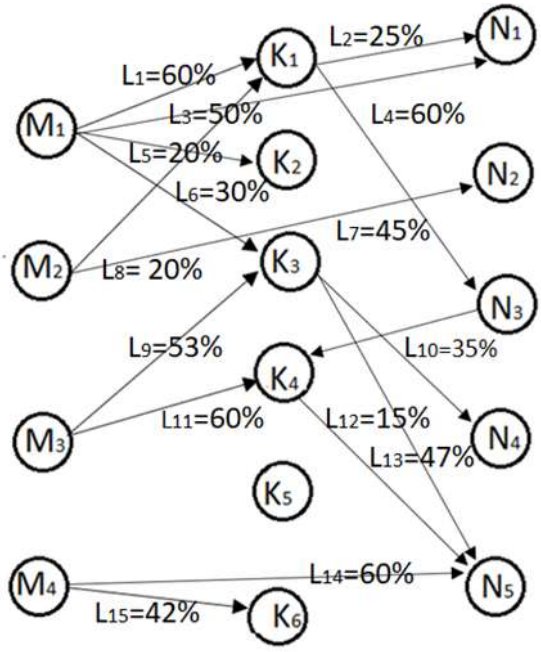


Figure 2: *Three-Tier Semantic Network of Forecasting Models*

Model consists of:

- Stage One Events (M): Initial driving factors, such as natural hazards or socio-political shocks.
- Stage Two Events (K): Transitional processes induced by Stage One events.
- Stage Three Events (N): Final outcomes, which are directly or indirectly affected by preceding stages.

This framework allows for the systematic mapping of cascading processes and facilitates multi-step risk prediction, highlighting the interplay between initial triggers, transitional dynamics, and ultimate consequences.

C. *Involvement of experts in forecasting*

While large volumes of data are required for accurate forecasting, in practice, statistical computation is often unavailable, and data are temporarily estimated using expert judgment. The use of experts is described in [8]. Initially, experts are selected for the predictive process, but following each event, expert selection is updated—some experts are removed from the core database, while others are added. Experts who repeatedly err two or three times are replaced, whereas consistently accurate experts have their reliability scores increased.

The new approach to forecasting assumes that there are at least two industry models that are different from event forecasting models, but if this is not the case, then we use experts. In general, the role of experts in predicting such events is very large, since the information obtained by automatic measurement sensors requires a great deal of knowledge and experience from the event specialist.

Article [9] discusses a hybrid forecasting model that initially evaluates “necessary” and “sufficient” models within the decision-making process, subsequently selecting optimal pairs or triplets of models, and finally engaging experts. The study outlines how to operate with a hybrid

model, determining when experts should be involved and according to which criteria. Algorithms are developed both for selecting new forecasting models and for determining the need to replace an expert. Importantly, expert selection is based on the accuracy of their predictions rather than solely on their competence.

IV. Detailed Data Integration: Meteorology, Glaciology, and Geology

The Shovi landslide resulted from a combination of meteorological, glaciological, and geological factors. Detailed integration of these datasets can substantially enhance the accuracy of predictive models.

A. Meteorological Analysis

Historical data from the Shovi region indicate that in the 48 hours preceding the landslide, cumulative precipitation exceeded 120 mm, significantly above the regional May average. Peak intensities reached approximately 25 mm per hour, leading to soil layer saturation and increased slope instability (see Figure 3). Precipitation measurements from nearby automated meteorological stations, combined with satellite-derived rainfall data, can be integrated into hybrid forecasting models to determine critical thresholds for slope failure.

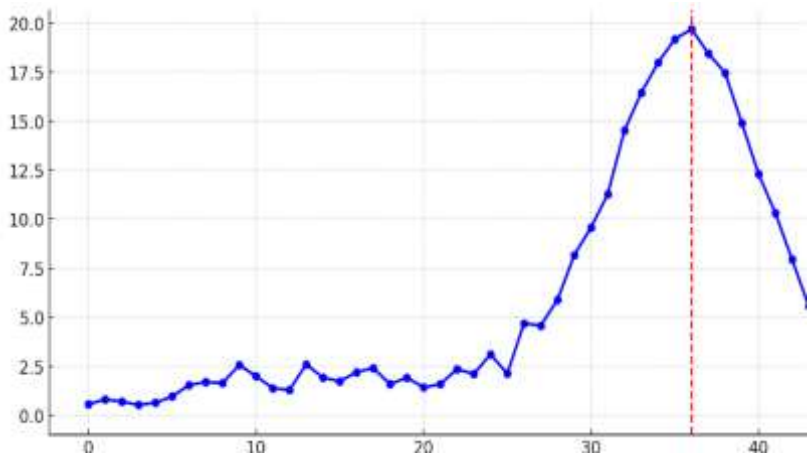


Figure 3: *Precipitation Intensity Series (for Shovi)*

The graph illustrates the precipitation dynamics leading up to the landslide. The red line marks the peak rainfall occurring 6–12 hours prior to the disaster.

B. Glaciological Observations:

The Buba Glacier, located above the Shovi settlement, experienced accelerated melt in the months preceding the catastrophe. Remote sensing imagery revealed approximately a 12% loss in glacier volume compared to the previous year. Subglacial water accumulation contributed to a sudden increase in river discharge, which, in turn, exerted additional stress on downstream slopes (see Figure 4). Incorporating glacial melt models into hybrid forecasting systems allows for the quantification of runoff contributions and flood potential.

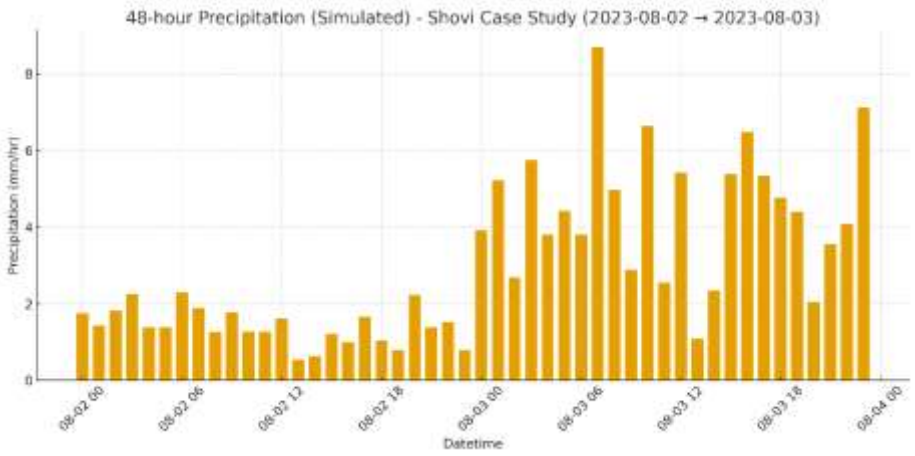


***Figure 4**: Glacial Melt Table (Hourly Water Discharge in m³/s or mm equivalent)*

Example: Increased water discharge corresponding to rising temperatures (°C).

Geological Assessments: Field surveys indicated that the landslide occurred on a slope with an average inclination of 35–40°, composed of loose alluvial deposits and heavily weathered rock. Previous minor landslides in the area suggested a predisposition to slope failure. Geotechnical parameters, including soil cohesion, internal friction angle, and pore water pressure, are critical for deterministic slope stability modeling. Integrating these parameters into statistical and machine learning models significantly enhances predictive capabilities.

C. Semantic Network Diagram of the Shovi Landslide:

A semantic network can represent the cascading interrelations of precipitation, glacial melt, and their propagative effects in the Shovi case. A consolidated, layered approach may be structured as follows (see Figure 5) :

- Initial Stimuli: Climatic triggers, historical antecedent conditions.
- Direct Events: Intense rainfall, glacier melt.
- Secondary Processes: Soil saturation → landslide initiation; glacial melt → debris and mudflows.
- Impacted Entities: Infrastructure, population.
- Mitigation and Response: Existing controls, monitoring, early warning systems.

V. Decision-Making Framework

Integrating hybrid forecasting and semantic network modeling into decision-making frameworks enhances disaster resilience. Key components include:

- Early Warning Protocols: Threshold-based alerts can trigger evacuations or protective actions. For example, if precipitation exceeds 100 mm within 24 hours combined with glacier runoff greater than 15 m³/s, local authorities may implement precautionary measures.
- Infrastructure Planning: Placement of retention walls, diversion channels, and monitoring stations can be optimized based on model outputs. Integration with Geographic Information Systems (GIS) allows for high-risk zone mapping.
- Community Engagement: Effective communication regarding hazard zones and risk levels is essential. Residents and local authorities must be trained to interpret warnings and implement mitigation strategies.

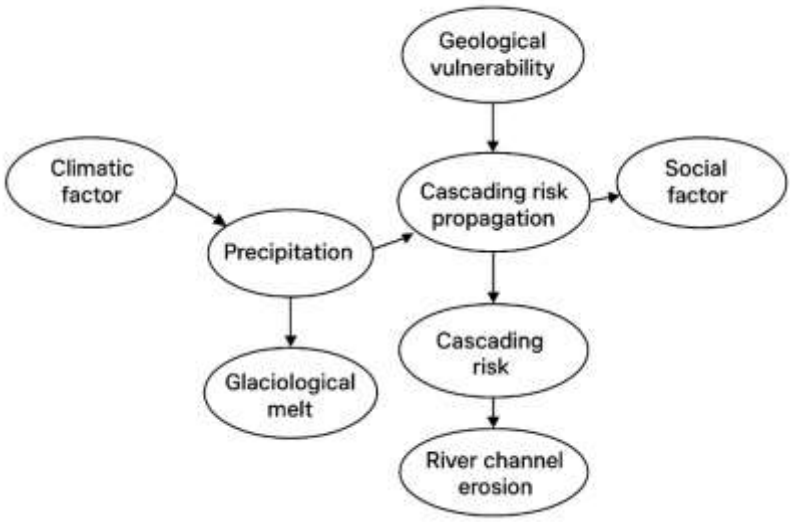


Figure 5: *Hierarchical diagram with arrows (→) illustrating the cascading chain of events.*

VI. Conclusion and Future Applications

The Shovi case underscores the importance of integrating multiple datasets and modeling approaches:

1. Data Integration: Single-source forecasting is insufficient for complex landslides; hybrid models that combine meteorological, glaciological, and geological data are more effective.
2. Forecast Accuracy: Incorporating semantic network analysis enables the identification of cascading effects and interdependent risk factors.
3. Decision Support: Real-time integration of forecasting outputs into decision-making processes facilitates timely mitigation and evacuation.

These lessons can be applied to other mountainous regions characterized by glaciers and highly variable precipitation, enhancing preparedness for large-scale disasters. The findings are expected to inform strategies for risk reduction, early warning mechanisms, and sustainable development practices in similar global mountainous contexts.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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FINANCE, INVESTMENT AND INSURANCE OF THE INFRASTRUCTURE OF THE REGIONAL ECONOMY

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Abstract

The article discusses key aspects of financing, investment and insurance for infrastructure facilities, considering their role in regional economic development. Particular attention is given to the relationship between the effectiveness of regional financial instruments and the sustainability of territorial economic growth. It examines modern mechanisms for attracting investment in infrastructure projects, including public-private partnerships, project financing, and infrastructure issuance. This allows the most promising areas for developing the financial architecture of regional economic systems to be identified. Particular attention is given to insuring infrastructure risks, which is an integral part of ensuring the long-term sustainability of regional investment projects and protecting the financial interests of everyone involved in infrastructure development.

Keywords: regional economy, infrastructure, financing, investment mechanisms, risk insurance, public-private partnership

I. Introduction

The efficiency of the use of the natural resource and social potential of the region largely depends on the availability of infrastructure - a set of enterprises and organizations belonging to industries that ensure the uninterrupted, effective functioning of a large number of other enterprises and organizations, often belonging to several industries and spheres of activity lies in the fact that they do not produce material products (goods), but mainly provide services necessary for the successful functioning of the branches of material production and, as a result, the economy as a whole [11]. The level of infrastructure development is one of the determining factors of the economic and social stability of the region, affecting its investment attractiveness, production efficiency and quality of life of the population.

II. Methods

With the help of general methods of scientific cognition, the role of infrastructure in the socio-economic and spatial development of the regions of the country is considered.

III. Results

Infrastructure is a complex of interrelated service structures, systems and facilities that provide the basis for the functioning of the economy and the life of society as a whole. In the economic

context, infrastructure includes fundamental structures, objects and systems necessary for the effective functioning of industries and ensuring the life of the population, creating technical and socio-economic conditions for the development of productive forces and improving the quality of life.

Depending on the functional purpose, the following main types of infrastructure are distinguished: production (transport networks, energy systems, water supply, telecommunications, logistics complexes), social (institutions of education, health care, culture, sports, social security), market (banking system, insurance companies, stock exchanges, marketing, consulting and information centers), institutional (government bodies, law enforcement agencies, judicial system), innovation (technology parks, business incubators, technology transfer centers, venture funds), digital (data centers, broadband access networks, software platforms, cloud services), as well as environmental (waste disposal systems, treatment facilities, renewable energy facilities) [5]. Each of these types of infrastructure performs specific functions, but together they form a single complex that ensures the integral functioning of the economy and creates conditions for the sustainable development of territories

Infrastructure plays a decisive role in ensuring the sustainable development of the region, acting as a fundamental basis for economic growth, social well-being and ecological balance of territories, which is manifested in the formation of attractive conditions for investment, reduction of business transaction costs, increasing the mobility of production factors and the efficiency of resource use. Developed infrastructure contributes to reducing spatial imbalances in regional development, ensures the availability of social services for the population, promotes the introduction of innovations and digital technologies, creates conditions for the environmental modernization of production and the transition to a low-carbon economy. At the same time, it is the quality and accessibility of infrastructure that determine the competitiveness of the regional economy, its ability to adapt to changing environmental conditions, withstand economic shocks and ensure long-term balanced development of all spheres of life in the region, which allows us to talk about infrastructure as a key factor of sustainability, linking the economic, social and environmental aspects of regional development into a single system. focused on improving the quality of life of present and future generations.

