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## **Pedagogical Sciences**

# PEDAGOGICAL CONDITIONS FOR IMPROVING ACADEMIC ACHIEVEMENT THROUGH THE DEVELOPMENT OF EMOTIONAL INTELLIGENCE

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### **Abstract**

This article presents a design-based and mixed-method research model for studying the pedagogical conditions under which the development of students emotional intelligence can contribute to improved academic achievement. The study is built around a digital Research Design Package platform that integrates emotional recognition, self-regulation, empathy, communication culture, motivation and achievement reflection into a structured learning environment. The platform includes a learner space, teacher panel, practical tasks, criteria-based assessment, simulation experiences and an analytical dashboard. The article synthesizes international evidence from social and emotional learning, emotional intelligence research, OECD social and emotional skills frameworks, UNESCO guidance and meta-analytical findings on the association between emotional intelligence and academic performance. The proposed model defines the pedagogical conditions as: a psychologically safe learning environment, explicit instruction in emotional vocabulary and self-regulation strategies, reflective tasks connected to learning goals, teacher observation based on transparent criteria, digital feedback, and an evidence-based cycle of diagnosis, intervention, monitoring and evaluation. Practical platform screenshots and classroom implementation photographs are used as visual evidence of the developed model and its testing context. The article offers a publication-ready framework for future empirical validation in school settings.

Keywords: emotional intelligence, academic achievement, social and emotional learning, self-regulation, empathy, learning motivation, digital pedagogy, mixed methods, teacher assessment, reflective learning.

### **INTRODUCTION**

Contemporary education increasingly recognizes that academic achievement is not produced only by cognitive ability, subject knowledge or the amount of instructional time. Students learn in emotionally saturated environments: they experience motivation, anxiety, confidence, frustration, curiosity, fatigue and social comparison. These emotional states influence attention, memory, classroom participation, persistence and the quality of decision-making during learning. Therefore, the development of emotional intelligence is becoming an important pedagogical condition for improving academic achievement, especially in learning environments that require independence, reflection and collaboration.

Emotional intelligence can be understood as the ability to perceive, understand, regulate and use emotions in a constructive way. In the educational context, this construct is closely

connected with self-awareness, self-management, social awareness, relationship skills and responsible decision-making. These categories are also reflected in social and emotional learning frameworks used internationally. The CASEL framework describes social and emotional learning as a foundation for developing competencies and environments that support students learning and development, while UNESCO emphasizes that SEL combines cognitive, social, emotional and relational aspects of learning to strengthen well-being, academic success and active citizenship.

The relevance of the topic is strengthened by international assessment and policy trends. The OECD Survey on Social and Emotional Skills studies the conditions and practices that foster or hinder the development of social and emotional skills in 10- and 15-year-old students. The OECD technical report for the 2023 cycle documents the collection of contextual information from students, teachers, principals and, in some sites, parents through standardized procedures, demonstrating that social-emotional indicators can be measured systematically in education systems. Meta-analytical studies also show a positive relationship between emotional intelligence and academic performance. However, many schools still lack practical tools that connect emotional development with everyday learning tasks and teacher diagnostics.

This study responds to that gap by proposing a platform-supported pedagogical model. The platform does not treat emotional intelligence as a separate psychological topic outside the curriculum. Instead, it embeds emotional recognition, calmness strategies, empathy, learning motivation and personal achievement reflection into a structured research design package. Students complete interactive tasks and reflective forms; teachers observe emotional and academic indicators through criteria; and the platform generates a meaningful basis for discussion, feedback and improvement.

#### **PURPOSE, RESEARCH QUESTIONS AND HYPOTHESES**

The purpose of the study is to develop and justify a platform-supported pedagogical model for improving academic achievement through the development of emotional intelligence and to describe the conditions under which this model may be implemented in school practice.

Component	Content
Object of the study	The educational process in which emotional intelligence development is integrated with academic learning tasks.
Subject of the study	Pedagogical conditions, digital tasks and assessment criteria that connect emotional intelligence with academic achievement.
Aim	To design, theoretically justify and practically describe a digital platform model that develops emotional intelligence and supports learning achievement.
Research Question 1	How can emotional intelligence be operationalized as a pedagogical condition for academic achievement?
Research Question 2	What platform components support students emotional recognition, self-regulation, empathy, motivation and reflective learning?
Research Question 3	How can teachers assess emotional-intellectual development without reducing it to a single score?
Hypothesis	If students regularly perform structured emotional reflection, self-regulation, empathy and motivation tasks in a safe digital learning environment, then their learning engagement and achievement indicators will improve.

*Table 1. Research logic of the proposed study.*

## LITERATURE REVIEW

International literature on emotional intelligence and social-emotional learning provides a strong basis for this topic. The CASEL framework identifies five interrelated competence areas: self-awareness, self-management, social awareness, relationship skills and responsible decision-making. These competencies directly correspond to the platform modules used in this study: mood identification, calmness strategy selection, empathy tasks, communication culture and learning motivation reflection.

UNESCO describes social and emotional learning as an approach that integrates cognitive, social, emotional and relational aspects of education. This is important because school success depends not only on mastery of disciplinary content, but also on a students capacity to remain engaged, manage emotional barriers, build constructive relationships and reflect on mistakes. UNESCOs position also supports the idea that emotional development should be mainstreamed in education rather than treated as an optional add-on.

OECD evidence demonstrates the growing international importance of assessing social and emotional skills. The Survey on Social and Emotional Skills is designed to identify and assess conditions and practices that foster or hinder social-emotional development. This perspective is relevant to the present article because the proposed platform creates a localized, teacher-friendly assessment space in which emotional stability, self-regulation, empathy, communication and motivation can be observed through student actions and written explanations.

Meta-analytical research reinforces the connection between emotional intelligence and academic achievement. MacCann and colleagues found that student emotional intelligence predicts academic performance across a large evidence base. Sánchez-Álvarez and colleagues also

reported a positive relationship between emotional intelligence and academic performance in secondary education. Quílez-Robres and co-authors further examined emotional intelligence and academic performance through a systematic review and meta-analysis, showing that emotional regulation and related competencies are relevant to learning outcomes. These findings justify the development of digital pedagogical conditions that translate emotional intelligence theory into everyday school practice.

At the same time, the literature suggests that emotional intelligence should not be measured only through abstract self-report scales. Students emotional skills are visible in how they explain feelings, select actions in difficult situations, communicate with others, persist in tasks, respond to feedback and write reflective conclusions. Therefore, the present model combines student self-report, teacher criteria, platform analytics and written tasks.

### METHODS AND RESEARCH MATERIALS

The study is designed as a design-based mixed-method research project. The design-based component focuses on developing and testing a digital pedagogical platform. The quantitative component may include pre- and post-diagnostic indicators of emotional intelligence and academic achievement. The qualitative component includes written student reflections, teacher observation notes and analysis of platform task responses. This structure allows the study to examine not only whether the platform produces improvement, but also how students experience emotional learning and how teachers interpret the results.

#### PRISMA-style source search strategy

A PRISMA-oriented logic was used to organize the literature base. The search focused on official international frameworks and peer-reviewed studies related to emotional intelligence, social and emotional learning, academic achievement, assessment and digital pedagogy. Databases and sources included ERIC, Google Scholar, Scopus/Web of Science search fields, OECD, UNESCO, CASEL and open-access scientific repositories.

Source	Core search string	Selection focus
OECD / UNESCO / CASEL	social emotional skills; social emotional learning; emotional intelligence; academic achievement	Official frameworks, international policy and assessment guidance
Scopus / Web of Science	("emotional intelligence" AND "academic performance") OR ("social emotional learning" AND achievement)	Peer-reviewed empirical studies and meta-analyses
ERIC / Google Scholar	SEL intervention school students self-regulation empathy motivation achievement	Educational intervention studies and school-based research
Open-access scientific repositories	emotional intelligence predicts academic performance meta-analysis	Full-text articles with transparent methods

*Table 2. Search strategy for constructing the theoretical and empirical basis of the article.*

**Inclusion and exclusion criteria**

Criterion	Included	Excluded
Topic relevance	Studies on emotional intelligence, SEL, self-regulation, empathy, motivation and academic performance	General psychology papers without educational relevance
Educational level	School, secondary education, teacher practice and student achievement contexts	Clinical or workplace studies unrelated to schooling
Evidence type	Peer-reviewed studies, meta-analyses, official frameworks and methodological reports	Non-verifiable blog texts and unsupported claims
Methodological clarity	Studies with defined variables, samples, instruments or theoretical frameworks	Texts without clear methodology or source transparency
Application	Research that can inform platform design, teacher assessment and reflective tasks	Studies with no practical connection to pedagogy

*Table 3. Inclusion and exclusion criteria for the review-based part of the study.*

**CONCEPTUAL MODEL OF THE PLATFORM**

The proposed platform is titled Research Design Package. It is designed as an authorial scientific-pedagogical environment for developing emotional intelligence and improving academic achievement. The central pedagogical idea is that students achievement is influenced by their ability to recognize emotions, regulate behavior, understand other people, maintain learning motivation and reflect on personal progress. Instead of presenting these abilities as abstract qualities, the platform turns them into observable learning actions.

The model contains several interconnected spaces. The research concept section explains the basic idea, aim and objectives. The scientific novelty section describes the model as an integrated system in which emotional intelligence and academic achievement are studied together. The methodological framework section includes personality-oriented, humanistic, empathic and supportive-environment principles. The research design page presents a six-stage process: initial diagnostics, observation, emotional intelligence tasks, interim monitoring, product collection and final analysis.

The learner space includes five interactive cards: my mood, my calmness, my empathy, my learning motivation and my achievement today. These cards transform emotional intelligence into short structured activities. The teacher panel provides criteria-based evaluation of emotional stability, self-regulation, empathy, communication skills and learning motivation. The tasks page gives practical reflective assignments, and the results page shows indicators that help interpret changes in emotional and learning development.

Platform component	Pedagogical function	Target EI dimension	Expected achievement link
Research concept	Explains why emotional intelligence matters in learning	Meaning and orientation	Students understand the learning purpose
Methodological framework	Defines supportive pedagogical principles	Safety, empathy, humanistic relation	Lower anxiety and stronger participation
Learner space	Provides interactive reflection cards	Self-awareness and self-regulation	Improved attention and task persistence
Teacher panel	Collects criteria-based observations	Empathy, communication, motivation	Better formative feedback
Research tasks	Organizes written reflection and action planning	Responsible decision-making	Improved metacognition and learning strategy use
Results dashboard	Visualizes progress and indicators	Integrated EI profile	Data-informed support for achievement

*Table 4. Conceptual architecture of the Research Design Package platform.*

#### PLATFORM QR CODE AND VISUAL DOCUMENTATION

The digital platform used in the study can be accessed through the QR code below. The following figures document both the interface structure and the practical classroom use of the platform. Captions are written in English so that the materials can be included directly in an international journal-style article.



*Figure 1. QR code linking to the Research Design Package platform for emotional intelligence and academic achievement.*

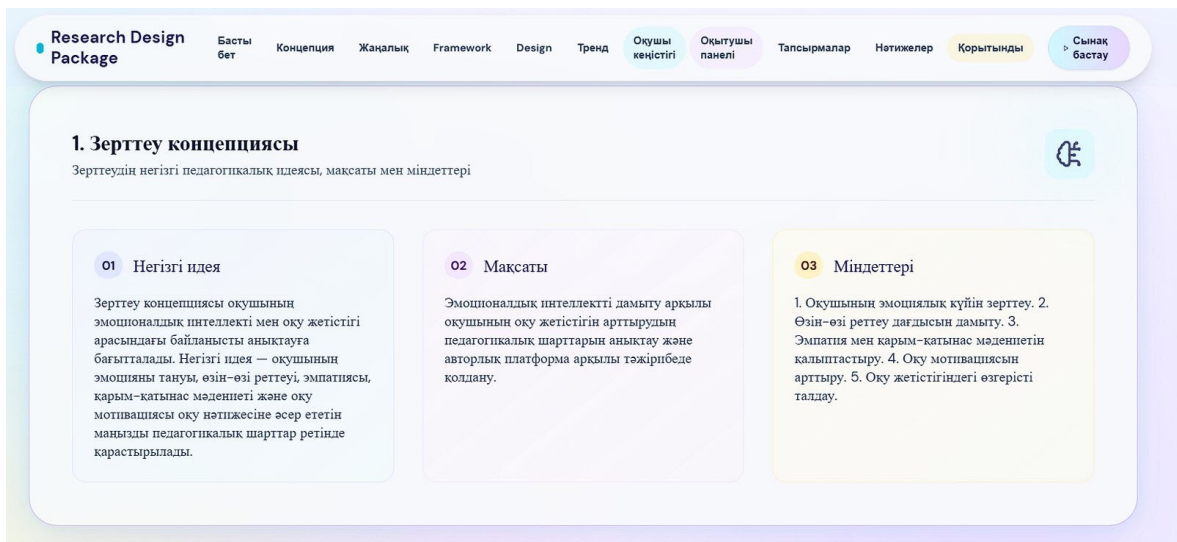


Figure 2. Research concept page presenting the core pedagogical idea, aim and objectives of the emotional intelligence platform.

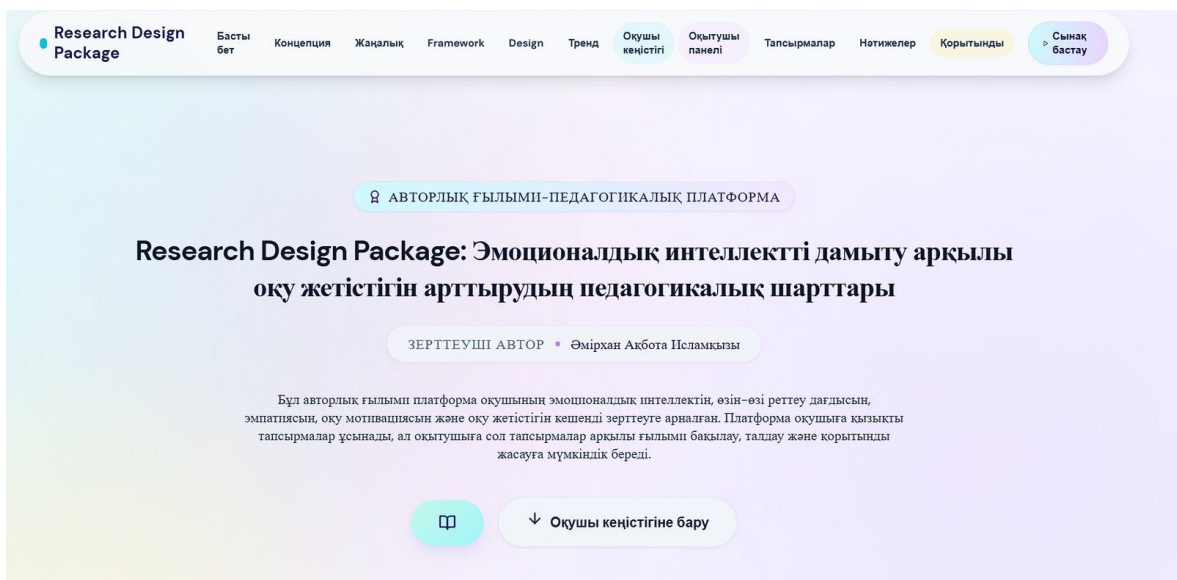


Figure 3. Research Design Package homepage for developing emotional intelligence and improving learning achievement.

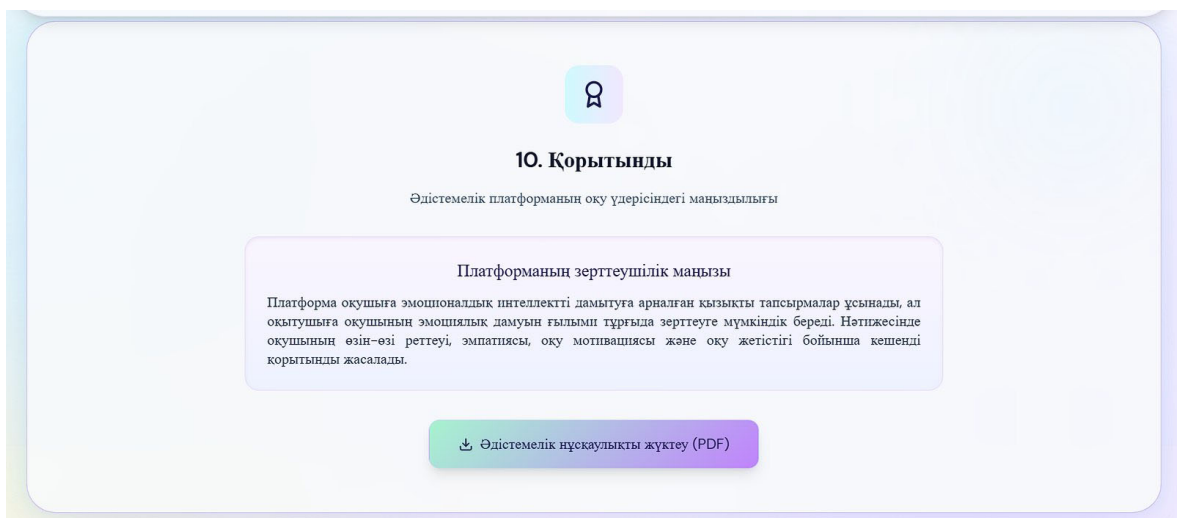


Figure 4. Conclusion section describing the research value of the platform in student emotional development and academic progress.