Infrastructure finance is a system of economic relations arising in the process of formation, distribution and use of monetary funds intended to finance the creation, modernization, operation and development of infrastructure facilities and complexes. This category includes a set of financial mechanisms, instruments and institutions that ensure the mobilization, accumulation and effective distribution of financial resources to meet the infrastructure needs of the economy and society as a whole. Financing of infrastructure facilities is characterized by a number of specific features that distinguish it from the financing of other sectors of the economy. First of all, infrastructure projects require significant capital investments with a long payback period (often 15-30 years or more), which creates a significant burden on sources of financing and increases the requirements for the long-term sustainability of financial models. Infrastructure projects are characterized by high upfront costs with relatively low operating costs, the difficulty of accurately estimating future cash flows due to many uncertainties (political, economic, technological, social), as well as the presence of significant positive externalities that are difficult to monetize directly [1]. These features determine the need for the use of specialized financial mechanisms and instruments adapted to the specifics of infrastructure projects, including complex structures for the distribution of risks between various participants, a combination of public and private financing, the use of project financing and other innovative approaches that provide an optimal ratio of return and risk for all stakeholders.

In the modern economy, a wide range of sources of financing infrastructure projects are used, including budget funds of various levels (federal, regional, municipal), extra-budgetary funds, funds of private investors (including institutional investors, such as pension funds, insurance companies, investment funds), bank credits and loans, funds raised in financial markets through

the issuance of bonds and other debt instruments, funds international development financial institutions, as well as financial resources mobilized through public-private partnership mechanisms. Depending on the specifics of the infrastructure project, its scale, socio-economic significance and potential commercial efficiency, an optimal financing structure is formed, which ensures a balance between the availability of financial resources, the cost of their attraction and the distribution of risks between various sources of financing, while an important role is played by the creation of favorable conditions for attracting long-term investments in infrastructure through development institutional environment, improvement of the regulatory framework and introduction of innovative financial instruments [4].

The Russian economy and financial market are operating in a wide range of challenges, primarily unprecedented sanctions pressure. At the same time, the Russian authorities are facing large-scale tasks of structural transformation of the economy, achieving technological independence and reorienting international economic relations. Transformation, in turn, is associated with a significantly increased need for financing structural changes [9].

The modern financial market offers a variety of instruments for financing infrastructure projects, including infrastructure bonds (including green, social and sustainable bonds), project finance, syndicated loans, mezzanine financing, securitization of infrastructure assets, infrastructure investment funds, concession agreements and life cycle contracts. Each of these tools has its own advantages and limitations that determine the feasibility of its use in specific conditions and for specific types of infrastructure projects. Innovative financial technologies, such as digital platforms for fundraising, asset tokenization, distributed finance models, and smart contracts based on blockchain technologies, open up new opportunities for resource mobilization, increased transparency of financial flows, and efficient financial management of infrastructure projects, which is especially important for emerging markets with limited traditional sources of financing.

IV. Discussion

The introduction of new technologies and support for innovations in the financial market contribute to increasing the availability of various types of financial and payment instruments for citizens and businesses, the development of competition and the emergence of new business models, increasing labor productivity and, ultimately, contribute to the structural transformation and development of the Russian economy [9].

Financial models of infrastructure projects are comprehensive tools that allow assessing the economic efficiency, financial stability and risks of projects at all stages of their life cycle. They include cash flow forecasting, sensitivity analysis to changes in key parameters, assessment of the cost of attracting various sources of financing, calculation of financial performance indicators (NPV, IRR, DSCR, LLCR, etc.), modeling of various scenarios for project implementation and stress testing to assess the stability of the financial structure in the face of adverse changes in the external environment. A high-quality financial model makes it possible to optimize the financing structure, determine acceptable parameters for the distribution of risks between project participants, assess the need for state support and form effective mechanisms for managing financial risks throughout the life cycle of an infrastructure facility, thereby ensuring its long-term financial stability and attractiveness for potential investors. Insurance is one of the key financial institutions of a market economy and a mechanism for effective protection of property interests of citizens, enterprises and organizations from various risks [10]. Infrastructure insurance is a complex system of economic relations aimed at the formation and use of special monetary funds to protect the property interests of owners, operators and users of infrastructure facilities from various risks. This type of insurance is a critical element in the overall risk management system of infrastructure projects, providing financial protection against unforeseen events that may lead to damage or destruction of infrastructure facilities, interruption of their normal operation or the emergence of liability to third

parties. In today's environment, the growing scale and complexity of infrastructure projects, the increasing frequency and severity of natural disasters associated with climate change, and the increase in technological and cyber risks make infrastructure insurance not only desirable, but a necessary component of ensuring sustainable economic development.

Insurance of infrastructure facilities is a special category of property insurance, characterized by a number of significant distinctive features, which together form a unique profile of this insurance segment. The large scale and complexity of infrastructure facilities inevitably require an individualized approach to the assessment of associated risks, the development of specific insurance programs and the determination of adequate insurance amounts, since standardized insurance products are often not able to fully meet the specific needs of large-scale infrastructure projects. The extraordinary cost of infrastructure insurance objects necessitates the use of complex mechanisms for diversifying risks realized through coinsurance and reinsurance with the involvement of multiple insurance companies, including international reinsurance organizations that have sufficient financial capacity to assume such risks. The long-term implementation characteristic of infrastructure projects creates additional challenges for insurers associated with the need to predict potential risks for long periods of time and take into account possible transformations of the risk profile in the long term.

The systemic interconnectedness of various infrastructure elements gives rise to the phenomenon of cascade of possible damages, when a destructive impact on one object can provoke a sequence of failures in the functioning of related systems, which requires a comprehensive analysis when assessing potential total losses. The dual nature of many infrastructure facilities, which combine a commercial component with high social significance, predetermines the need to take into account not only direct financial losses, but also a wider range of socio-economic consequences when developing the parameters of insurance coverage. The involvement of government agencies in the implementation of infrastructure projects can significantly affect the configuration of insurance protection, in particular, through mechanisms for providing state guarantees for certain categories of risks or through the creation of specialized insurance pools for insuring risks that commercial insurers are not ready to accept for their own retention [7].

The insurance industry has developed specialized products to protect infrastructure facilities at all stages of their life cycle:

1) Construction and installation risk insurance (CAR/EAR) provides protection against property risks at the stage of construction of infrastructure facilities, including damage or loss of building materials, equipment, structures, as well as liability to third parties. This type of insurance is often supplemented by Delay in Commissioning Insurance (ALOP), which compensates for financial losses from the delay in the start of commercial operation of the facility.

2) Property insurance of infrastructure operators covers the risks of damage or destruction of completed facilities during their operation. For complex infrastructure facilities, individual insurance programs are developed, taking into account the specifics of the risks associated with a particular type of infrastructure and the conditions of its operation.

3) Business interruption insurance (BI) compensates for loss of income and additional expenses arising from property damage. For infrastructure facilities that provide critical services, cascade effects insurance associated with the disruption of interconnected systems can also be applied.

4) Civil liability insurance includes general civil liability (to third parties), product/service liability, environmental liability, professional liability (for designers, engineers, consultants), as well as specialized types of liability for specific types of infrastructure (e.g. operators of airports, ports, railways).

5) Political risk insurance protects investors in infrastructure projects from expropriation of assets, political violence, breach of contracts by government authorities, restrictions on currency conversion or repatriation of profits.

6) Parametric insurance is an innovative approach in which payments are made on the basis of predetermined parameters (e.g. earthquake strength, precipitation level, wind speed) without the

need to assess the actual damage. This type of insurance is especially effective for quickly obtaining funds to rebuild infrastructure after natural disasters.

7) Cyber insurance covers the financial consequences of cyberattacks, data leaks, failures in the operation of information systems, which is becoming more and more in demand for operators of digital and intelligent infrastructure.

A comprehensive approach to infrastructure risk insurance, combining traditional and innovative insurance solutions, is an integral element of an effective strategy for financing and managing infrastructure projects. In the context of the increasing complexity and interconnectedness of infrastructure systems, as well as the increasing influence of climatic, technological and socio-political factors, the importance of insurance as a mechanism for the transfer and distribution of risks will only increase, requiring constant improvement of insurance products and risk assessment methodologies.

The Central Ring Road (CRR) project is a good example of an integrated approach to financing large-scale regional infrastructure in Russia using the mechanism of public-private partnership. The total investment in this infrastructure project exceeded 350 billion rubles, and financing was carried out from multiple sources, including funds from the National Welfare Fund, the federal budget, private investment and the issuance of infrastructure bonds through LLC SEC CRR [12]. A feature of this project was the formation of a complex multi-level system of risk distribution between government agencies and private investors, in which commercial risks were mainly transferred to the private sector, and regulatory and political risks remained in the area of responsibility of the state. Insurance protection for the project was organized through the formation of an insurance pool, including leading Russian insurers with reinsurance support from international companies, which made it possible to cover risks at the stages of construction and operation of the road, including insurance of construction and installation works, civil liability and insurance against business interruptions. This case demonstrates the effectiveness of integrating various financial instruments and risk sharing mechanisms for the implementation of capital-intensive infrastructure projects of regional importance. Optimization of financial mechanisms for the development of regional infrastructure requires an integrated approach based on interrelated strategic areas that contribute to the sustainable economic growth of territories. A fundamental condition for the successful modernization of regional infrastructure is the improvement of the regulatory framework, which involves the formation of transparent and stable rules for the interaction of all participants in infrastructure projects, the creation of effective investment protection tools, the simplification of administrative procedures related to the approval and implementation of infrastructure projects, as well as the introduction of tax preferences for investors investing in development critical regional infrastructure facilities.

Stimulating private investment in regional infrastructure is an equally important area that requires the development and implementation of innovative mechanisms of public-private partnership that take into account regional specifics and ensure a fair distribution of risks between the public and private sectors, the creation of infrastructure bonds and other specialized financial instruments aimed at attracting long-term capital to infrastructure projects, as well as the formation of a system of state guarantees for strategically important regional infrastructure projects, increasing their investment attractiveness for private capital [3].

The main condition for attracting investment for infrastructure projects at the regional level is the investment attractiveness of the region and the prospects for the profitability of the facilities being created [2].

The development of regional financial development institutions is the next key component of optimizing financial mechanisms for infrastructure development, which involves the creation of regional infrastructure funds that accumulate financial resources from various sources for the implementation of priority infrastructure projects, the formation of specialized regional banks or development agencies with competencies in the field of structuring and financing complex infrastructure projects. infrastructure projects, as well as the development of interregional financial

institutions that contribute to the implementation of large-scale infrastructure projects that go beyond the administrative boundaries of individual entities, which together will create a sustainable financial ecosystem for the planned and balanced development of regional infrastructure that meets modern economic and social challenges.

It should be noted that the dynamic development of infrastructure, which requires the attraction of both private and public investment, largely determines the trajectory of the development of the region's economic system. The implementation of infrastructure projects should be based on a comprehensive analysis of the regional economy with a clear statement of the goals and objectives of the project, as well as an understanding of the consequences of its implementation. The implementation of the strategic goals and objectives outlined in the Strategy for Spatial Development of Russia [8] will require a transition from the central-peripheral model of development, characterized by the permanent emergence of zones of intensive development and areas of depressed territories, to a polycentric model aimed at smoothing out territorial asymmetry and integrating regional economies into the geo-economic space of the country [6].

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INTERDEPENDENCIES OF INFRASTRUCTURE SYSTEMS AND THE STRATEGY FOR SOCIO-ECONOMIC DEVELOPMENT OF THE NORTH CAUCASUS FEDERAL DISTRICT UNTIL 2030

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Abstract

This article analyses the interdependencies between infrastructure systems within the context of implementing the Strategy for the Socio-Economic Development of the North Caucasus Federal District by 2030. It considers the features of the functioning and interaction of various types of infrastructure in the region, including transport, energy, information and communication, and social infrastructure. The mechanisms through which infrastructure interdependencies influence the achievement of the NCFD's strategic development goals are investigated, and critical points and nodes of interaction are identified. Particular attention is paid to analyzing the risks of cascading infrastructure system failures and their potential impact on the region's socio-economic development. The article proposes approaches to optimizing the management of infrastructure interdependencies to ensure the NCFD's sustainable development in accordance with strategic priorities until 2030.

Keywords: infrastructure systems, NCFD, strategic planning, regional development, infrastructure, sustainability

I. Introduction

Modern regional development is characterized by an increasing complexity of interactions between different infrastructure systems, which requires an integrated approach to strategic planning and management of territorial development. The concept of "infrastructure system" is often used in the literature, and in some cases, they are used as synonyms. Infrastructure as a system object is considered within the framework of several sciences: economics, management, economic geography, regional economy, which determines its properties.

The North Caucasus Federal District (NCFD), characterized by special geographical, geopolitical and socio-economic conditions, is a unique territory where infrastructural interdependencies are manifested with particular acuteness and require in-depth analysis to ensure the sustainable development of the region.

II. Methods

The methodological basis of the research is a set of general scientific methods (observation, analysis, synthesis, induction and deduction, modeling) and methods of applied research (system approach, statistical and graphical analysis, method of expert assessments, etc.).

III. Results

The Strategy for the Socio-Economic Development of the North Caucasus Federal District for the Period up to 2030 [7] defines ambitious goals to transform the region into a dynamically developing territory with a diversified economy, a high standard of living of the population and modern infrastructure, which implies the need to create a synergistic effect from the interaction of various infrastructure systems. Transport, energy, information and communication, water management and Social infrastructure should function as a single interconnected complex that provides a multiplier effect for the socio-economic development of the region, which requires a deep understanding of the mechanisms of their interaction and interdependence. The availability of infrastructure facilities, the conditions of their functioning, the level of infrastructure provision affect the parameters of the economic space, changes in its configuration, and act as factors of regional development [6].

The theoretical foundations of the analysis of interdependencies of infrastructure systems are based on the system approach, which involves the consideration of infrastructure as a complex multi-level system, the elements of which are in constant interaction and mutual influence. Conceptual approaches to the study of infrastructure interdependencies include network theory, systems theory, risk management theory, and sustainable development theory, which together provide a methodological framework for understanding the complex processes of interaction between different types of infrastructure. Of particular importance in this context is the concept of critical infrastructure, which considers infrastructure facilities and systems from the point of view of their importance for the functioning of the economy and society, as well as vulnerability to various types of impacts.

The spatial infrastructure system of the region can be presented as a multifunctional dynamically developing complementary structure that forms the spatial framework of socio-economic activity, ensuring the development of interrelated systems, elements, and objects of territories of different hierarchical levels that interact with each other and the external environment on the basis of the principle of complementarity [5].