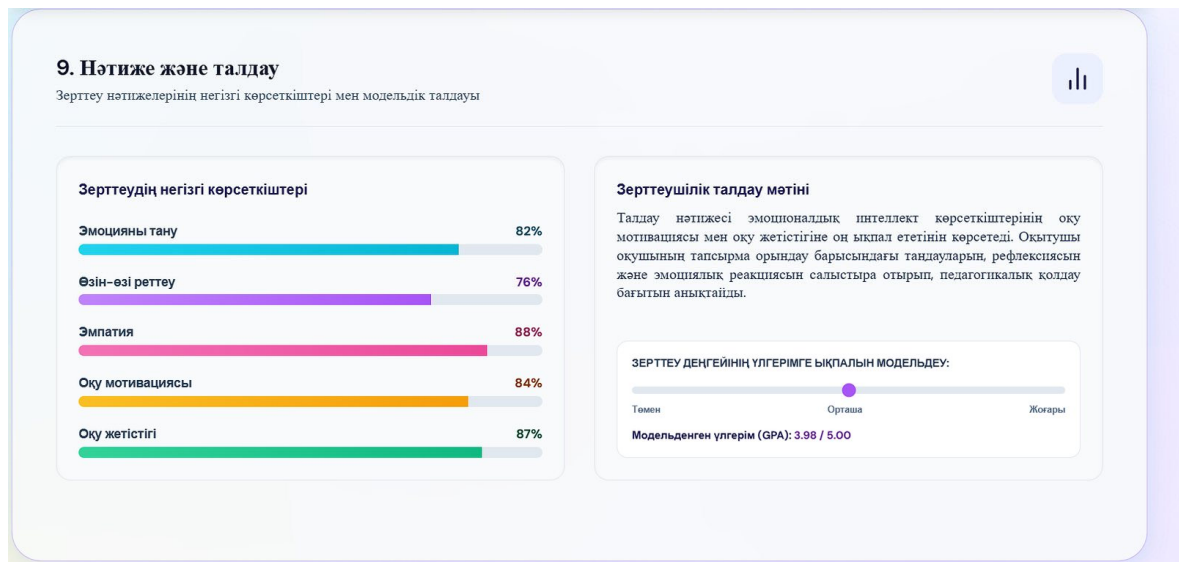


Figure 5. Results and analysis dashboard displaying emotional recognition, self-regulation, empathy, motivation and achievement indicators.

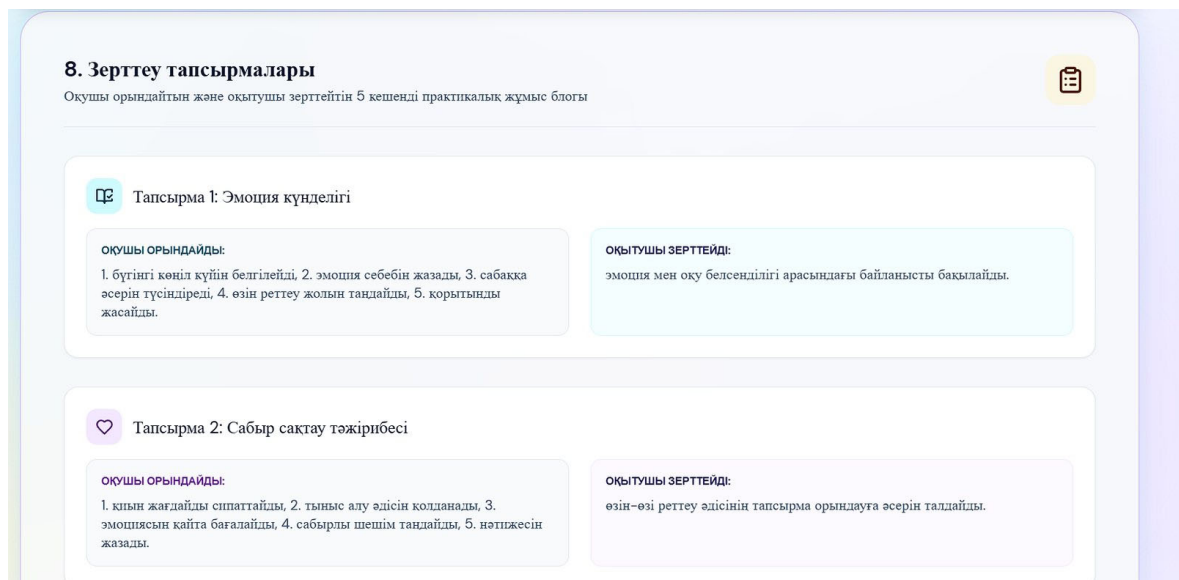


Figure 6. Research tasks page showing practical blocks for emotion diary and calmness practice tasks.

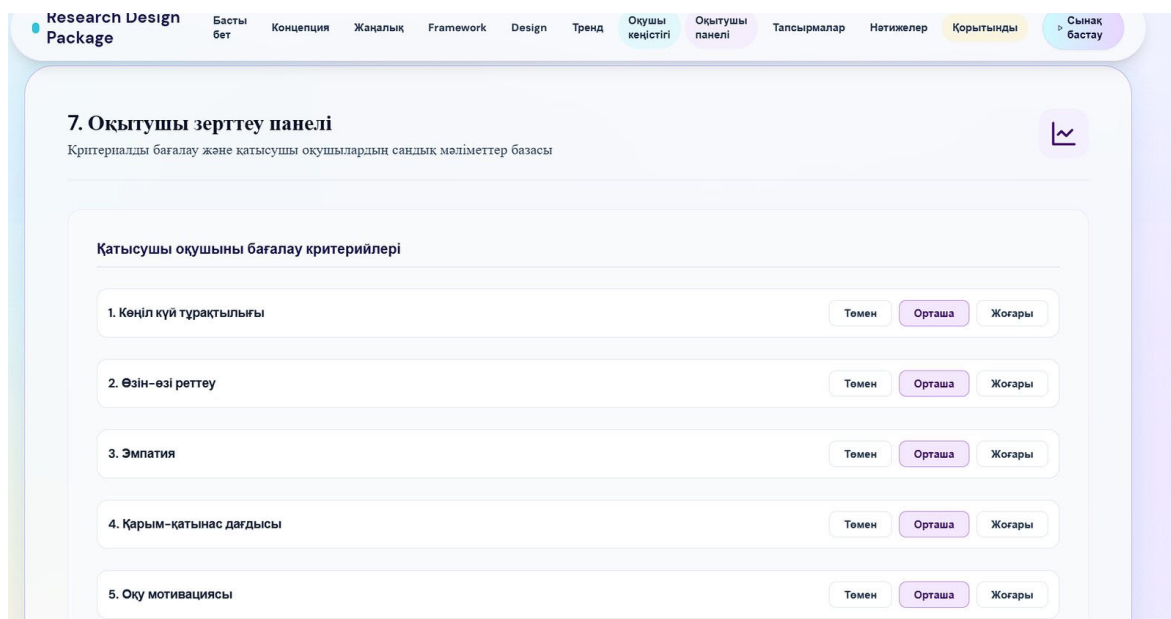


Figure 7. Teacher research panel with criteria-based assessment options for emotional stability, self-regulation, empathy, communication and motivation.

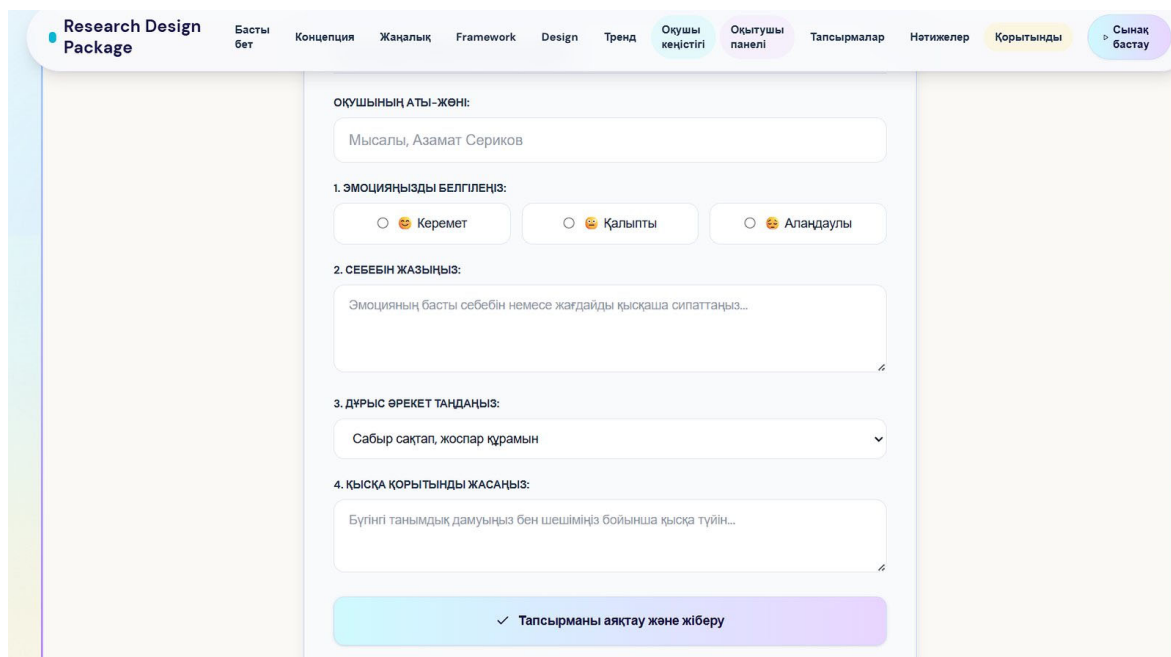


Figure 8. Student space interface requiring the learner to identify emotions, describe causes, choose constructive action and write reflection.

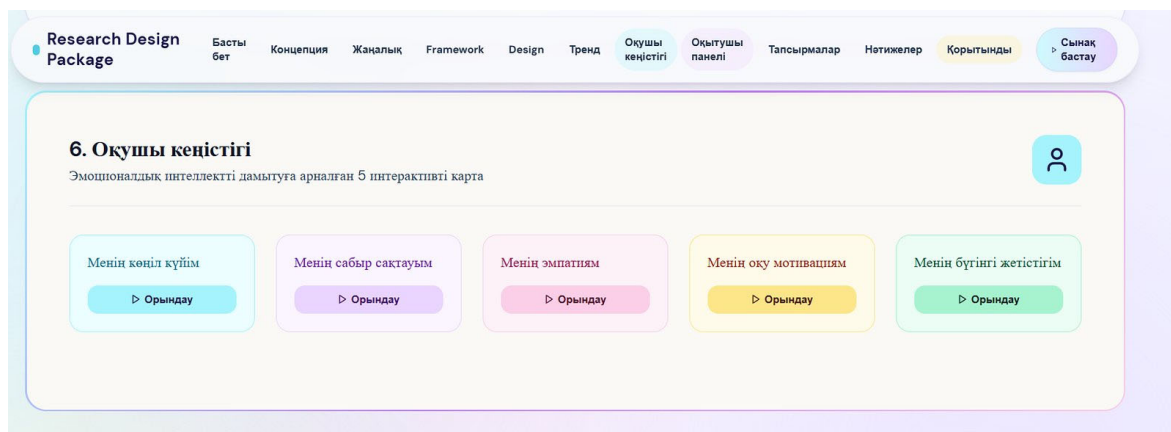


Figure 9. Student space page with five interactive cards for mood, calmness, empathy, learning motivation and personal achievement.

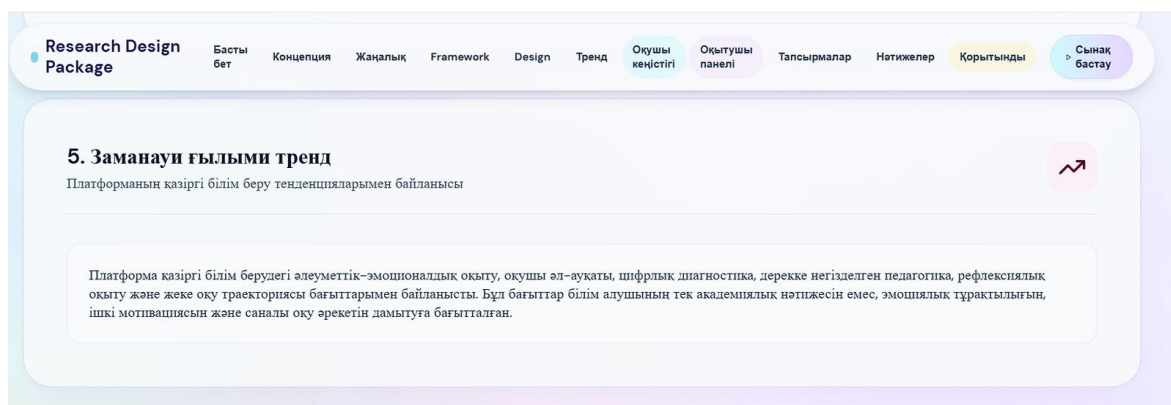


Figure 10. Modern scientific trend section linking the platform to social-emotional learning, well-being, digital diagnostics and reflective pedagogy.

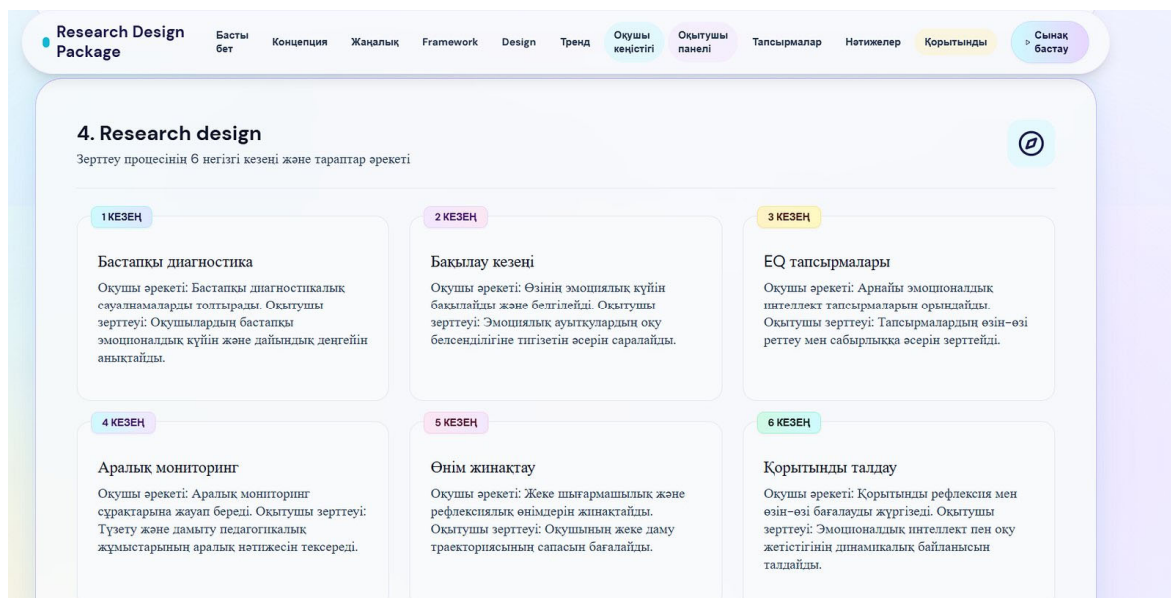


Figure 11. Research design page presenting six stages from initial diagnostics to final analysis.

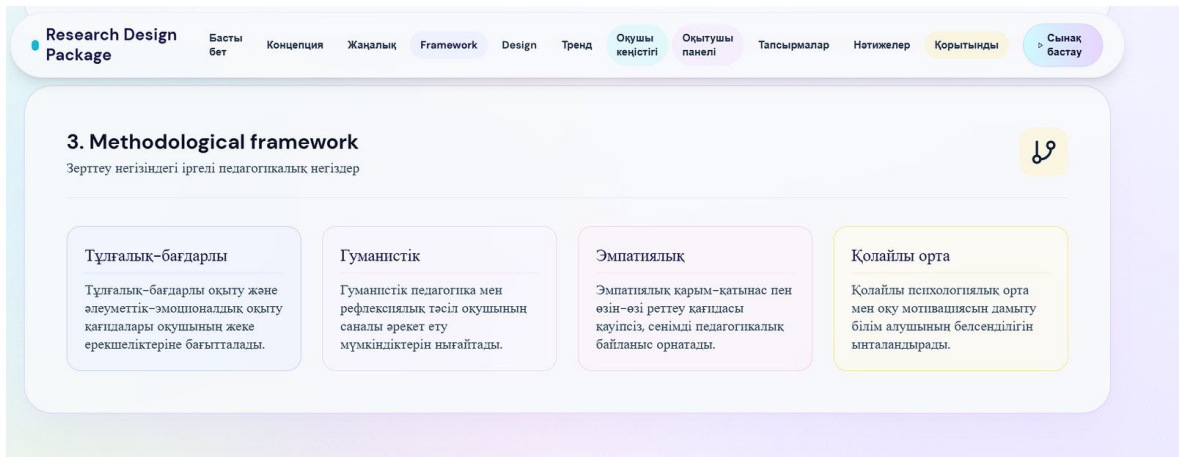


Figure 12. Methodological framework page showing personality-oriented, humanistic, empathic and supportive-environment principles.

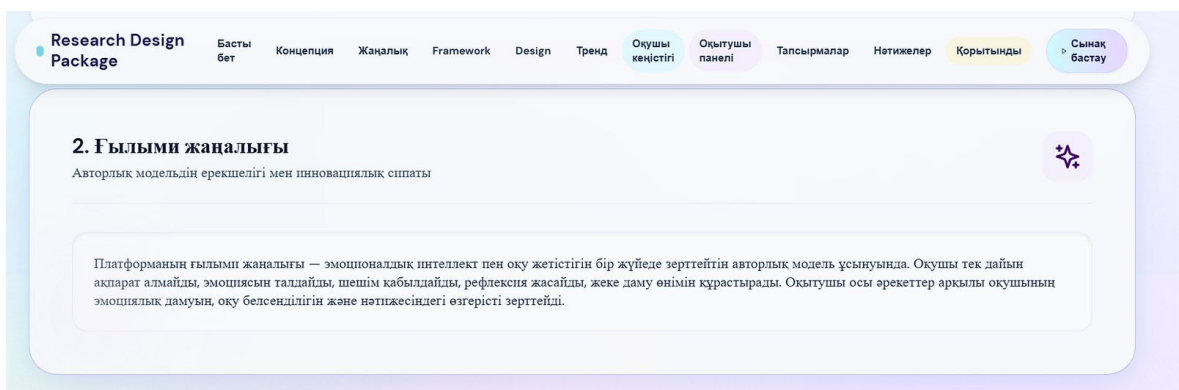


Figure 13. Scientific novelty section explaining the platform model as an integrated system of emotional intelligence and learning achievement.