The methodology for assessing critical infrastructure includes a set of methods and approaches that make it possible to identify key elements of infrastructure systems, assess the degree of their interdependence and impact on the functioning of other systems, as well as identify potential risks and threats to the sustainable development of the territory. System analysis of interdependencies involves the use of mathematical models, simulation modeling, expert assessments and other tools that make it possible to quantitatively and qualitatively assess the nature and intensity of interrelations between different infrastructure systems. An important aspect of the methodology is also taking into account the spatial factor, since infrastructural interdependencies have a pronounced territorial specificity and require a differentiated approach to analysis depending on the characteristics of a particular territory [1].

The characteristics of the infrastructure complex of the NCFD indicate the presence of significant disproportions in the development of various types of infrastructure and the unevenness of their territorial distribution, which creates special conditions for the formation of interdependencies between infrastructure systems. The transport infrastructure of the region is characterized by insufficient development of federal and regional roads, limited opportunities for railway communication in mountainous areas and underdevelopment of inland waterways, which

creates systemic restrictions for economic development and forms specific interdependencies with other types of infrastructure. The energy infrastructure of the North Caucasus Federal District demonstrates high dependence on external energy supplies with the simultaneous presence of a significant hydropower potential in mountainous areas, which creates prerequisites for the development of interdependencies between energy and transport infrastructure in the context of the delivery of energy resources and the development of renewable energy sources.

The information and communication infrastructure of the region is characterized by the uneven development of digital technologies and telecommunication networks, which creates digital gaps between different territories and social groups, affecting the efficiency of the functioning of other infrastructure systems, which are increasingly dependent on information technologies for their management and monitoring. The social infrastructure of the North Caucasus Federal District is experiencing serious challenges associated with the need to ensure equal access to quality educational, health and cultural services throughout the region, which requires close coordination with the development of transport and information and communication infrastructure to ensure the availability of social services for all categories of the population.

The regional features of the infrastructure development of the NCFD are due to difficult geographical conditions, including mountainous territories, foothills and plain zones, each of which is characterized by specific requirements for infrastructure support and forms special types of interdependencies between infrastructure systems. Mountainous areas are characterized by increased risks for infrastructure facilities associated with natural disasters, difficult conditions of construction and operation, which requires special approaches to ensuring the stability and reliability of infrastructure systems. The ethnocultural diversity of the region also creates specific requirements for the development of social infrastructure, which should take into account the needs of different ethnic groups and ensure the preservation of cultural heritage while ensuring equal opportunities for the socio-economic development of all groups of the population.

The analysis of interdependencies between the infrastructure systems of the NCFD reveals a complex network of interconnections that manifest themselves at different levels and in various forms, determining the nature and intensity of the impact of changes in one infrastructure system on the functioning of other systems. Transport and logistics interrelations in the region are characterized by a high degree of interdependence between different modes of transport, when restrictions in the development of one mode of transport create an additional burden on other modes of transport and affect the efficiency of the entire transport system. Road transport in the mountainous areas of the region is experiencing increased loads due to the limited capabilities of railway transport, which creates additional risks for the transport system and requires increased attention to the condition of roads and their resistance to natural impacts [2].

The interdependencies between transport and energy infrastructure are manifested in the need to ensure energy supply to transport facilities, especially in the context of the development of electric transport and modern traffic control systems, as well as the dependence of the energy system on transport support for the delivery of energy resources and equipment for energy facilities. The development of renewable energy sources in the mountainous regions of the region creates new types of interdependencies, as the location of wind and solar power plants requires appropriate transport accessibility for construction and maintenance, as well as the development of electrical networks to transmit the produced energy to consumers.

Energy and utility interdependencies in the NCFD are characterized by close interdependencies between electricity, heat, gas and water supply systems, where disruptions in the functioning of one system can cause cascading failures in other systems and seriously affect the livelihoods of the population and the functioning of the economy. The heat supply system of many settlements in the region depends on the reliability of power supply for the operation of pumping equipment and automation systems, which creates critical interdependencies, especially in winter, when failures in the heat supply system can have catastrophic consequences for the population. Water supply and sanitation are also characterized by a high dependence on electricity supply for

the operation of pumping stations and treatment facilities, which requires special attention to ensure backup power supply to critical water infrastructure facilities.

Digital infrastructure and information connections form a new type of interdependencies, which is becoming increasingly important for the functioning of other infrastructure systems in the context of digitalization of the economy and society. Modern systems for managing transport, energy, water supply and other types of infrastructure are increasingly dependent on information and communication technologies, which creates new vulnerabilities and risks related to cybersecurity and the reliability of digital systems. The development of smart cities and the digital economy in the region involves the integration of various infrastructure systems based on common digital platforms, which creates both new opportunities for improving the efficiency of infrastructure management and new risks associated with possible failures in digital systems [3].

The impact of infrastructure interdependencies on the implementation of the strategic priorities for the development of the NCFD until 2030 is manifested in the fact that the effectiveness of achieving the goals of the strategy is largely determined by the ability to ensure a synergistic effect from the interaction of various infrastructure systems and minimize the negative consequences of their interdependencies. The impact on the economic development of the region is manifested in the fact that infrastructure interdependencies can both contribute to economic growth through the creation of agglomeration effects and reduce transaction costs, and create restrictions on economic development through the formation of infrastructure barriers and increased risks for business. Industrial development in the region requires the coordinated development of transport, energy and information and communication infrastructure, since deficiencies in any of these systems can significantly reduce the competitiveness of industrial enterprises and limit the opportunities for attracting investment.

IV. Discussion

The tourism industry, which is considered as one of the priority sectors of the NCFD economy, is especially sensitive to the state of infrastructure systems and their interdependencies, since the quality of tourism services directly depends on the reliability of transport links, energy supply, water supply and information and communication services. The development of the agro-industrial complex of the region also requires taking into account infrastructural interdependencies, since the efficiency of agricultural production depends on the state of transport infrastructure for the delivery of products to markets, energy infrastructure for ensuring technological processes and information systems for managing agronomic processes and logistics.

The social aspects of infrastructure interdependencies in the NCFD are related to the impact of the state of infrastructure systems on the quality of life of the population, the availability of social services and opportunities for social mobility, which is of particular importance for a region with a high level of social differentiation and uneven development of territories. The availability of quality education in the region largely depends on the state of the transport infrastructure, which provides the opportunity to attend educational institutions, and the information and communication infrastructure, which allows the use of distance learning technologies, especially in the context of a pandemic and other emergencies. The region's health system is highly dependent on transport infrastructure to ensure the availability of medical services in remote areas, energy infrastructure for the functioning of medical equipment, and information systems for coordinating the activities of medical institutions and exchanging medical information.

The risks of cascading failures and threats to the sustainable development of the NCFD associated with infrastructure interdependencies are a serious challenge to ensure the stable functioning of the regional economy and society, requiring the development of comprehensive measures to prevent and minimize the consequences of systemic failures in infrastructure systems. The identification of critical interaction nodes between infrastructure systems shows that the most

vulnerable facilities are those that ensure the intersection and interaction of different types of infrastructure, such as large transport hubs, power substations that supply many consumers, and information and communication centers that provide control of various infrastructure systems. Infrastructure facilities located in high-risk areas of natural disasters typical for the mountainous areas of the North Caucasus Federal District are particularly dangerous, where earthquakes, landslides, floods and other natural phenomena can simultaneously affect several infrastructure systems and cause cascading failures.

Scenarios for the spread of system failures in the infrastructure systems of the North Caucasus Federal District can develop along different trajectories depending on the nature of the primary impact and the characteristics of interdependencies between the systems, which requires the development of comprehensive plans for the prevention and elimination of emergency situations that take into account the specifics of infrastructure interdependencies. The most dangerous scenarios are those associated with failures in the energy system, which can cause the shutdown of transport systems, life support systems, information and communication systems and social infrastructure, which can lead to the paralysis of the life of large areas and the creation of humanitarian crises. Climate change poses additional risks to the region's infrastructure systems, as changes in precipitation patterns, temperature conditions and the increased frequency of extreme weather events can significantly affect the reliability and resilience of infrastructure facilities, especially when they are highly interdependent.

In accordance with the Strategy, the goal of spatial development of the Russian Federation is to ensure sustainable and balanced spatial development of the Russian Federation, aimed at reducing interregional differences in the level and quality of life of the population, accelerating the pace of economic growth and technological development, as well as ensuring the national security of the country [8]. In this regard, strategic approaches to the management of infrastructure interdependencies in the NCFD should be based on the principles of consistency, complexity and sustainability, which involve the consideration of infrastructure systems as a single interconnected complex that requires coordinated management and development. Mechanisms for coordinating the development of infrastructure systems should include institutional, organizational and methodological tools that ensure coordinated planning, financing and implementation of infrastructure projects, taking into account their interdependencies and synergistic effects (Fig. 1).

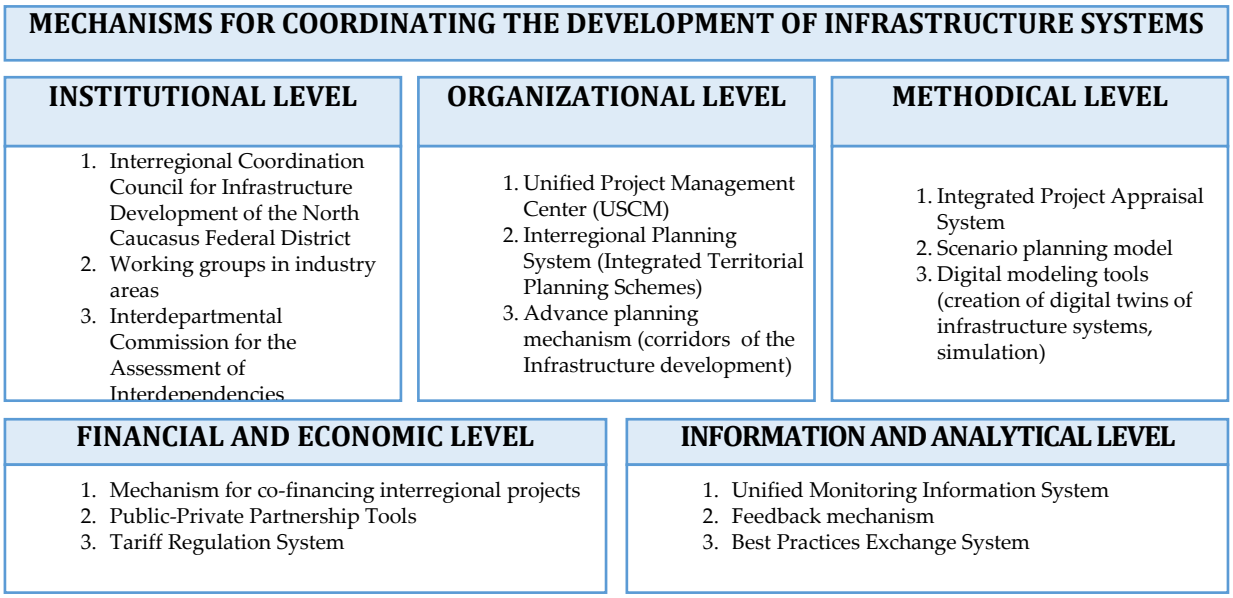


Figure 1. *Mechanisms for coordinating the development of infrastructure systems in the NCFD*

International cooperation in the field of infrastructure development can become an important factor in improving the efficiency of management of infrastructure interdependencies in the North Caucasus Federal District, especially taking into account the border location of the region and its role in international transport corridors. The development of cross-border infrastructure creates new opportunities for the economic development of the region, but at the same time creates new types of interdependencies that transcend national borders and require international coordination to ensure their effective management.

The economic and geographical position of the North Caucasian Federal District at the intersection of transit directions to the countries of Transcaucasia and sublatitudinal routes between the Black Sea and Caspian basins, along with the peculiarities of the settlement system, determined the high density of transport infrastructure in the North Caucasian Federal District with a large number of transport hubs [7]. The strategic importance of the NCFD in the context of international transport corridors is determined not only by its geographical location, but also by its potential for creating integrated infrastructure complexes capable of ensuring the uninterrupted functioning of logistics chains connecting various regions of Eurasia. The formation of such complexes requires the coordination of efforts to standardize technical solutions, harmonize regulatory approaches and create unified risk management mechanisms at the cross-border level.

Of particular relevance is the development of digital infrastructure, which can serve as the basis for the creation of intelligent systems for managing cross-border traffic flows. The introduction of modern information technologies makes it possible not only to optimize logistics processes, but also to create mechanisms for a prompt response to changes in the functioning of the infrastructure systems of neighboring states. The development of energy infrastructure within the framework of international cooperation opens up opportunities for the creation of regional energy hubs that can ensure the energy security of not only the North Caucasus Federal District itself, but also neighboring regions. Such projects require long-term planning and the establishment of mechanisms to manage the technical and economic risks associated with the integration of different energy systems.

Social infrastructure can also be developed through cross-border cooperation, especially in education and health. The creation of joint educational and medical centers can contribute to the formation of a single space of knowledge and competencies, which in the long term will become an important factor in the sustainable development of the region. Financing international infrastructure projects requires innovative mechanisms that include public-private partnerships, international investment funds and multilateral development banks. Effective management of such projects involves the creation of specialized institutions capable of ensuring coordination between various actors and minimizing the risks associated with the cross-border nature of infrastructure interdependencies.

At the same time, the most important from the point of view of ensuring the effectiveness of the implementation of socio-economic policy belongs to the determination of its priorities that are adequate to the current conditions of territorial development, as well as corresponding to the main trends, the manifestation of which will take place in the strategic perspective [4].

The prospects for optimizing infrastructure interdependencies in the NCFD until 2030 are associated with the implementation of an integrated approach to infrastructure development based on a deep understanding of the mechanisms of interaction between various infrastructure systems and taking into account their impact on the achievement of strategic goals of the region's socio-economic development.

Directions for further research in the field of infrastructure interdependencies in the NCFD should include the development of better methods for modeling and predicting the behavior of complex infrastructure systems, the study of the impact of new technologies on the nature of infrastructure interdependencies, as well as the study of social and environmental aspects of infrastructure development.

The development of digital twins of infrastructure systems can be an important tool for a deeper understanding of infrastructure interdependencies and the development of optimal strategies for managing them, but it requires significant investment in the development of appropriate technologies and competencies.

International experience in managing infrastructure interdependencies in difficult geographical and socio-economic conditions can also become a serious source of knowledge for improving approaches to managing infrastructure development in the NCFD, which requires intensifying international cooperation in the field of infrastructure research and the exchange of best practices.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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APPLICATION OF ARTIFICIAL INTELLIGENCE IN THE PROBLEMS OF ANALYSIS AND SYNTHESIS OF TECHNOGENIC AND ANTHROPOGENIC RISKS

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Abstract

This article explores the use of artificial intelligence in assessing and managing man-made and anthropogenic risks. It analyses the potential of neural networks, machine learning and intelligent data processing methods for forecasting and identifying risks associated with human activity. It considers intelligent systems for monitoring and assessing risks that provide increased accuracy in predicting negative events and optimizing management decisions in situations of uncertainty. The key areas of evolution of intelligent risk management systems, and their role in strengthening industrial safety and environmental protection, are also identified.

Keywords: artificial intelligence, anthropogenic risks, technogenic risks, forecasting, predictive analytics, risk management, industrial safety

I. Introduction

Technogenic and anthropogenic risks are the probability of occurrence of negative consequences caused by technical human activity and its impact on the environment, human health and stability of socio-economic systems. Technogenic risk is a potential threat arising as a result of human activity in the technical and technological sphere. It is an integral companion of scientific and technological progress and is manifested through the possibility of accidents, disasters and other adverse events at industrial facilities, transport systems, power plants and other technical complexes. This risk is of a potential nature, can lead to complex negative consequences for the population and the environment, has varying degrees of controllability and predictability, depends on many factors (human factor, equipment wear, design flaws, disruption of technological processes), and also tends to increase due to the growth of industrial production, continuous complication of technologies, increased energy saturation of production processes and concentration of potentially hazardous objects, which requires a systematic approach to the assessment and prevention of such risks through technical control, improvement of the regulatory framework and enhancement of safety culture.

The concept of anthropogenic risk has a broader meaning and covers the entire spectrum of negative consequences of human activity for the environment, human health and social systems. Anthropogenic risks are associated with both direct human impact on natural ecosystems and indirect influence through changes in natural, social and technological processes, which can manifest themselves on various time and space scales. While man-made risks often manifest themselves as discrete events (accidents, incidents), anthropogenic risks can be realized gradually,

over a long period of time, which complicates their timely identification and assessment. The key characteristics of modern man-made and anthropogenic risks are:

- complexity and interconnectedness – many risks are systemic in nature and interconnected, which leads to the possibility of a cascading development of emergency situations;
- dynamism – changes in risk parameters over time under the influence of technological progress, socio-economic factors and natural processes.
- uncertainty – limited knowledge about the probability and possible consequences of risks, especially in the context of the emergence of new technologies and changes in the external environment.
- cumulative effect – accumulation of negative effects from anthropogenic impact over a long period of time;
- transboundary nature – the spread of the consequences of the implementation of risks beyond administrative and state borders [[3]].

In the modern world, the analysis and forecasting of man-made and anthropogenic risks are becoming critically important due to the growing complexity of technological systems and the increasing impact of human activity on the environment. Technological progress contributes to an improvement in the quality of life, but at the same time creates unprecedented pressure on natural ecosystems and generates new categories of risks.

II. Methods

Systematic assessment of man-made and anthropogenic risks is a necessary tool for ensuring safety and sustainable development. This approach allows identifying potential threats before they materialize, making a quantitative assessment of possible damage and developing effective preventive measures. The result is a significant reduction in the likelihood of emergency situations and minimizing their consequences. Such analysis is especially important in the context of accelerated urbanization, territorial concentration of industrial facilities and the introduction of innovative technologies, where the price of an error is measured not only in economic losses, but also in human lives.

Comprehensive risk analysis forms a scientifically sound basis for making management decisions at all levels – from individual enterprises to public policy. It promotes the development of a safety culture, optimization of resources allocated to prevent negative consequences of human activity, and improvement of the regulatory framework in the field of technological and environmental safety. In the era of global challenges, including climate change, depletion of natural resources and accelerated technological transformation, risk analysis is becoming a strategic tool for achieving a balance between economic development, social well-being and preserving a favorable environment for future generations.

III. Results

The rapid development of artificial intelligence (AI) technologies opens up unprecedented opportunities for improving the methodology for analyzing man-made and anthropogenic risks. The ability of AI to process colossal volumes of heterogeneous data, identify non-obvious relationships and patterns, and model complex scenarios allows us to take the processes of forecasting and risk assessment to a qualitatively new level. The integration of machine learning technologies, neural networks, and predictive analytics into security monitoring systems creates the basis for the transition from reactive to proactive risk management, which is critically important in the context of the increasing complexity of the technosphere and increasing anthropogenic impact on the biosphere.

The key areas of application of artificial intelligence in the tasks of analysis and synthesis of man-made and anthropogenic risks are presented in Fig. 1.

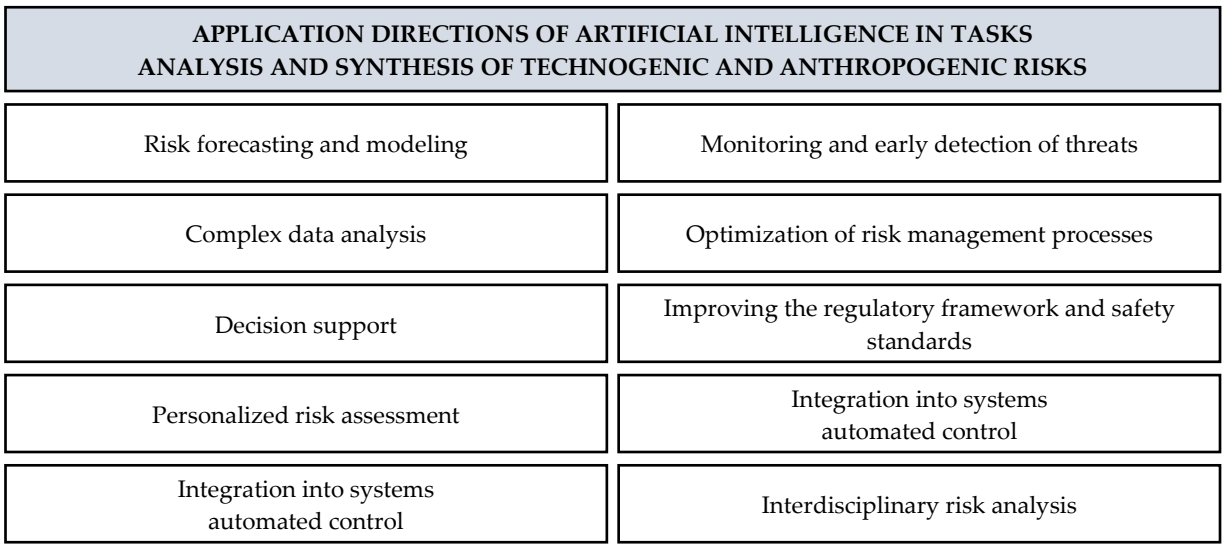


Figure 1: *Directions of application of artificial intelligence in tasks analysis and synthesis of man-made and anthropogenic risks*

Thus, artificial intelligence offers revolutionary approaches to forecasting man-made and anthropogenic risks that go far beyond traditional statistical methods. Modern AI systems are capable of processing petabytes of data from various sources, including historical information on accidents, process parameters, geographic and meteorological data, creating multidimensional models of probable scenarios for the development of events. This allows not only to assess the probability of certain incidents, but also to simulate chains of interconnected events that can lead to cascading accidents. An important advantage of AI in this area is the ability to simulate complex scenarios for the spread of pollution in the atmosphere, hydrosphere and lithosphere, taking into account many factors. For example, in the case of a toxic release, machine learning algorithms can predict not only the trajectory of the pollutant, taking into account weather conditions, but also assess the potential impact on ecosystems and human health in the short and long term, which is critical for making operational decisions in emergency situations [[1]].

AI monitoring systems are redefining approaches to early detection of potential threats by continuously analyzing huge amounts of data from thousands of sensors in real time. Machine learning algorithms trained on historical data on the normal operation of technical systems can effectively detect even minor deviations from standard operating modes long before these anomalies become obvious to traditional monitoring systems. Deep learning methods and recurrent neural networks, which are able to capture complex temporal dependencies in data streams, are especially effective in this regard. The advantage of AI monitoring also lies in the ability to integrate and analyze heterogeneous data from various sources - from temperature and vibration sensors to satellite images and environmental monitoring data. For example, modern systems can simultaneously track changes in the composition of the atmosphere above an industrial facility, anomalies in the vibration characteristics of equipment and structural changes in structures, linking this data into a single picture to identify potential risks at the early stages of their formation.

The use of artificial intelligence for big data analysis enables a qualitative breakthrough in identifying and forecasting man-made and anthropogenic risks by processing petabytes of heterogeneous information from distributed sources. Modern machine learning algorithms, especially deep neural networks, successfully integrate telemetry data from production equipment, environmental monitoring readings, meteorological observations, satellite images, information from social networks and open sources, forming multidimensional models to identify precursors of

potential accidents and environmental disasters. AI systems for big data analysis are capable of detecting implicit correlations and anomalies that remain unnoticed when using traditional statistical methods, which is especially valuable for early warning of emerging threats based on identifying deviations from normal patterns of functioning of technical or natural-technical systems.

A key benefit of AI-powered big data analytics is the ability to create dynamic risk models that take into account the temporal and spatial aspects of the development of potentially hazardous situations in near real time. For example, natural language processing (NLP) systems can analyze thousands of incident reports to identify common patterns and risk factors, and computer vision systems can automatically recognize potentially hazardous situations at industrial facilities based on video surveillance data [[5]]. Stream processing systems with integrated machine learning algorithms can continuously analyze information from thousands of sensors at industrial facilities, identifying specific sequences of events preceding incidents and generating predictive estimates of accident probability with a high degree of detail in time and localization. Such systems become the basis for the creation of intelligent risk management centers, where big data processing algorithms not only identify threats, but also model the effectiveness of various preventive measures, optimizing response strategies and resource allocation to minimize potential damage.

Artificial intelligence is transforming approaches to risk management by automating and optimizing the processes of risk identification, analysis, and control. Machine learning algorithms are capable of not only automating routine risk assessment tasks, but also significantly increasing their accuracy, taking into account the complex relationships between multiple factors. AI systems can perform multi-factor prioritization of risks in real time, taking into account both the probability of their occurrence and potential damage, which allows for more efficient allocation of limited resources for preventive measures. The use of AI-based optimization methods for planning investments in security systems and preventive measures is especially significant. Algorithms such as genetic algorithms and evolutionary computations make it possible to find optimal solutions in a multidimensional space of variables, taking into account budget constraints, the effectiveness of measures, time frames, and interdependencies of various risk mitigation measures. This makes it possible to multiply the return on investment in security, ensuring maximum risk reduction under given resource constraints.

Modern decision support systems (DSS) based on artificial intelligence provide a qualitatively new level of management of man-made and anthropogenic risks due to the integration of cognitive analysis and machine learning methods. These systems not only provide decision makers with up-to-date information on the current state of risks, but also generate intelligent recommendations based on a multi-criteria analysis of possible scenarios. The key advantage of such systems is the ability to generate and evaluate alternative courses of action in real time with modeling of their probable consequences, taking into account complex networks of interdependent factors and the stochastic nature of uncertainties. This functionality is of particular importance in crisis situations characterized by time shortages, high stress levels, and a limited information base. The most important distinguishing feature of modern DSS is their adaptability, implemented through continuous self-learning mechanisms based on feedback. The use of reinforcement learning algorithms allows systems to evolve, accumulating empirical data on the effectiveness of decisions made and optimizing their predictive models accordingly. In particular, such systems are capable of analyzing the effectiveness of preventive measures, dynamically adjusting the analysis parameters and recommendation algorithms, which ensures a progressive improvement in the quality of management decisions in the field of risk management and technical safety.

IV. Discussion

Industrial and environmental safety regulation is also receiving a powerful boost in transformation thanks to the introduction of artificial intelligence technologies. Machine learning algorithms can perform a comprehensive analysis of existing regulations, assessing their effectiveness by simulating different scenarios and comparing them with real data on incidents and accidents. Such analysis helps identify gaps and inconsistencies in current regulations, as well as areas where regulations do not correspond to the current level of technological development or do not take into account new types of risks. AI systems can also generate informed proposals for improving safety standards based on the analysis of large volumes of incident data, equipment specifications, and scientific research. Particularly valuable is the ability of AI to simulate the potential impact of proposed regulatory changes on safety, which enables a more informed approach to regulation [[1]]. In the context of rapid technological development and the emergence of new types of production and technologies, such a proactive approach to the formation of regulatory requirements becomes critically important to ensure an adequate level of safety.

The transition from unified approaches to personalized risk assessment is one of the most promising areas of AI application in the field of security. Machine learning algorithms make it possible to create unique risk models for specific objects, taking into account their individual characteristics – from the technical characteristics of equipment and the specifics of technological processes to geographical location and climatic conditions. This approach significantly increases the accuracy of risk assessment compared to the use of standardized methods that do not take into account the unique characteristics of each object. The use of transfer learning and federated learning methods is especially effective, allowing general risk assessment models to be adapted to the specifics of specific enterprises without the need to develop such models from scratch. This allows even relatively small organizations to gain access to highly accurate personalized risk assessment tools, previously available only to large corporations with solid R&D budgets. As a result, a fairer and more uniform risk management system is formed on the scale of the entire industry or the economy as a whole.

The integration of AI algorithms into automated process control systems represents a qualitatively new level of ensuring industrial safety. Unlike traditional control systems based on hard-coded rules, systems with elements of artificial intelligence are capable of adaptively responding to changing conditions, potential threats and abnormal situations. Such systems can not only detect deviations from normal operation, but also proactively adjust process parameters to prevent the development of dangerous situations. An important aspect is the use of self-learning algorithms that allow control systems to constantly improve their models and response strategies based on accumulated experience. Reinforcement learning methods enable systems to optimize their actions to achieve the highest level of safety while maintaining the efficiency of production processes. At the same time, special attention is paid to ensuring the reliability and interpretability of the AI components, which is critical for systems on the stability of which the safety of people and the environment depends [[2]].

Artificial intelligence is fundamentally changing approaches to training specialists in the management of man-made and anthropogenic risks through the creation of realistic virtual environments for training and education. Modern virtual and augmented reality systems controlled by AI algorithms allow simulating complex emergency situations with a high degree of realism, providing personnel training in conditions as close to real as possible. Such simulators make it possible to practice skills for responding to critical situations without risks to people, equipment and the environment. Of particular value are adaptive training systems that can adapt to the individual characteristics of each trainee - their level of training, speed of information perception, strengths and weaknesses. Machine learning algorithms analyze the trainee's actions, identify gaps in their knowledge and skills, and based on this, create a personalized training program. This methodology significantly surpasses conventional educational practices in terms of training

effectiveness, which is of paramount importance in the development of professional skills necessary for the control and administration of technological complexes with an increased level of danger.