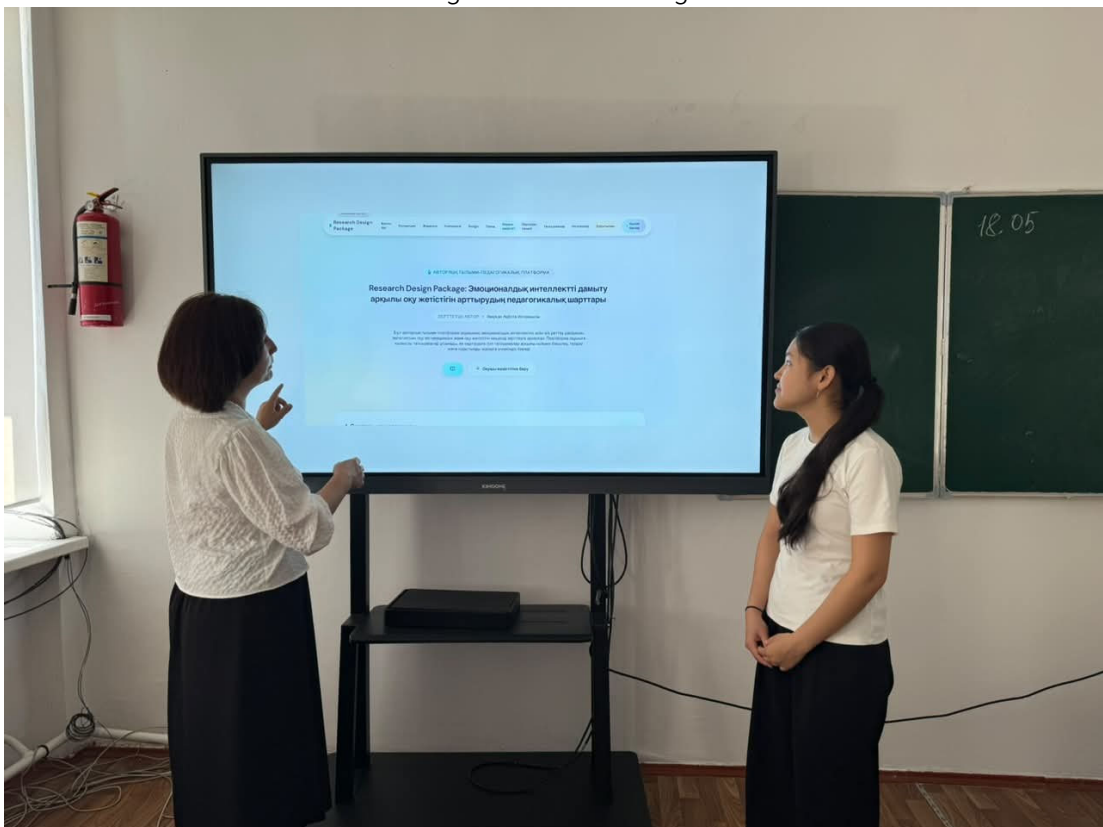


Figure 14. Practical classroom demonstration of the Research Design Package platform on the interactive board during the emotional intelligence learning session.

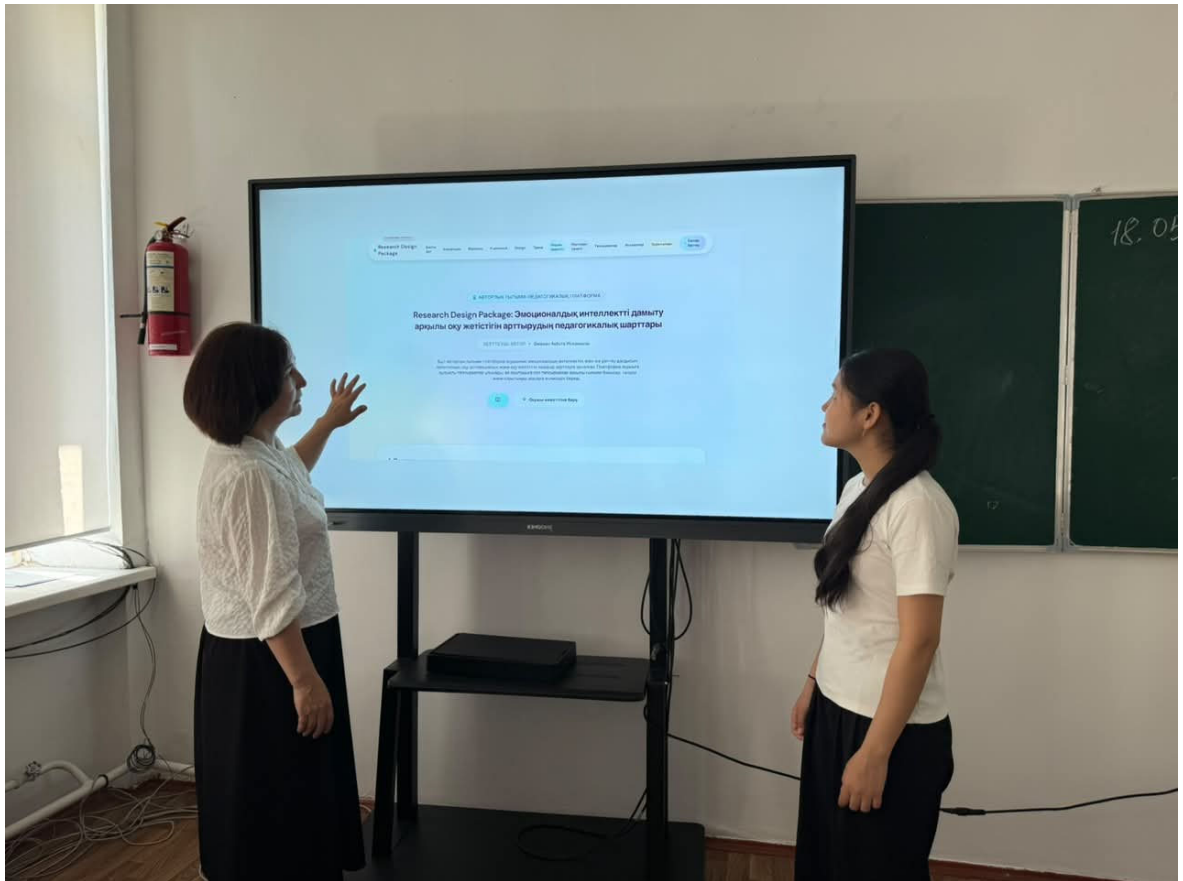
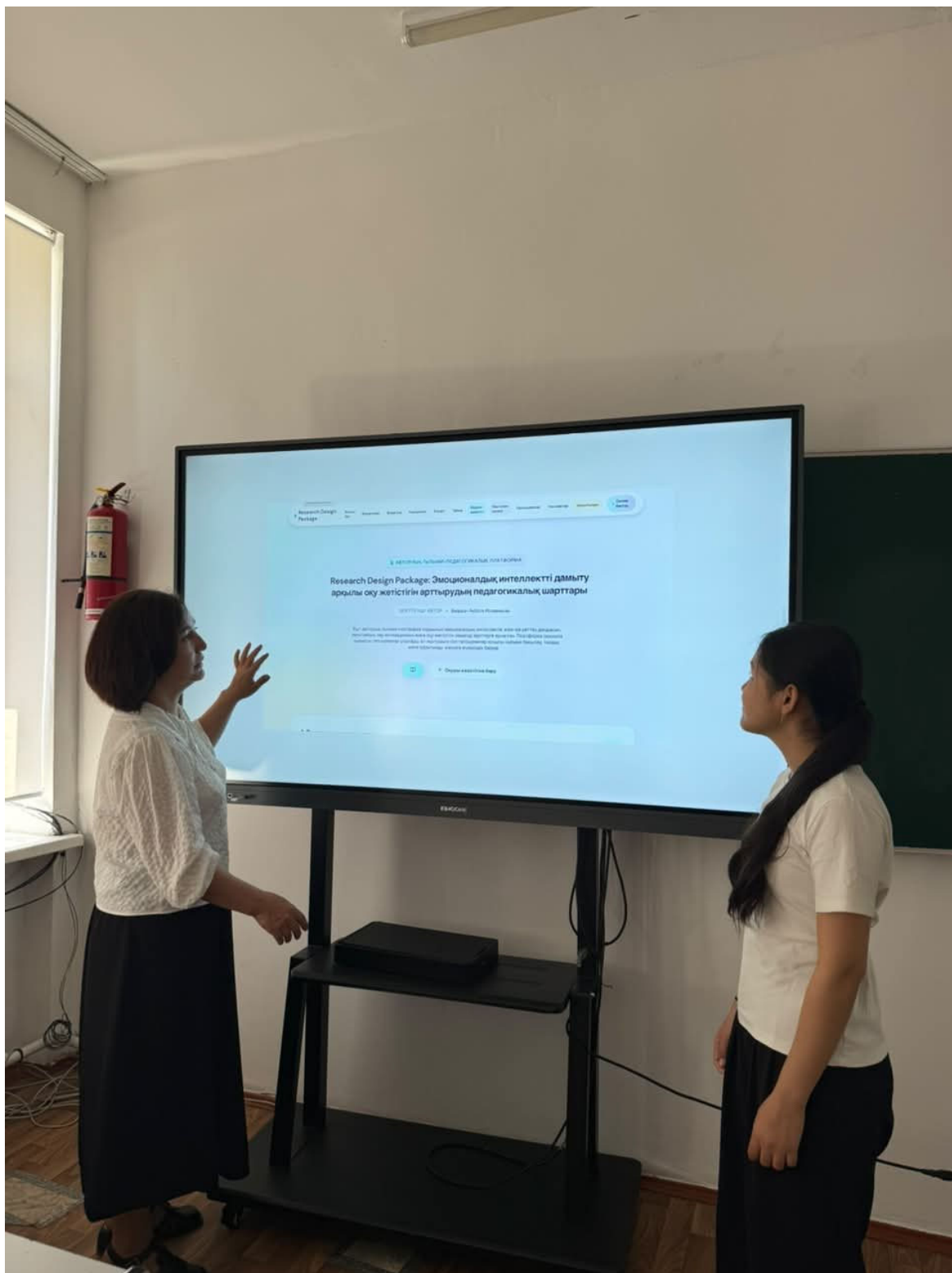


Figure 15. Teacher-guided explanation of the platform homepage and research entry point for emotional intelligence development.