Interdisciplinary analysis of anthropogenic and technogenic risks using AI helps overcome traditional fragmentation in threat assessment by combining technical, environmental, economic and social aspects into a single comprehensive system. The integration of machine learning and deep neural networks allows processing unprecedented volumes of data from diverse sources, including geographic information systems, industrial equipment sensors, meteorological stations, socio-economic indicators and Earth remote sensing data. Artificial intelligence algorithms are able to identify non-obvious correlations between risk factors, predict the development of complex systems and model cascade effects that could go unnoticed using traditional analysis methods. This allows expanding the forecasting horizon and increasing the accuracy of assessing the probability of adverse events in conditions of multi-parameter uncertainty.

Of particular value is the ability of artificial intelligence systems to self-learn and adapt risk assessment methodologies based on accumulated experience and new data. Intelligent decision support systems based on AI technologies provide continuous monitoring of dynamic risk indicators and automatic adjustment of predictive models in real time. This creates a qualitatively new level of risk management, when preventive measures can be implemented even before obvious signs of a threat appear. In addition, the use of AI contributes to the democratization of risk analysis, making complex analytical tools available to a wide range of specialists and decision-makers, which ultimately increases public resilience to man-made and anthropogenic threats and contributes to the formation of a culture of proactive risk management.

Despite its significant potential, the use of artificial intelligence in the analysis of man-made and anthropogenic risks faces a number of challenges. These include:

1) The “black box” problem – many modern AI algorithms, especially deep neural networks, operate on the “black box” principle, which makes their results difficult to interpret and reduces the trust in them on the part of decision makers;

2) Dependence on the quality and completeness of data – the effectiveness of AI systems directly depends on the quality and representativeness of the training data. Lack of information about rare events can lead to underestimation of the corresponding risks;

3) Vulnerability to deliberate attacks – AI systems can be susceptible to manipulation and attacks aimed at distorting their operation, which is especially critical for security systems;

4) Difficulty in taking social factors into account – many AI algorithms are focused on analyzing technical parameters and have difficulty taking into account the complex social, cultural and psychological factors that influence the emergence and perception of risks.

Further development of artificial intelligence technologies opens up new horizons in the field of analysis and management of man-made and anthropogenic risks. Particularly promising areas are:

1) Development of Explainable AI – creation of algorithms that are capable of not only making accurate predictions, but also providing human-readable explanations of their decisions, which is critically important for risk management systems;

2) Integration of AI with quantum computing technologies, which will allow solving highly complex modeling and optimization problems that are inaccessible to modern computers;

3) Creation of collaborative “human + AI” systems that combine the strengths of human intelligence (intuition, creativity, empathy) and artificial intelligence (big data processing, pattern detection, non-stop work).

4) Development of federated learning and other methods that allow training AI models without centralized collection of sensitive data, which is especially important for international cooperation in the field of risk management.

5) Use of augmented reality technologies in combination with AI to visualize risks and train personnel to act in emergency situations.

In conclusion, it should be noted that artificial intelligence is becoming not just an auxiliary tool, but a fundamental element of modern systems for analyzing and managing man-made and anthropogenic risks. The integration of AI methods with traditional approaches to ensuring security creates a synergistic effect, allowing us to solve the problems of preventing man-made disasters and minimizing the negative impact of human activity on the environment at a qualitatively new level. At the same time, the key factor for success is the balance between the automation of processes based on AI and maintaining human control over the adoption of critical decisions.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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INCREASING THE STRATEGIC RESILIENCE OF COMPANIES IN CONDITIONS OF MARKET TURBULENCE BASED ON DIVERSIFICATION, FLEXIBLE MANAGEMENT AND DIGITAL TECHNOLOGIES

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Abstract

In the current economic climate, companies face many challenges due to market instability. This study comprehensively examines the mechanisms that enable enterprises to function and develop effectively in conditions of economic turbulence. The analysis reveals the relationship between external sources of instability and internal company processes, offering an integrated approach to business adaptation. The author considers diversification of activities, flexible resource management, and digital transformation to be key elements of strategic sustainability. Based on the systematization of modern risk management and business process optimization practices, practical recommendations for anti-crisis policy formation are formulated. The article demonstrates that corporations that can quickly transform their activities and utilize digital technologies have a significant advantage in conditions of market turbulence.

Keywords: economic instability, company development, crisis management, risk diversification, strategy, microeconomics

I. Introduction

Economic instability is a state of the economic system characterized by unpredictable fluctuations and changes in macroeconomic indicators, disruption of the equilibrium of market mechanisms and increased volatility of key economic indicators. In modern economic theory, instability is considered from several different positions. Thus, within the framework of macroeconomic theory, economic instability is understood as a complex phenomenon expressed in the imbalance of fundamental economic indicators (production, consumption, inflation, employment), which leads to a disruption of equilibrium at the macro level and creates structural imbalances in the economic system.[6]]. The institutional approach focuses on the imperfections of market and state institutions as the root cause of instability. According to this approach, economic instability arises from the insufficient effectiveness of legal, financial and social institutions regulating economic relations [[3]]. Within the framework of the structural approach, instability is considered as a result of disproportions in the structure of the economy – imbalances between different sectors, industries, regions. Particular attention is paid to the dependence of the economy on certain sectors (for example, raw materials dependence) and uneven development [[11]].

II. Methods

The cyclical approach links economic instability with the natural phases of the economic cycle (boom, peak, recession, trough). The modern understanding of the cyclical approach includes not only classical business cycles, but also financial cycles, technological cycles and globalization cycles [[4]]. In the context of the management approach, instability is characterized through the prism of uncertainty, which complicates the decision-making process of economic agents. The key characteristics are volatility, unpredictability and turbulence of the market environment [[7]]. The synergetic approach considers economic instability as a manifestation of the nonlinear dynamics of complex systems prone to self-organization through chaos and crisis phenomena. In this paradigm, instability is a necessary condition for qualitative transformations of the economic system [0]. The globalization approach links instability with the increasing interdependence of national economies, the spread of the "contagion effect," when crisis phenomena quickly cross borders and spread globally [[2]].

III. Results

Modern economic science integrates many theoretical concepts, recognizing the complexity and multifactorial nature of economic instability. Entrepreneurs should consider instability not as an anomaly, but as a fundamental property of modern economic systems, requiring the development of adaptive mechanisms and flexible management approaches in conditions of uncertainty. It is important to understand the ambivalence of economic instability, which is both a source of risks and a catalyst for new development opportunities. This feature emphasizes the importance of creating integrated methods for forecasting economic fluctuations that will allow organizations to make proactive decisions in a dynamic market environment, minimizing destructive effects and effectively capitalizing on the benefits arising from the transformation of institutional and market conditions.

The key challenges that company face in an unstable economy are summarized in Figure 1.

KEY PROBLEMS OF COMPANIES IN THE CONDITIONS OF AN UNSTABLE ECONOMY			
Impossibility of predicting financial results	Supply chain disruptions and logistical disruptions	Rising cost of raw materials and supplies	Inflationary pressure and declining purchasing power of customers
Increased interest rates and higher cost of lending	Reduction of investments and freezing of development projects	Personnel issues: layoffs, retention of key specialists	Changing consumer behavior and demand
Regulatory risks and unpredictability of legislative changes	Reduction of investments and freezing of development projects	Growing cyber threats and the need to invest in security	Difficulties in strategic planning due to uncertainty

Figure 1: *Key problems of companies in an unstable economy*

Exchange rate volatility and the difficulty of forecasting financial results are becoming a critical challenge, especially for companies operating in international markets. Sharp fluctuations in exchange rates can significantly affect production costs, reduce margins and complicate financial planning. Companies are forced to develop complex risk hedging strategies, which requires additional resources and expertise. At the same time, companies are faced with supply chain disruptions and logistical failures. Geopolitical tensions, trade wars and local crises disrupt well-established supply routes, which leads to delays, increased transportation costs and the need to find alternative suppliers.

One of the most significant factors influencing the activities of enterprises is a significant increase in the cost of raw materials and supplies, which creates serious obstacles to the effective functioning of manufacturing companies. The growth of prices for energy resources, metal products, food raw materials and other basic production resources leads to a significant decrease in profitability indicators and requires prompt adjustment of the pricing policy of enterprises. However, the implementation of such adjustments is often difficult in a highly competitive market environment, where an increase in prices can lead to a loss of competitive positions. Inflation processes and the accompanying decrease in consumer purchasing power create an additional dilemma for companies that are forced to find a balance between the need to increase prices to maintain an acceptable level of marginality and the risk of losing their customer base, especially in segments characterized by high price sensitivity. In response, many enterprises resort to optimizing their product range, modifying packaging solutions or changing the recipe and component composition of products in order to curb the growth of final prices while maintaining an acceptable level of profitability. Along with price challenges, enterprises are faced with the need for a radical transformation of logistics strategies. When traditional supply chains are disrupted, companies are forced to either hold excess inventory to ensure continuity of production processes, which entails additional costs for warehousing and inventory management, or undertake a full-scale revision of logistics concepts with a search for alternative suppliers and delivery routes.

The financial component of the operating activities of enterprises is also subject to significant pressure as a result of a significant increase in interest rates and the general rise in the cost of credit resources. These changes in monetary policy create additional barriers to the implementation of investment projects, refinancing of existing liabilities and maintaining an optimal level of working capital, which together requires the management of companies to develop new approaches to financial planning and cash flow management. Companies with a high debt burden find themselves in a particularly difficult position. Against the background of general uncertainty, there is a process of reducing investments and freezing projects aimed at developing companies. Businesses are taking a wait-and-see attitude, postponing expensive strategic initiatives and focusing on maintaining current operating activities. In the context of an unstable economy, personnel problems are also particularly acute. Companies are forced to resort to staff reductions to optimize costs, while trying to retain key specialists who become even more valuable during a crisis. Such a situation can lead to technological lag, and in the long term - to the loss of competitive advantages.

In an unstable economy, traditional long-term planning models are becoming ineffective, forcing companies to move to more flexible approaches, scenario planning, and the creation of adaptive strategies that can quickly transform when external conditions change. Overcoming these problems requires modern companies not only financial stability, but also organizational flexibility, innovative thinking, and the ability to quickly adapt to changing conditions, turning threats into new opportunities for development.

The company's development directions in the context of an unstable economy are presented in Fig. 2.

Financial stability in an unstable economy requires a comprehensive approach to cash management, including optimizing cash flows to maintain liquidity and ensure timely payments on obligations. Forming reserve funds creates the necessary "safety cushion" that allows the company to overcome periods of economic downturns without critical consequences for operating activities

[[10]]. Diversification of sources of financing minimizes dependence on one creditor or investor, which is especially valuable when individual channels for raising capital are frozen during a crisis. Constant control and cost reduction ensures that profitability is maintained even with a decrease in revenue, allowing the business to remain profitable in difficult economic conditions. Geographic diversification reduces dependence on the economic situation in a specific region, distributing risks between different territorial markets with different development dynamics. The creation of additional business areas that are synergistically linked to the company's core business strengthens the overall position of the business and creates potential conditions for cross-selling between different categories of clients.

DIRECTIONS OF COMPANY DEVELOPMENT IN THE CONDITIONS OF AN UNSTABLE ECONOMY

Financial stability

- ❑ Optimization of cash flows
- ❑ Formation of reserve funds
- ❑ Diversification of funding sources
- ❑ Control and reduction of costs

Flexibility of the business model

- ❑ Adaptation of the product line
- ❑ Pricing review
- ❑ Implementation of new distribution channels
- ❑ Flexible contracts with suppliers

Diversification

- ❑ Expanding the range of products/services
- ❑ Entering new market segments
- ❑ Geographical diversification
- ❑ Development of additional business areas

Digital transformation

- ❑ Business Process Automation
- ❑ Developing an online presence
- ❑ Implementation of analytical tools
- ❑ Using cloud technologies

Innovative development

- ❑ Investments in R&D
- ❑ Creation of new products
- ❑ Improving existing offerings
- ❑ Implementation of technological innovations

Risk management

- ❑ Systematic risk analysis
- ❑ Creating anti-crisis plans
- ❑ Hedging financial risks
- ❑ Key Asset Insurance

Development of human capital

- ❑ Improving the qualifications of employees
- ❑ Attracting talent with new competencies
- ❑ Flexible forms of employment
- ❑ Personnel motivation programs

Partnerships

- ❑ Strategic Alliances
- ❑ Joint ventures
- ❑ Integration with suppliers and clients
- ❑ Cooperation with competitors in certain areas

Customer focus

- ❑ Improving customer experience
- ❑ Personalization of offers
- ❑ Loyalty programs
- ❑ Customer Satisfaction Monitoring

Sustainable development

- ❑ Implementation of ESG principles
- ❑ Energy efficient solutions
- ❑ Social responsibility
- ❑ Responsible use of resources

Figure 2: *Directions of company development in an unstable economy*

IV. Discussion

Digital transformation is no longer considered a competitive advantage, becoming a necessary condition for the existence and development of a business, including the automation of business processes, which allows reducing operating costs, minimizing the human factor and increasing the speed of data processing and strategic decision-making. The development of an online presence ensures the company's availability to customers 24/7, expanding the geography of sales and creating additional points of contact with the target audience. The introduction of analytical tools makes it possible to make decisions based on data, identify patterns of consumer behavior and predict changes in the market situation with high accuracy. The use of cloud technologies ensures the flexibility of the IT infrastructure, reduces capital expenditures on equipment and allows you to quickly scale computing power in accordance with current business needs.

Innovative development is a key area of corporate strategy that ensures the adaptation of organizations to changing market conditions through the implementation of advanced technological solutions, the development of new products and services, and the optimization of business processes. In conditions of economic instability, innovative activity becomes a critical factor in competitiveness, since it allows companies not only to survive in a turbulent environment, but also to transform challenges into opportunities for growth and development.

Risk management in today's economic environment requires a comprehensive approach to identifying, analyzing and minimizing potential threats, including financial, operational, reputational and strategic risks, which involves creating effective monitoring and control systems. Professional risk management allows organizations not only to protect their assets and stakeholders' interests during periods of economic turbulence, but also to turn potential threats into competitive advantages through the use of proactive strategies.

Human capital development is a fundamental area of organizational development, which includes continuous personnel training, formation of key competencies, creation of motivational programs and development of a corporate culture that facilitates maximum disclosure of employees' potential. In the conditions of an unstable economy, qualified and motivated employees become the most important strategic asset, ensuring organizational flexibility, innovation and efficiency of functioning in a dynamically changing business environment.

Partnerships involve the formation of long-term mutually beneficial relationships with key participants in business processes, including suppliers, distributors, customers and other stakeholders, which helps to create synergies and increase the overall sustainability of the business ecosystem. Strategic partnerships in the context of economic instability allow companies to pool resources, distribute risks and gain access to new markets, technologies and competencies, which significantly strengthens the competitive positions of all alliance members.

Customer focus is a strategic business concept based on the priority of customer needs and expectations when making management decisions and organizing business processes, which requires a deep understanding of consumer behavior, personalization of offers and continuous improvement of service quality. In conditions of economic instability, customer loyalty becomes a critical factor in the survival of a company, since retaining an existing customer base is much cheaper than attracting new customers, and trust and loyalty to the brand ensure income stability.

Sustainable development encompasses the integration of environmental, social and economic aspects into the company's strategic planning and operational activities, assuming a responsible attitude to natural resources, fulfillment of social obligations and consideration of the long-term economic interests of all stakeholders. The principles of sustainable development in conditions of economic instability not only contribute to the formation of a positive corporate image and strengthening of reputation, but also create the basis for long-term success through the efficient use of resources and minimization of negative impact on the environment and society.

Thus, successful development of a company in an unstable economy requires a balance between short-term anti-crisis measures and a long-term strategic vision, between cost reduction

and investments in the future, between centralization of management for quick response and delegation of authority to stimulate innovation. Companies that are able to ensure such a multidimensional balance not only overcome periods of economic turbulence with minimal losses, but also strengthen their market positions, using the crisis as a catalyst for qualitative transformations and a source of new opportunities for growth.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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ENSURING ECONOMIC SECURITY OF AN ENTERPRISE IN A MARKET ECONOMY

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Abstract

The modern market environment is characterized by a high degree of uncertainty and fluctuations in supply and demand, as well as the influence of various external factors, such as inflation, currency fluctuations and legal changes. In such conditions, enterprises must develop effective strategies to safeguard their financial, material, and intellectual resources. In practice, economic security is achieved by implementing a series of measures designed to protect capital, enhance financial transparency, and optimize operational efficiency. Implementing a set of measures to ensure economic security enables you to minimize potential risks and strengthen your company's position in the market.

Keywords: economic security, enterprise security, financial security, market economy, risks, microeconomics

I. Introduction

A market economy is a system of management in which economic decisions about the production, distribution, and consumption of goods and services are made on the basis of supply and demand. The main regulatory mechanism in a market economy is the market, which determines prices and production volumes through the interaction of buyers and sellers. In such a system, each entity – from an individual consumer to a large corporation – makes decisions independently, focusing on their own interests and the possibility of making a profit. A market economy is the opposite of a centrally planned system, where all decisions are made at the state level.

A comprehensive study of various scientific sources [2], [5] allows us to identify several key features of a market economy (Fig. 1).

The modern market economy is characterized by instability, which is reflected in serious fluctuations in exchange rates, economic growth, inflation and unemployment. Such a state of the economy can be caused by various factors, including global economic crises, political instability, conflicts, natural disasters, etc. The main problem of an unstable economy is the high level of uncertainty for businesses and consumers. This complicates the development of business strategies, financial planning and making long-term investment decisions.

The business climate is becoming less attractive to investors, which may lead to slower economic growth, increased unemployment and increased social tension. Thus, global economic uncertainty has a serious impact on the stability of the social system and forces governments to develop measures to stimulate business processes, regulate inflation, reduce unemployment and improve the investment climate in the country.

SIGNS OF A MARKET ECONOMY	
Economic freedom	Business entities have freedom of choice, they can decide for themselves what exactly and how much to produce, and how to sell their products
Diversity of forms of ownership	In the economy, state, municipal, private and mixed property exist simultaneously. They are equally protected by law.
Competition	The competitive environment forces companies to improve product quality, reduce costs and develop innovations to maintain and increase their market share.
Free pricing	Prices are set on the market based on supply and demand, rather than being fixed by the state, which facilitates the optimal allocation of resources
Limited government intervention	The state performs mainly regulatory functions aimed at maintaining law and order, protecting property rights, and preventing crises.
Profit as the main motive	The main motive of enterprises is to make a profit. This motivates them to find new and effective ways to meet the needs of society.

Figure 1: *Signs of a market economy*

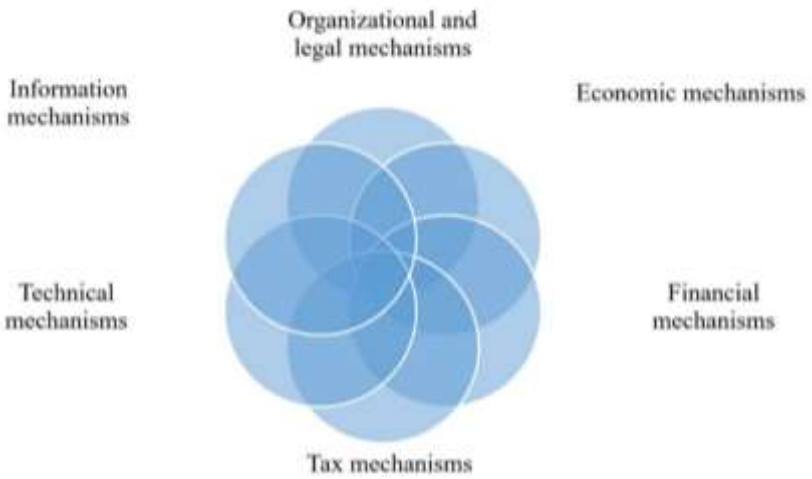


Figure 2: Mechanisms for ensuring economic security of the enterprise [6]

One of the most important tasks of companies in the conditions of an unstable market economy is to ensure their own economic security. Economic security of an enterprise is a complex concept that has both a substantive and functional interpretation. From a substantive position, economic security is characterized as the company's ability to maintain its economic stability and profitability in conditions of uncertainty and risk. From a functional position, economic security is a set of measures aimed at supporting the sustainable functioning of a company in conditions of economic instability and ensuring a reduction in costs, an increase in profitability and protection from external and internal threats [6].

Mechanisms for ensuring the economic security of an enterprise are a system of measures and instruments aimed at protecting the enterprise from internal and external threats that may jeopardize its stable functioning and financial sustainability. These mechanisms play a key role in maintaining the competitiveness of economic entities in a dynamic market environment, they ensure the stability of income and profit, help maintain investment attractiveness and a good reputation in the market.

The system of ensuring economic security of an enterprise in a market economy is presented in Fig. 2.

II. Methods

Organizational and legal mechanisms ensuring economic security is a set of measures aimed at creating a sustainable legal framework and management system that minimizes external and internal threats to the enterprise's activities. The system of legal mechanisms for ensuring the economic security of an economic entity includes four levels:

- federal regulatory legal acts (the Constitution of the Russian Federation, the Civil Code of the Russian Federation, the Tax Code of the Russian Federation, the Labor Code of the Russian Federation, the Federal Law of December 28, 2010 No. 390-FZ "On Security" and others);
- regional regulatory legal acts (laws and regulations governing investment, tax and other aspects of the functioning of enterprises in the region);
- municipal regulatory legal acts (decrees regulating the procedure for taxation by local taxes, issues of placement of retail outlets and municipal support for small and medium-sized businesses);
- corporate regulatory legal acts (charter, internal regulations, staffing schedule, internal work regulations, job descriptions, accounting policies, orders of the manager, etc.).

The organization of enterprise management includes the construction of an effective organizational structure, the distribution of roles and responsibilities among employees and managers, and the formation of a management system capable of supporting the stable functioning of the company. Within the framework of this system, responsible persons are appointed, their functions and powers are clearly defined, and internal procedures and standards of labor activity are formed. Such measures ensure the optimal distribution of resources, increased efficiency of the labor process and the minimization of conflict situations, which is a key element in ensuring the internal stability of the company.

Organizational mechanisms for ensuring the economic security of an economic entity can be differentiated by the frequency of their implementation into one-time, as well as those implemented as needed, periodically and systematically. An example of a one-time event is the development of a company's charter and other constituent documents that are formed at the stage of its foundation. One-time mechanisms also include the establishment of key internal procedures and regulations - anti-corruption policy, policy in the field of economic security, policy in the field of data confidentiality. Organizational measures for anti-crisis management are implemented as needed, when a company faces financial difficulties or a sharp change in market conditions.

The category of periodically conducted organizational measures to ensure economic security includes distribution of encryption keys, tax audits, employee training on security issues and compliance with corporate standards, review and update of contracts with key partners to assess the relevance of the terms of cooperation. On an ongoing basis, companies monitor financial indicators, assess business risks and control compliance with internal regulations to ensure economic security.

An integral element of the organizational and legal mechanism for ensuring the economic security of an enterprise is the internal control system. The internal control system (ICS) is a set of procedures aimed at ensuring compliance with internal and external regulatory requirements, as well as increasing the transparency and predictability of all business processes. It includes

monitoring of financial and operational indicators, comprehensive audit of activities and compliance with established quality standards. A developed ICS at an enterprise helps to identify deviations from established standards and allows for promptly taking corrective measures, ensuring protection against potential losses arising from errors or unfair actions of employees.

An important aspect of ensuring economic security is the introduction of a corporate culture that helps employees develop a conscious attitude towards economic security issues. Supporting corporate values and encouraging responsible behavior of employees at all levels helps strengthen loyalty and reduce the likelihood of information leakage, unauthorized actions, and other internal violations.

Economic mechanisms ensuring security allows us to determine the strategic directions of enterprise development, as well as to form an effective system of financial, production and marketing management. They also allow us to optimize production processes and reduce costs, which in turn increases the competitiveness of an economic entity in the market and ensures its security in an unstable economy [3]. Ensuring a stable position in the market requires the enterprise to constantly adapt to changing environmental conditions, primarily through the release of competitive products. The solution to this problem involves tracking consumer preferences, implementing innovative solutions, and optimizing the use of material, human and financial resources.

Regular marketing research helps reduce uncertainty in the process of making management decisions and allows you to determine the most promising areas for the development of the enterprise in a market economy. Reputation and brand management play an important role in ensuring economic security, since a positive image of the company protects it from the negative impact of external factors. Consumer loyalty, formed through marketing activity and high product quality, reduces the company's sensitivity to short-term economic shocks and helps it to function stably in the market.

III. Results

Optimization of production processes is a key tool for increasing the efficiency and competitiveness of enterprises. Activities in this area allow for cost reduction through the introduction of energy-saving technologies, improvement of the inventory management system and the use of rational production methods. Thus, modern enterprises often implement a lean manufacturing system - this is a special production model, as well as a management concept and philosophy based on the continuous identification and elimination of non-production losses, development of production processes and involvement of personnel in improvement processes. The main aspects of lean manufacturing are the organization of the process of pulling orders by consumers, reduction of order fulfillment time, continuity and uniformity of the order flow, flexibility and widespread reduction of losses. The concept of lean manufacturing is based on a set of principles, including strategic focus, organization of the value creation flow for the consumer, continuous improvement, loss reduction, strict adherence to standards, visualization and transparency, priority safety, built-in quality and others.

The lean manufacturing system includes three key subsystems, the interaction of which is based on the use of classical and flexible project management tools: "Management", "Production Organization" and "Continuous Learning". Each of the listed subsystems corresponds to a certain set of lean manufacturing methods. The most common lean manufacturing methods are kaizen, 5S methodology, quick equipment changeover (SMED), TPM system, "5 why", visualization method, Ishikawa diagram and many others. It should be noted that lean manufacturing methods demonstrate particular relevance when it is necessary to ensure business sustainability in conditions of economic uncertainty. maintaining sustainability and improving the enterprise's activities in conditions of economic uncertainty.

The implementation of automated control systems in production allows for the accuracy, flexibility and efficiency of production process management, minimization of the human factor, and increase in productivity and product quality. The listed optimization tools create a significant safety margin for the enterprise, reducing its dependence on market fluctuations.

The key financial mechanism for ensuring the economic security of an enterprise is the formation of an effective financial management system, including budget planning, accounting and analysis of financial indicators, monitoring and control over the implementation of financial plans. The effectiveness of this mechanism is based on a comprehensive assessment of the current state and performance of the company using various financial indicators - economic potential, profitability, liquidity, financial stability, profitability and business activity. The main source of information for analyzing the financial and economic activities of an enterprise are the data of accounting (financial) statements, in particular - the balance sheet and the report on financial results.

The results of a comprehensive analysis of the financial and economic activities of an enterprise are the information basis for financial planning, within the framework of which its financial resources are managed in order to achieve certain business goals and ensure sustainable growth. Financial planning involves the development of current operating, investment and financial budgets, the preparation of forecast balance sheets and financial performance reports, as well as the assessment of future cash flows in order to eliminate cash gaps.