*Figure 16. Full-view classroom presentation of the emotional intelligence development platform and its pedagogical research focus.*

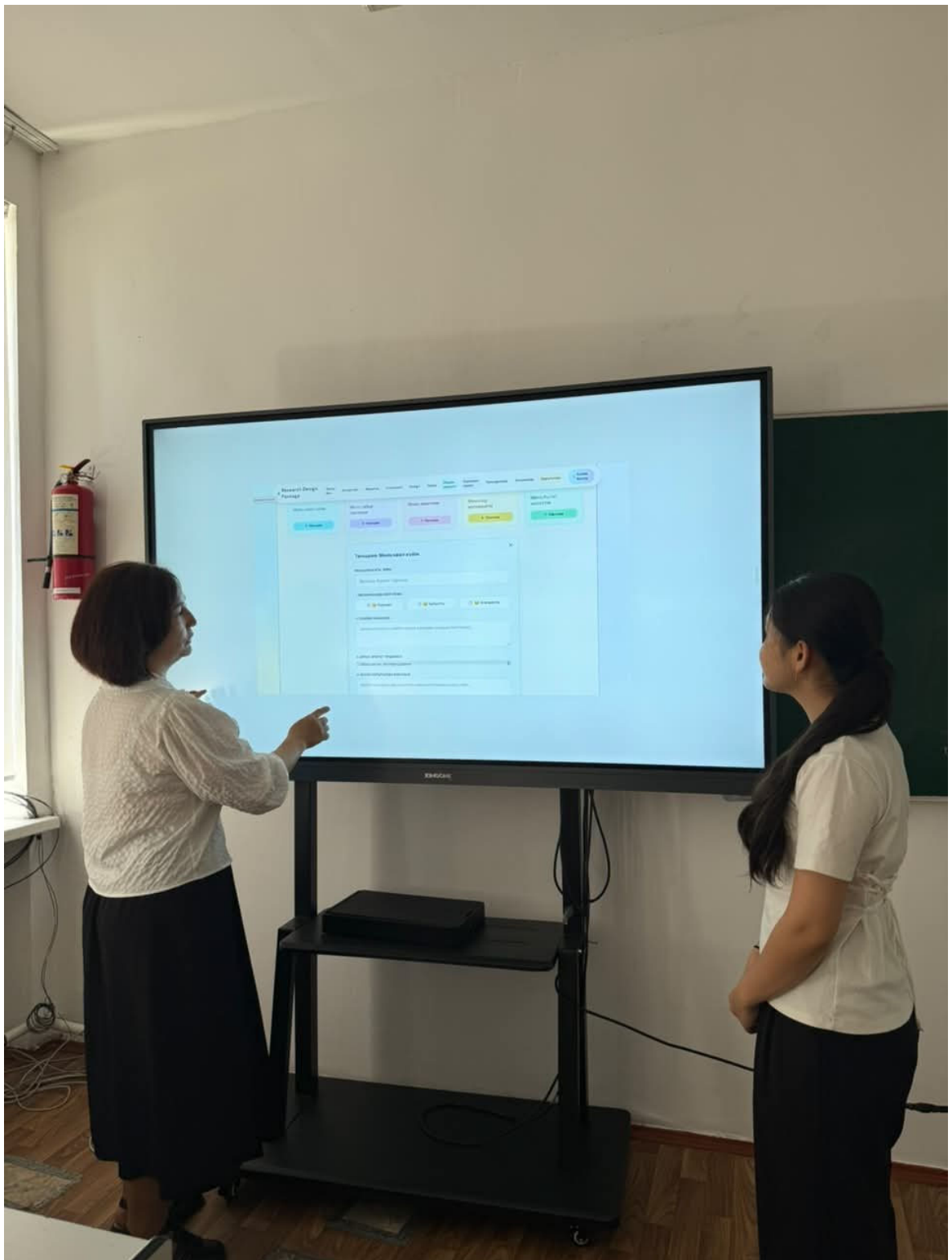


Figure 17. Demonstration of the teacher panel and task-monitoring interface during practical validation.

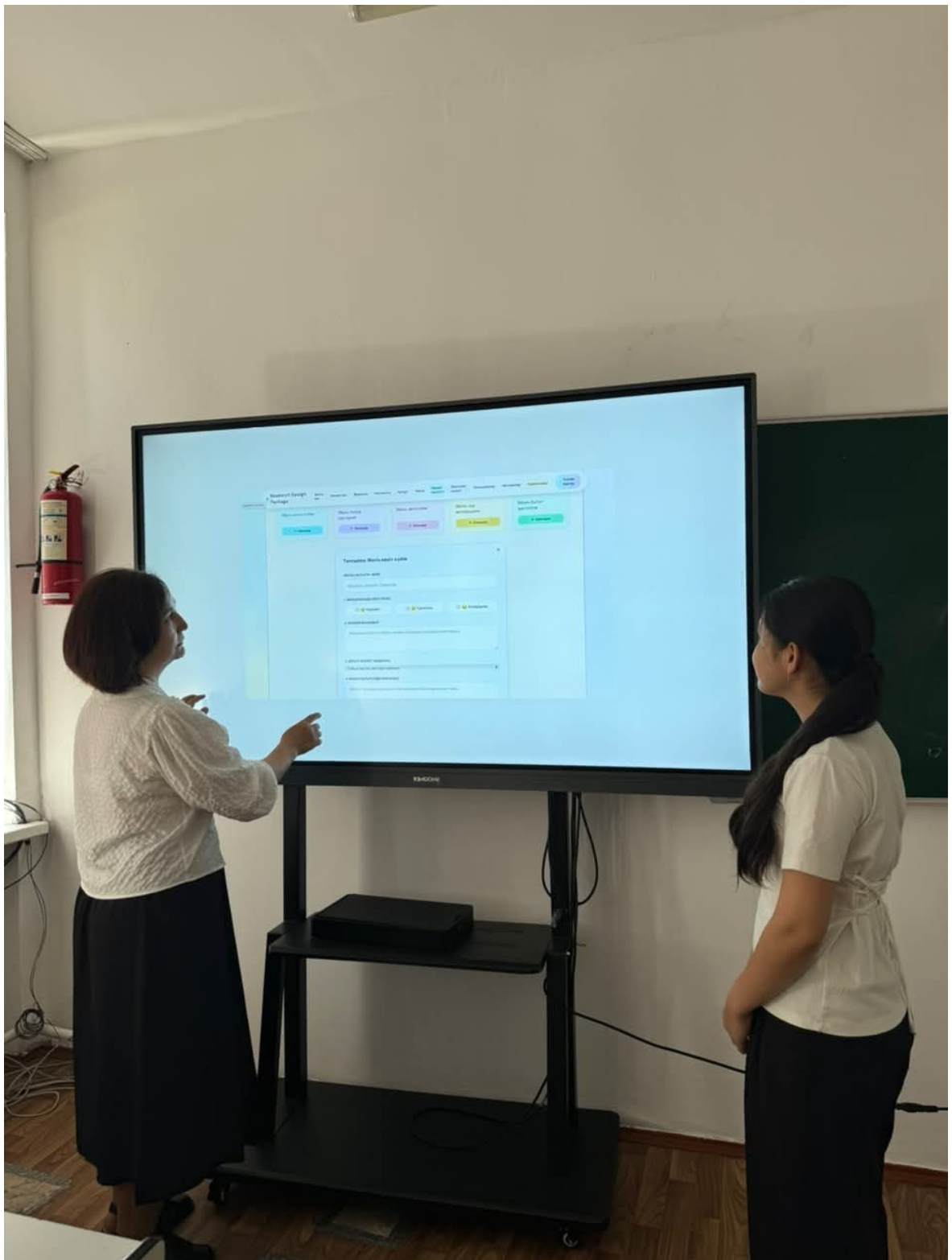
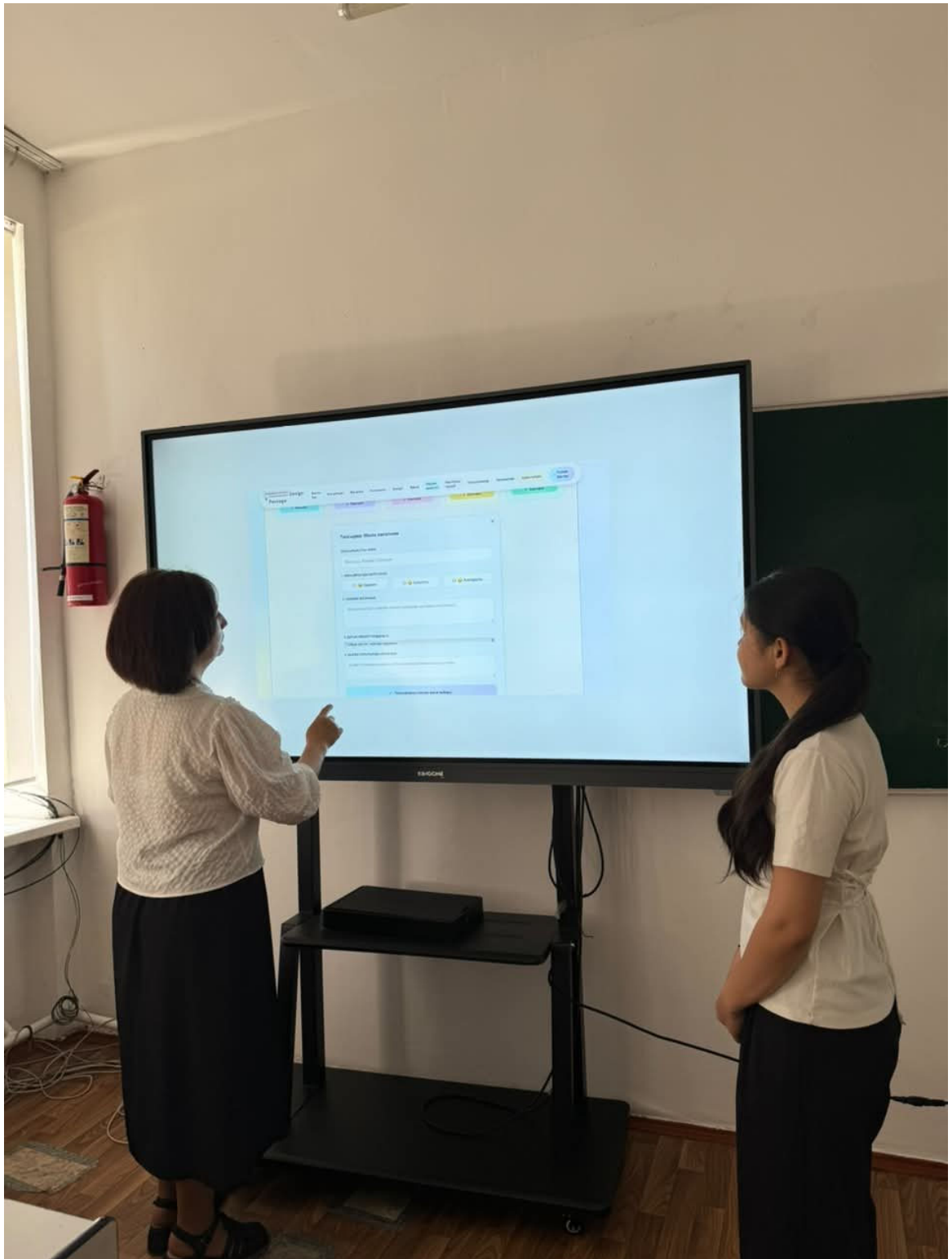