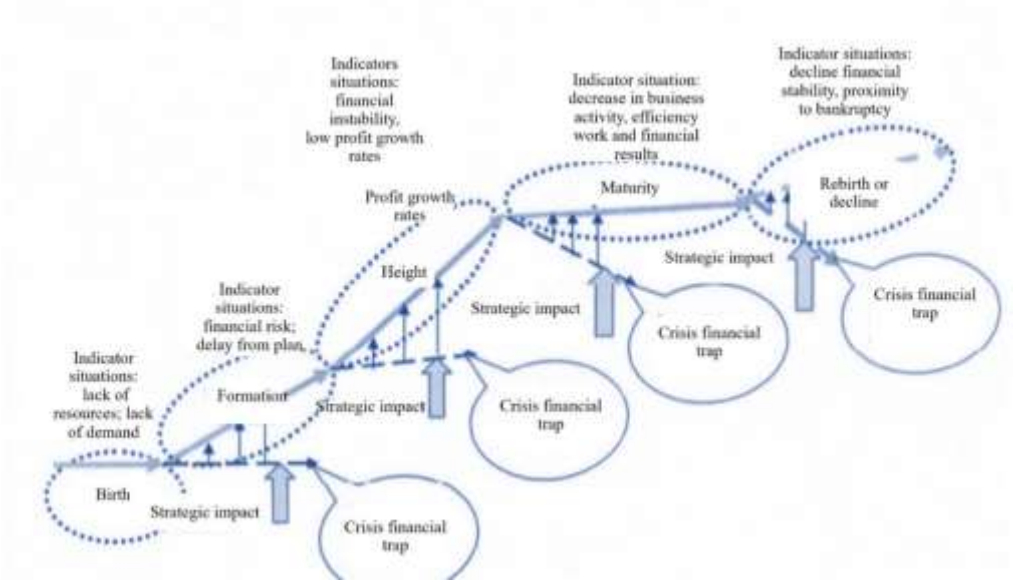


Figure 3: *Financial strategy by stages of the enterprise life cycle [1]*

An integral structural component of financial planning is the formation of a financial strategy that allows an enterprise to ensure financial stability and efficiency. According to researcher I.A. Blank, a company's financial strategy is understood as a long-term plan for managing the company's financial resources and capital, aimed at achieving its strategic goals and ensuring sustainable development [1**Ошибка! Источник ссылки не найден.**]. Financial strategy includes determining sources of financing, capital allocation and use, income and expense management, and minimizing financial risks. This tool helps a company ensure sufficient liquidity, optimize the structure of assets and liabilities, and effectively use financial resources to maintain and grow its business. Financial strategy is closely linked to the overall business strategy of an enterprise, as it allows for the coordination of financial activities with production, marketing, and investment goals, ensuring a balance between growth and financial stability.

The development and implementation of the financial strategy of the enterprise require a comprehensive approach and close integration with the overall development strategy of the

organization. This allows for effective management of financial resources, reduction of risks and provision of sustainable growth in the conditions of a dynamically changing external environment. A feature of planning the financial strategy is its close relationship with the life cycle of the economic entity, which is clearly shown in Fig. 3.

Effective financial planning allows organizations to anticipate potential financial risks, optimize resource use and ensure liquidity, which ultimately contributes to increased economic security and competitiveness.

Tax mechanisms. Ensuring the economic security of an enterprise is a set of measures aimed at minimizing tax risks and ensuring compliance with tax legislation. Such mechanisms include, first of all, tax planning - the process of developing and implementing strategies to optimize a company's tax obligations within the framework of current legislation. The main goal of tax planning and optimization is to minimize the tax burden and maximize the use of tax benefits, deductions and other advantages provided by law. The key tools of tax optimization are presented in Fig. 4.



Figure 4: *Tax optimization tools in the activities of enterprises [4]*

One of the most common tax optimization tools is the use of tax incentives provided by law. For example, from 2021 to 2023, the profit tax rate for Russian IT companies was 3%, and in 2024 it was reduced to 0%. To receive this benefit, the company must be accredited by the Ministry of Digital Development of the Russian Federation, and income from the sale of IT products and services must be at least 90% of its total revenue. In many innovative industries, enterprises can use increased depreciation rates to reduce the amount of taxable profit.

IV. Discussion

The choice of the legal form of a company can significantly affect tax liabilities. For example, legal entities and sole proprietors are taxed at different rates and methods, which allows you to choose a form depending on the volume and types of activities. In addition, holding structures allow you to distribute profits and losses between subsidiaries, which makes it possible to optimize tax payments in a group of companies. Many countries offer special tax regimes for small and medium-sized businesses or individual sectors of the economy. For example, the simplified tax system (STS) in Russia allows small businesses to pay a lower tax at a rate of 6% of income or 15% of the difference between income and expenses, while insurance premiums paid for employees are deducted from the tax amount. It also provides for a patent tax system and a single agricultural tax, which significantly reduce the tax burden for the relevant types of activities.

For large corporations with an international structure, transfer pricing is an important tool. It allows you to regulate prices for goods and services transferred between related parties in order to optimize taxation in different countries. This mechanism allows you to redistribute profits to jurisdictions with lower tax rates, thereby reducing the overall tax burden at the level of a group of companies. For international companies, it is also important to use agreements on the avoidance of double taxation, which regulate the procedure for taxing profits earned abroad. These agreements

allow you to avoid double taxation of income and optimize the tax burden in international activities, which is especially important for large companies with assets or businesses abroad.

As part of tax planning, companies can reinvest profits into business development, which allows them to reduce the taxable base and defer tax payments to a later period. For example, profits can be used to finance new projects, modernize production facilities, or expand the range of products. This tool reduces the amount of profit subject to taxation and promotes company growth. Some companies use offshore jurisdictions or countries with low tax rates to register their divisions or store assets.

The economic security of the enterprise is also supported by the use of measures to ensure the safety of property from man-made accidents, fires and intruders. Security and fire alarm systems ensure the safety of the enterprise, protecting it from unauthorized access and preventing damage from fires.

The company's security software includes a wide range of solutions aimed at protecting against cyber threats, data leaks and other risks that threaten information resources and business infrastructure.

Antivirus software protects against viruses, malware, and spyware. Intrusion detection and prevention systems (IDS/IPS) monitor the network and identify suspicious activity. Security information and event management (SIEM) systems aggregate and analyze security data from multiple sources, helping to identify and respond to incidents in real time. Data protection tools (DLP systems) prevent unauthorized leakage and access to confidential information. Antispam programs and email protection combat phishing attacks, spam, and viruses that are distributed through email services.

Information mechanisms ensuring the economic security of the enterprise is a set of measures and methods for the protection, processing and analysis of information aimed at preventing threats to economic stability and protecting the company's confidential data. Unlike technical mechanisms, information mechanisms are focused on the creation, processing and use of data that ensure the sustainable development of the company, risk prevention and increased management efficiency.

Thus, the mechanism for ensuring the economic security of an enterprise is a set of organizational, economic, legal, technical and other measures aimed at reducing risks and ensuring the financial stability of the enterprise in conditions of uncertainty and competition in the market. It includes a comprehensive assessment of the economic situation, identification of threats and risks, analysis of the financial condition of the enterprise, management of financial flows, optimization of tax and personnel policies, control over resources and risks, as well as the development and implementation of a risk management strategy.

To implement the mechanism for ensuring the economic security of an enterprise, it is necessary to use modern risk management methods, such as methods for modeling and analyzing financial flows, analyzing statistical data, and information and analytical systems. In addition, it is necessary to comply with legislative and regulatory requirements, conduct an audit and control over the financial activities of the company, and organize a system for training and improving the qualifications of personnel.

In general, the mechanism for ensuring the economic security of a company is an important element of its long-term sustainability and success in the market. It allows preventing financial risks and ensuring the competitiveness of business in an unstable economy.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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DEVELOPMENT OF TOURISM IN RUSSIA IN THE PARADIGM OF SUSTAINABLE NATURE MANAGEMENT

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Abstract

In modern conditions, tourism development in Russia is becoming especially relevant as a strategic direction for economic diversification and sustainable regional development. The country's rich natural resource potential creates fundamental prerequisites for the formation of a competitive tourism product. However, increasing anthropogenic pressure on natural ecosystems, climate change and worsening environmental problems require a rethinking of traditional approaches to organizing tourism activities. The paradigm of sustainable nature management offers a conceptual basis for harmonizing the economic, social and environmental aspects of tourism, ensuring the preservation of the natural and cultural heritage for future generations. This approach is of particular importance in the context of the growth of domestic tourism in Russia observed in recent years and the need to develop tourism infrastructure in specially protected natural areas. The article analyzes modern trends and features of the formation of the tourism potential of Russian regions taking into account environmental, social and economic factors, identifies key contradictions between the intensification of tourism activities and the preservation of natural ecosystems, proposes a conceptual model of sustainable tourism development based on the principles of rational use of natural resources, minimization of anthropogenic impact and distribution of economic benefits among local communities.

Keywords: sustainable tourism, recreational load, nature management, specially protected natural areas, ecotourism, tourism, ecology.

I. Introduction

The formation of a scientific and methodological basis for tourism development in the paradigm of sustainable nature management is a complex interdisciplinary process integrating the conceptual provisions of the theory of sustainable development, rational nature management, regional economics, social ecology, and recreational geography. Sustainable tourism is considered not only as a specific form of economic activity, but also as a complex socio-ecological phenomenon that has a multifaceted impact on natural ecosystems, the socio-cultural environment, and the economic development of territories. The actualization of theoretical research in the field of sustainable tourism is due to a number of objective factors: the growing role of tourism in the structure of the world economy; increased anthropogenic impact on natural complexes in tourist destinations; the need to ensure a balance between the economic interests of tourism market entities,

the social needs of local communities, and the imperatives of preserving the natural heritage for future generations.

The genesis of the concept of sustainable tourism is inextricably linked with the formation and development of a broader paradigm of sustainable development, which received fundamental justification in the report of the World Commission on Environment and Development "Our Common Future" (1987) [[18]]. The original interpretation of sustainable development was "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [[16]], was specified in relation to the field of tourism in the works of such researchers as J. Swarbrook [[14]], D. Weaver [[17]], B. Bramwell [[2]].

Several stages can be distinguished in the evolution of conceptual approaches to sustainable tourism. At the initial stage (late 1980s – early 1990s), the eco-centric interpretation dominated, focusing on minimizing the negative impact of tourism activities on natural ecosystems. This approach was reflected in the works of R. Butler [[4]], who presented the concept of the "life cycle of a tourist destination" and substantiated the need to take into account the maximum recreational capacity of the territory.

The second stage (mid-1990s – early 2000s) saw the expansion of the conceptual framework of sustainable tourism by including socio-economic aspects. In particular, D. Hunter [[8]] proposed to interpret sustainable tourism as an "adaptive paradigm" that involves balancing environmental, social and economic interests. During this period, the World Tourism Organization (UNWTO) formulated a definition of sustainable tourism as "tourism that takes full account of its current and future economic, social and environmental impacts, while meeting the needs of visitors, industry, the environment and host communities" [[19]].

II. Methods

The modern stage (from the mid-2000s to the present) is characterized by the integration of the concept of sustainable tourism into the broader context of global challenges, including climate change, loss of biodiversity, and social inequality. A significant contribution to the development of the theoretical foundations of sustainable tourism was made by the works of S. Goessling and K. Hall [[7]], which substantiated the need for a systematic and interdisciplinary approach to the study of sustainable tourism.

In the Russian scientific school, the theoretical foundations of sustainable tourism were developed in the works of such researchers as S.A. Bogolyubova [[1]], S. Dagman [[5]], D.A. Kotelnikov [[9]], O.P. Zvyagintseva [[13]], S.A. Tumenova.

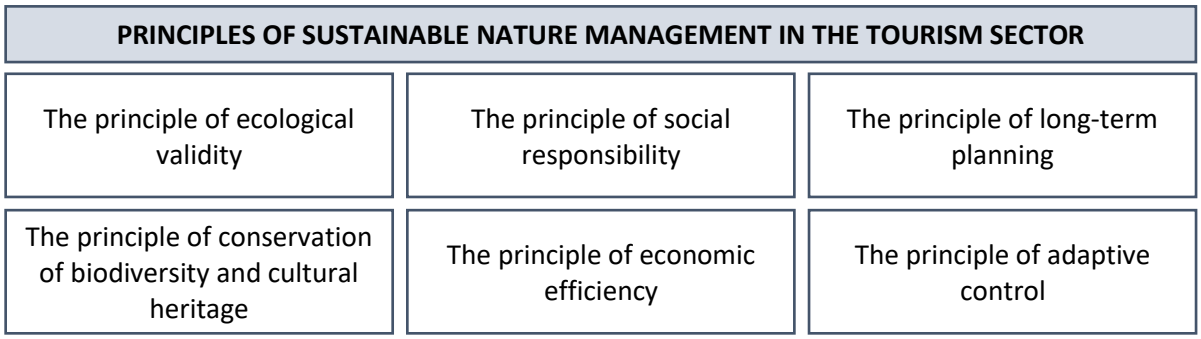


Figure 1: Principles of sustainable nature management in the tourism sector

Particular attention in the works of domestic researchers was paid to the issues of adapting international principles of sustainable tourism to Russian conditions, taking into account the specifics of the natural resource potential, socio-economic development of the regions and the institutional environment.

The theoretical and methodological basis for sustainable nature management in the tourism sector is formed by key principles (Fig. 1).

The principle of ecological justification assumes the conformity of forms and scales of tourist activity with the ecological capacity of the territory, taking into account the limits of stability of natural ecosystems to anthropogenic impacts. The principle of conservation of biodiversity and cultural heritage focuses on minimizing the negative impact of tourism on biological diversity and cultural and historical resources of the territory, which are the fundamental basis for the attractiveness of tourist destinations. The principle of social responsibility emphasizes the need to take into account the interests of local communities, their involvement in the processes of planning and management of tourist activities, and the fair distribution of economic benefits from tourism.

III. Results

The principle of economic efficiency provides for ensuring the profitability of tourism activities subject to compliance with environmental and social sustainability criteria. The principle of long-term planning focuses on the development of strategic approaches to tourism development, taking into account long-term consequences for the natural environment and local communities. The principle of adaptive management assumes the flexibility and adaptability of management approaches to changing environmental, social and economic conditions, the use of feedback mechanisms to adjust tourism development strategies [[10]].

Tourism development in Russia is characterized by progressive dynamics, accompanied by the expansion of the geography of tourist routes and an improvement in the quality of tourist infrastructure. In recent years, there has been a significant increase in domestic tourism, which was facilitated by both state programs to support the industry, including the tourist cashback program, and the active development of new tourist clusters in various regions of the country. According to S.A. Bogolyubova, diversification of the tourist offer is becoming an important trend - in addition to the traditional areas of cultural, educational and beach tourism, ecological, gastronomic, medical and event tourism are actively developing, which allows for a more complete disclosure of the tourist potential of various regions of Russia [[1]].

Despite positive trends, the development of the tourism industry faces a number of challenges that require systemic solutions. Key issues include insufficient transport accessibility of a number of promising tourist destinations, seasonality of tourist demand, shortage of qualified personnel and non-compliance of service quality with international standards in some regions. To overcome these barriers, it is necessary to comprehensively develop tourism infrastructure, including modernization of transport networks, improvement of the personnel training system for the hospitality industry, introduction of modern technologies for managing tourist flows and digitalization of tourism services. Strategic planning of tourism development taking into account regional specifics and focus on the principles of sustainable development will create the basis for the formation of a competitive national tourism product.