Figure 18. Teacher and student observing the digital research design interface and formative assessment sections.



*Figure 19. Close practical demonstration of the platform interface showing simulation and learner profile components.*

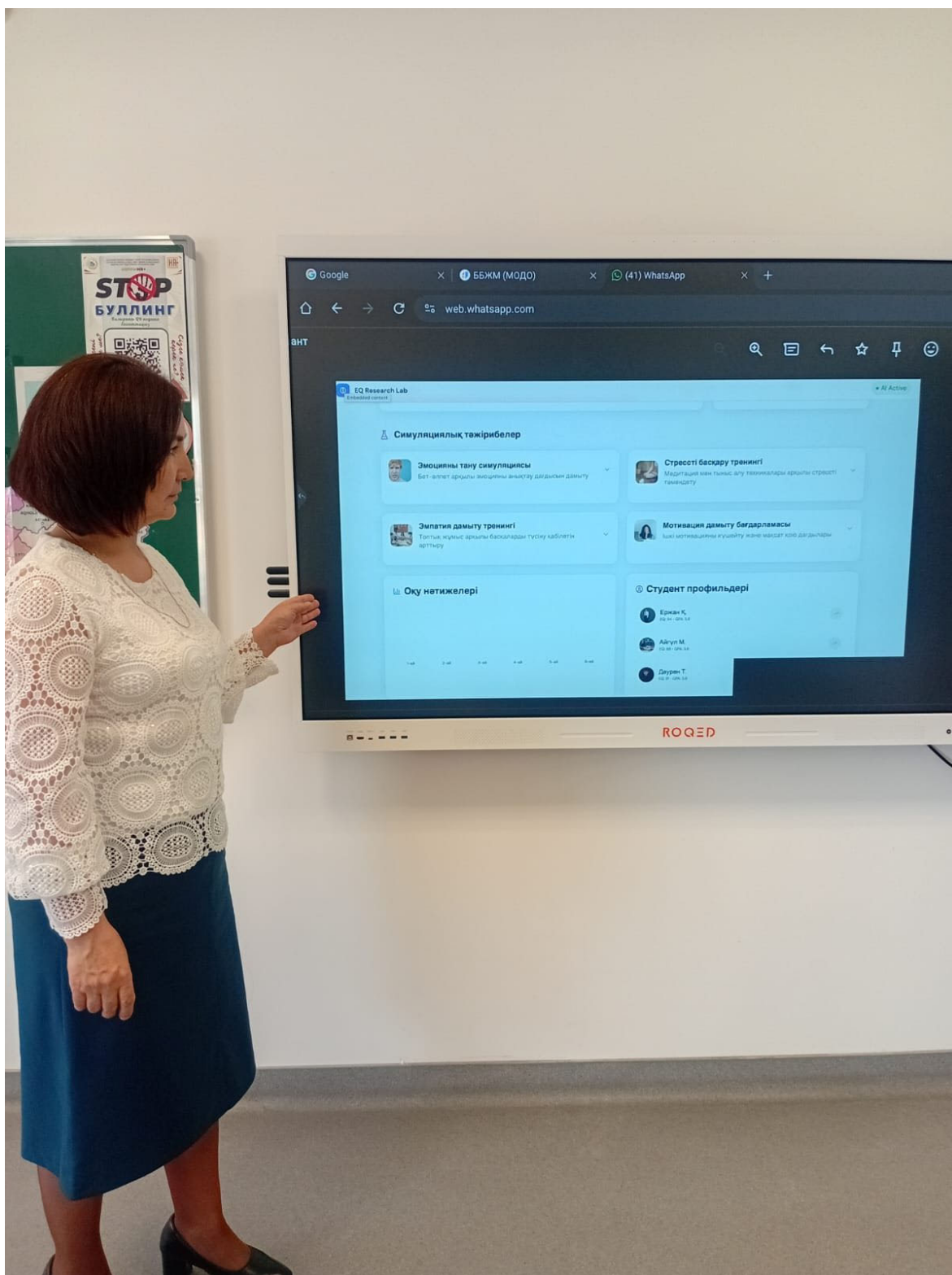


Figure 20. Teacher presents the emotional intelligence simulation experiences and student profile dashboard on the classroom screen.

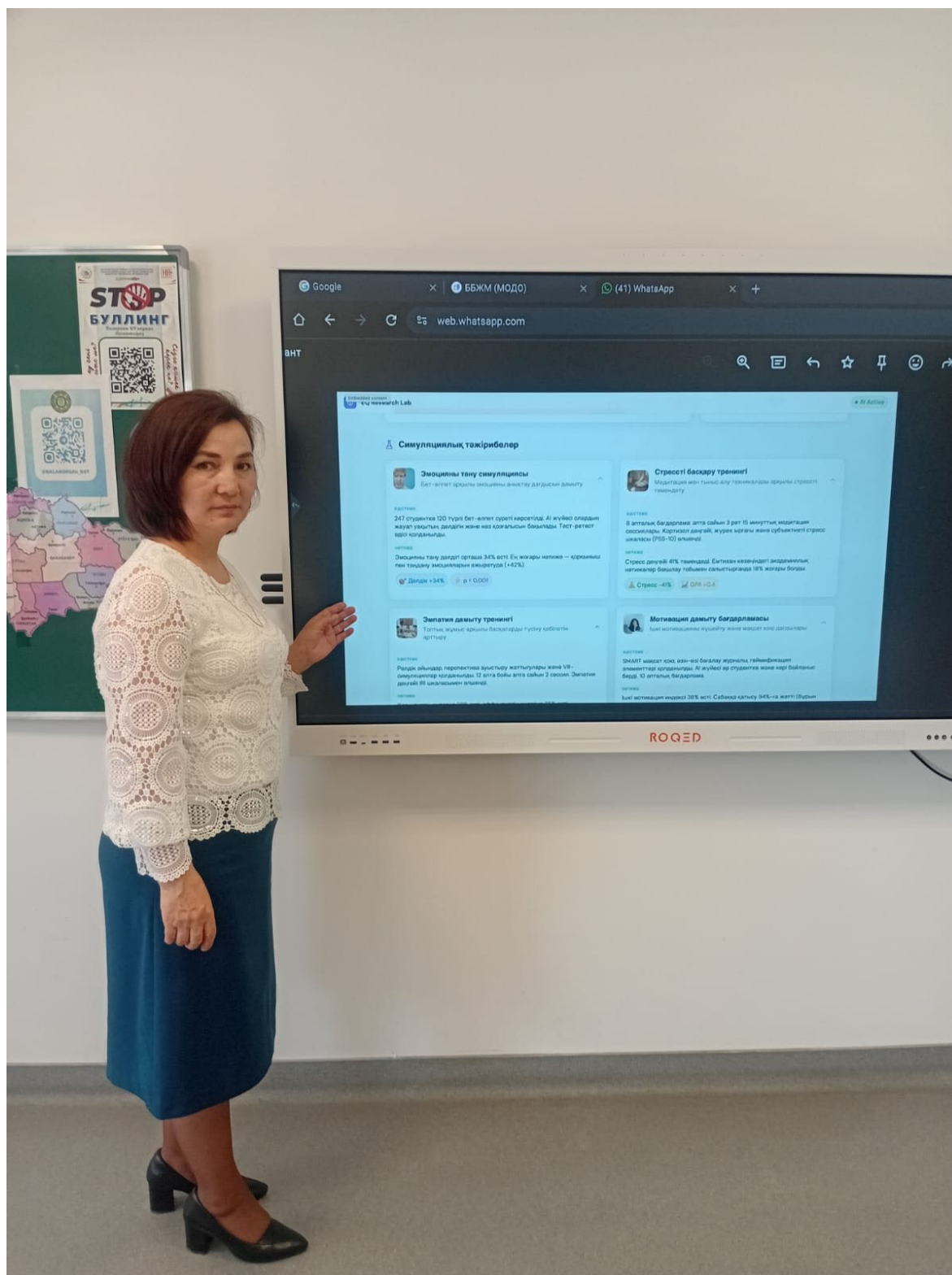


Figure 21. Practical validation of the emotional recognition and stress-management training modules within the platform.