The most significant anthropogenic impact of tourism on natural ecosystems in Russia is observed in several types of tourist destinations: coastal zones, mountainous areas, specially protected natural areas, suburban recreational zones of large agglomerations. Coastal tourist destinations (the Black Sea coast of the Krasnodar Territory, the Crimean coast, the Baltic coast of the Kaliningrad Region) are characterized by a high degree of concentration of tourist infrastructure and seasonal peaks of anthropogenic load. As S.A. Tumenova notes, on the Black Sea coast of the Krasnodar Territory in the high season, the recreational load reaches 1500-2000 people/ha/day, which is 5-7 times higher than the maximum permissible indicators for this type of ecosystem [[15]]. The main negative consequences of excessive anthropogenic load are: erosion of the coastline, pollution of coastal waters, degradation of coastal ecosystems, fragmentation of natural landscapes, reduction of biodiversity. On the coast of Crimea, there is an uneven distribution of recreational load with the formation of "hot spots" of anthropogenic impact in the areas of popular beaches and

attractions. Of particular concern is the state of coastal ecosystems in the area of the southern coast of Crimea, where degradation of relict plant communities, disruption of the hydrological regime, and pollution of the sea area are observed.

IV. Discussion

Mountain tourist destinations (the Caucasus, Altai, Ural, Sayan) are experiencing increasing anthropogenic impact due to the development of ski tourism, active recreation, and mountaineering. As shown by the research of Yu.P. Suprunenko [15], in the Caucasus in the areas of large ski resorts (Krasnaya Polyana, Dombay, Elbrus region) a complex of negative environmental consequences is observed: disturbance of the soil and vegetation cover on the slopes, activation of erosion processes, changes in the hydrological regime, transformation of habitats of rare species, pollution of high-mountain reservoirs [[20]]. In the Altai region, the state of natural complexes in the area of Lake Teletskoye and Mount Belukha is of particular concern, where in recent years there has been a significant increase in tourist flow without the corresponding development of environmental infrastructure. Studies show that during the high season, the recreational load on the coastal areas of Lake Teletskoye exceeds the maximum permissible values by 3-4 times, which leads to the degradation of unique natural complexes [[11]].

Specially protected natural areas (SPNA) of Russia are becoming increasingly popular objects of tourist interest, which creates complex problems of combining nature conservation and recreational functions. Analysis conducted by S. Dagman [[5]], shows that in the national parks of Russia the most acute situation with exceeding the maximum permissible recreational loads is observed in the Sochi, Curonian Spit, Pribaikalsky, and Russian North national parks. In particular, in the Curonian Spit national park during the peak days of the high season, the recreational load on some areas of the dune complex reaches 1200-1500 people/ha/day, which exceeds the optimal indicators by 8-10 times [[9]]. In the Pribaikalsky National Park, the most significant anthropogenic impact is observed on the coast of Lake Baikal in the area of the village of Listvyanka and Olkhon Island, where the degradation of coastal ecosystems, pollution of the water area, problems with waste disposal, and disruption of the traditional way of life of local communities are recorded.

Suburban recreational zones of large agglomerations (Moscow, St. Petersburg, Yekaterinburg, Novosibirsk) are characterized by high intensity and regularity of recreational impact. Research by D.A. Kotelnikov shows that in the forest park belt of Moscow and the Moscow region, more than 60% of the territories are at stages 3-5 of recreational digression, which is manifested in the disturbance of the forest litter, soil compaction, changes in the species composition of vegetation, and a reduction in the number of birds and small mammals [[9]].

The system of environmental monitoring of tourist areas in Russia is in the process of formation and is characterized by fragmentation, insufficient coordination between various departments and a lack of modern instrumental and methodological support. The most developed monitoring systems operate in specially protected natural areas, where scientific departments and regular observation programs exist.

The Sochi National Park implements a comprehensive environmental monitoring program, including observations of the state of vegetation on tourist routes, the quality of surface water, the dynamics of rare species populations, and the processes of restoration of disturbed ecosystems. Particular attention is paid to monitoring the environmental impacts of the operation of ski resorts in the Krasnaya Polyana area. The Curonian Spit National Park has developed a system of sustainable tourism indicators that allows assessing the environmental impacts of recreational activities and the effectiveness of management decisions. The system includes indicators of the state of dune ecosystems, forest plantations, water bodies, as well as socio-economic indicators reflecting the interaction of tourism activities and local communities.

At the federal level, attempts are being made to create a unified system for monitoring tourist destinations. The Ministry of Natural Resources and Environment of the Russian Federation,

together with the Federal Agency for Tourism, are developing methodological recommendations for organizing monitoring of the impact of tourism on the environment in protected areas. A promising direction for the development of environmental monitoring systems for tourist areas is the introduction of modern geoinformation technologies, methods of remote sensing of the Earth, and mobile applications for data collection.

Meanwhile, an analysis of existing practices of environmental monitoring of tourist areas in Russia allows us to identify a number of problems that require solutions: insufficient coordination of the activities of various departments and organizations, fragmentation of observations in space and time, a shortage of qualified personnel and modern equipment; lack of uniform standards and methods, insufficient use of modern technologies, problems with funding monitoring programs, and weak integration of monitoring results into the system of making management decisions.

To solve the above problems, it seems appropriate to develop and implement a conceptual model of sustainable tourism development in Russia. The proposed conceptual model is based on a systemic approach integrating three key components: environmental, socio-cultural and economic. The fundamental principles of the proposed model are:

- balancing the interests of all stakeholders (government, business, local population, tourists);
- long-term focus on preserving resources for future generations
- adaptability to regional characteristics of Russia;
- inclusiveness in planning and decision-making;
- innovative approaches to organizing tourism activities.

The model of sustainable tourism development in Russia can be structured into six interconnected blocks (Fig. 2).

Thus, the regulatory and legal block in the developed model of sustainable tourism development in Russia provides for the development of specialized legislation and standards in the field of sustainable tourism. The institutional block establishes a multi-level management system with a clear delineation of powers between the federal, regional and local levels. The environmental block ensures the conservation of natural resources through monitoring, determining the recreational capacity of territories and the introduction of environmental technologies. The socio-cultural block in the model is aimed at involving local communities and preserving cultural heritage. The economic block creates mechanisms for the economic sustainability of the tourism industry. The information and analytical block ensures monitoring and analysis of indicators of sustainable development of territories.

The functional mechanisms for implementing the conceptual model of sustainable tourism development in Russia are an interconnected system of tools and processes that ensure the practical implementation of theoretical provisions in real management decisions and actions. The key role in this system is played by strategic planning based on the development of a long-term national strategy for sustainable tourism development with a horizon up to 2040. This strategy is not an isolated document, but is organically integrated into the system of national projects and state programs, which ensures a synergistic effect and intersectoral interaction. At the regional level, specialized strategies are formed that take into account the tourism specifics of the territories, their natural and climatic features and cultural and historical heritage. In parallel with planning, financial and economic mechanisms are being introduced, including the creation of the Sustainable Tourism Development Fund, a system of environmental fees with flexible differentiation by seasons and types of territories, as well as programs of preferential lending and grant support for innovative "green" projects in the tourism sector.

A special place in the system of functional mechanisms is occupied by educational and scientific initiatives and marketing strategies. The introduction of educational standards on sustainable tourism in higher education institutions, the creation of specialized research centers at leading universities and the implementation of advanced training programs for current industry specialists create a personnel and scientific-methodological base for sustainable tourism

development. At the same time, a national brand "Sustainable Tourism of Russia" is being formed, promoted both in the domestic and international markets. The integration of Russian destinations into international sustainable tourism programs and the development of a system of national eco-labeling of tourist services contribute to increasing the competitiveness of the domestic tourism product and the formation of a positive image of Russia as a country committed to the principles of sustainable development. The combination of these functional mechanisms ensures the systematic implementation of the sustainable tourism model and its adaptation to changing external conditions, which is the key to the long-term effectiveness of the proposed approach.

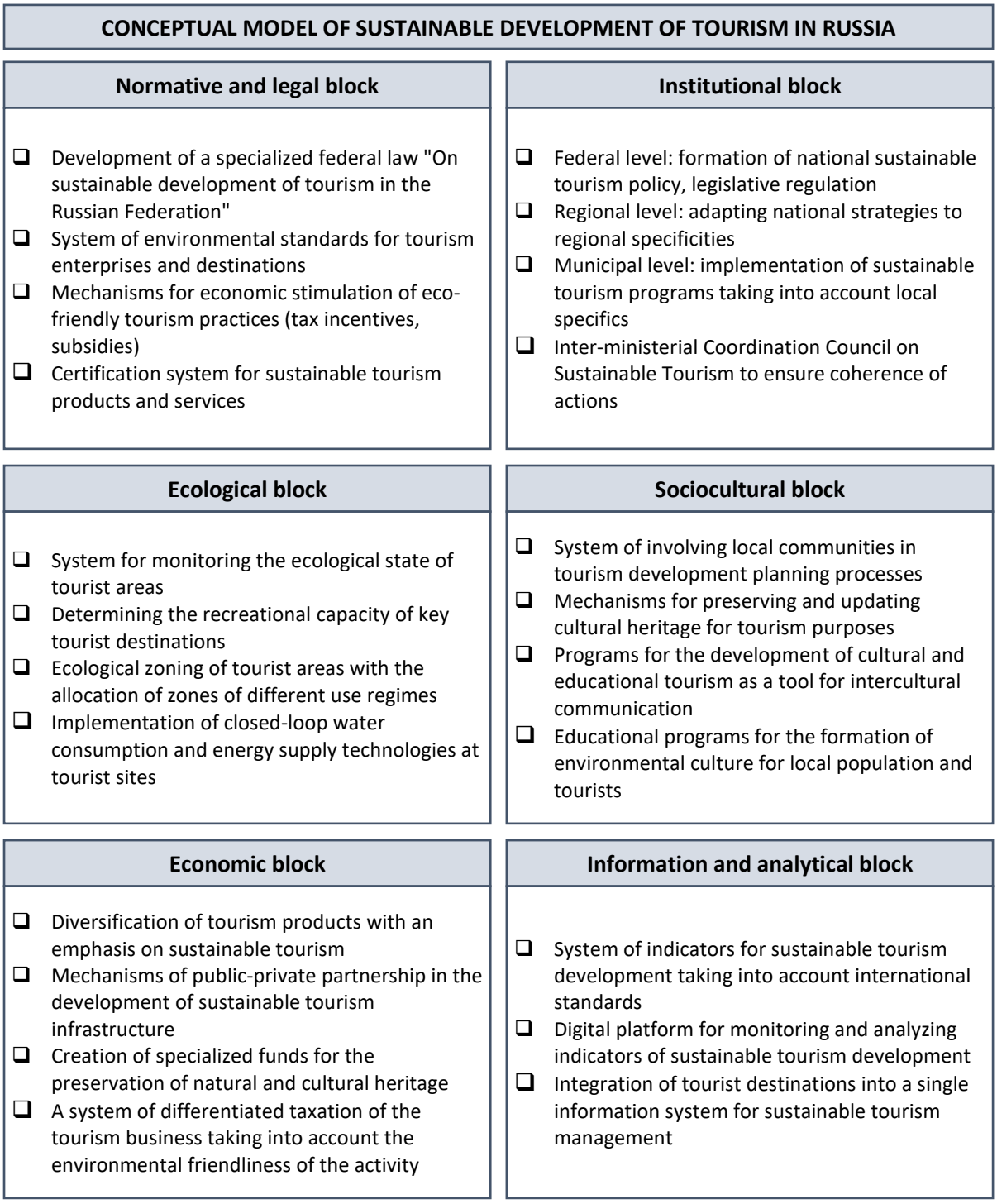


Figure 2: Conceptual model of sustainable tourism development in Russia

Regional differentiation in the conceptual model of sustainable tourism development in Russia acts as a key principle for adapting uniform methodological approaches to the diversity of territorial conditions in the country. Given the unprecedented diversity of natural and climatic zones, cultural and historical features and levels of socio-economic development in Russia's regions, the universal application of standardized mechanisms will inevitably lead to a decrease in the efficiency of the model. Nature-oriented regions, which include territories with unique ecosystems, such as the Baikal region, Altai, and Kamchatka, require priority attention to environmental monitoring, strict regulation of tourist flows, and the introduction of technologies with minimal impact on the environment. For these territories, it is advisable to establish maximum permissible indicators of anthropogenic load and a system of visitor quotas in particularly vulnerable areas. In turn, cultural and historical centers, such as the cities of the Golden Ring, St. Petersburg, and historical settlements of the North Caucasus, need a balanced approach to preserving tangible and intangible cultural heritage while ensuring tourist accessibility of sites.

Coastal areas, including the Black Sea and Azov coasts, the Kaliningrad Region, and coastal areas of the Far East, face the problem of pronounced seasonality and peak loads in the summer, which requires the development of a system for seasonal regulation of tourist flows and stimulation of the development of alternative types of tourism for the low season. The use of differentiated tax rates and fees depending on the season can become an effective economic tool for equalizing the tourist load. Particular attention should be paid to the northern and Arctic regions of Russia, where tourism development should take into account not only the increased environmental vulnerability of the territories, but also specific climatic conditions that require special approaches to organizing infrastructure and ensuring the safety of tourists. For this group of regions, it is advisable to develop special technical regulations for the construction of tourist facilities and the formation of a unique tourist offer based on Arctic exoticism and the phenomena of northern nature. Thus, regional differentiation not only takes into account territorial features, but also creates conditions for the formation of a diverse and competitive tourist product reflecting the diversity of Russia's natural and cultural wealth.

Thus, the formation and implementation of a conceptual model of sustainable tourism development in Russia is a complex task that requires a systematic approach and coordinated actions of all stakeholders. The study shows that sustainable development of the tourism industry is impossible without integrating environmental, socio-cultural and economic aspects into a single paradigm of nature management. The proposed model with its multi-level structure, differentiated regional approach and clear functional mechanisms creates a methodological basis for the balanced development of tourism that contributes to the conservation of natural resources and cultural heritage while ensuring economic growth and improving the quality of life of the local population.

Prospects for further development of tourism in Russia in the paradigm of sustainable nature management are associated with the need to institutionalize the proposed approaches, improve the regulatory framework and form a system of incentives for the introduction of environmentally responsible practices in the tourism industry. Key factors for the successful implementation of the model are the integration of sustainable development principles into educational programs, the development of public-private partnerships and the formation of public consciousness focused on the values of responsible tourism. The use of a differentiated approach to various types of tourist regions while observing uniform methodological principles will allow the most effective use of Russia's recreational potential, preserving it for future generations.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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