**RESEARCH INSTRUMENTS AND DATA COLLECTION**

Instrument	Purpose	Format	Analysis use
Initial emotional-state form	Identify baseline mood, readiness and emotional vocabulary	Short questionnaire and student self-description	Baseline diagnostic profile

Emotional intelligence task set	Develop recognition, regulation, empathy, motivation and reflection	Five interactive cards and written responses	Task completion and qualitative analysis
Teacher assessment panel	Evaluate observable emotional and learning behaviors	Criteria: low, medium, high	Rubric-based formative assessment
Academic achievement record	Compare achievement before and after platform use	Grade scores, teacher marks or task performance	Quantitative outcome variable
Learning motivation reflection	Identify perceived reasons for learning engagement	Open-ended response	Thematic analysis
Platform analytics	Record progress, completed tasks and result indicators	Digital counts and progress values	Engagement measure
Teacher observation notes	Document classroom behavior and support needs	Field notes	Contextual interpretation

*Table 5. Research instruments for platform-based emotional intelligence assessment.*

#### VARIABLES AND STATISTICAL ANALYSIS PLAN

The main independent variable is participation in the platform-supported emotional intelligence development cycle. Dependent variables include academic achievement score, learning motivation, self-regulation indicator, empathy indicator, communication quality and task completion rate. Control variables may include grade level, prior academic achievement, digital literacy and attendance. Descriptive statistics should summarize means, standard deviations, frequencies and percentages. If pre- and post-intervention data are collected, paired-sample t-tests or Wilcoxon signed-rank tests can be applied. Group comparisons may be conducted through independent-sample t-tests or Mann-Whitney U tests. Correlation analysis can examine the relationship between emotional intelligence indicators and academic achievement. Multiple regression may be used to test whether self-regulation, empathy and motivation predict academic progress when baseline achievement is controlled.

Variable group	Example indicators	Measurement level	Recommended analysis
Emotional recognition	Ability to name and describe emotions	Ordinal/rubric score	Descriptive and pre-post comparison
Self-regulation	Choice of constructive action in difficult learning situations	Ordinal/rubric score	Correlation with task persistence
Empathy	Ability to understand another persons emotional state	Ordinal/rubric score	Rubric and thematic analysis
Learning motivation	Interest, effort and goal orientation	Scale score/open response	Regression and qualitative coding
Academic achievement	Subject grade, test score or task quality	Interval/ordinal	Pre-post and correlation analysis
Platform engagement	Completed cards, tasks and progress percentage	Count/percentage	Predictor of outcome change

Table 6. Variable structure and analysis plan.

### ETHICAL CONSIDERATIONS

The study requires an ethical approach because it collects information related to students emotional states and learning behavior. Participation should be voluntary, data should be anonymized, and the platform should be used for pedagogical support rather than labeling. Emotional intelligence indicators must not be interpreted as fixed personality traits. They should be treated as developmental signals that help the teacher choose appropriate support strategies.

Ethical issue	Practical solution
Voluntary participation	Students and parents receive clear information about the purpose of the activity.
Confidentiality	Names are replaced with codes in analysis files and publication materials.
Non-stigmatization	Low scores are interpreted as support needs, not as personal failure.
Psychological safety	Students are not forced to disclose deeply personal experiences.
Teacher responsibility	The teacher uses results for feedback, guidance and improvement.
Data protection	Digital records are stored securely and used only for educational research purposes.

Table 7. Ethical safeguards for emotional intelligence research in school settings.

### EXPECTED RESULTS AND DISCUSSION

The expected result of implementing the model is the improvement of students emotional awareness, self-regulation, empathy, communication culture and learning motivation. These outcomes are expected to support academic achievement indirectly by improving attention, persistence, classroom participation and readiness to respond constructively to learning difficulties. The platform is especially valuable because it transforms emotional intelligence from a theoretical concept into visible tasks that can be completed, observed and discussed.

The results dashboard shown in the platform screenshots presents a model of how emotional and learning indicators may be summarized. Indicators such as emotional recognition, self-regulation, empathy, learning motivation and achievement create a holistic picture of the learner. This structure is preferable to a single emotional intelligence score because it allows the teacher to identify which component requires support. For example, a student may have strong empathy but weak self-regulation, or good motivation but low emotional vocabulary. A differentiated pedagogical response becomes possible.

The teacher panel is another important element. It makes assessment more transparent by organizing observation criteria into levels. This supports formative assessment: the teacher can discuss progress with the student, select new tasks and monitor change over time. The platform therefore becomes not only a student-facing learning tool but also a teacher research instrument.

The practical classroom photographs demonstrate that the platform can be integrated into a real lesson using an interactive board. This format supports teacher explanation, peer discussion and individual reflection. Students can observe the platform together, answer tasks, compare choices and formulate conclusions. The classroom setting also shows that digital emotional-intelligence tasks do not replace teacher interaction; rather, they enrich it by providing structure and evidence.

#### PEDAGOGICAL CONDITIONS FOR EFFECTIVE IMPLEMENTATION

Condition	Description	Implementation in the platform
Psychologically safe environment	Students must feel respected and not judged when discussing emotions	Neutral language, supportive tasks and non-stigmatizing teacher feedback
Explicit emotional vocabulary	Students need words to identify and explain emotional states	Mood and emotion identification tasks
Self-regulation practice	Students should learn specific actions for coping with learning difficulties	Calmness practice and constructive-action selection
Empathic communication	Learning achievement improves when students can cooperate and understand others	Empathy cards and communication criteria
Motivational reflection	Students should connect effort, goal and achievement	Learning motivation and achievement today tasks
Evidence-based teacher observation	Teachers need clear criteria to evaluate progress	Teacher panel with low, medium and high indicators
Digital feedback loop	Students and teachers need visible progress data	Results dashboard, progress indicators and completion records

*Table 8. Pedagogical conditions for developing emotional intelligence as a factor of learning achievement.*

#### LIMITATIONS

This article presents a platform-supported methodological model and a ready empirical design, but full effectiveness can be confirmed only after systematic implementation with a defined sample, control or comparison group, validated instruments and repeated measurement. Emotional intelligence is multidimensional; therefore, it cannot be fully captured by short tasks alone. Future studies should combine platform analytics with validated questionnaires, teacher

ratings, student interviews and academic achievement records. Another limitation is that platform screenshots and classroom photographs document usability and practical relevance, but they do not by themselves prove learning gains. They should be interpreted as implementation evidence within a broader research design.

### CONCLUSION

The development of emotional intelligence is a meaningful pedagogical condition for improving academic achievement because emotional recognition, self-regulation, empathy, communication and motivation shape how students participate in learning. The proposed Research Design Package platform provides a structured and practical way to integrate these dimensions into school education. It combines student reflection, teacher observation, digital progress indicators and task-based emotional learning. The model is consistent with international SEL frameworks, OECD social and emotional skills assessment logic, UNESCO guidance and meta-analytical evidence linking emotional intelligence with academic performance.

The article demonstrates that emotional intelligence can be studied and developed through a digital pedagogical environment when the learning process is organized as a cycle of diagnosis, guided practice, reflection, teacher assessment and result analysis. The platform can be used as an authorial scientific-pedagogical tool for future experimental research, professional development and classroom innovation. Its strongest contribution is the transformation of emotional intelligence from an abstract construct into a concrete, observable and pedagogically manageable learning process.

### DECLARATIONS

Item	Statement
Author contribution	To be completed by the author.
Funding	No external funding is declared unless otherwise specified by the author.
Conflict of interest	The author declares no conflict of interest.
Data availability	Data will be available from the author upon reasonable request after anonymization.
Ethics	The study design requires voluntary participation, confidentiality and non-stigmatizing use of emotional indicators.

*Table 9. Publication declarations.*

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**APPENDIX A. PLATFORM IMPLEMENTATION CHECKLIST**

Step	Teacher action	Student action	Evidence
1	Introduce the purpose of emotional intelligence development	List current learning emotions	Initial reflection form
2	Explain platform navigation and task logic	Open learner space and complete first card	Progress indicator
3	Guide self-regulation and empathy tasks	Choose constructive action and write short explanation	Task response
4	Use teacher panel criteria	Observe and mark emotional-learning indicators	Teacher rating
5	Discuss results individually or in groups	Reflect on personal achievement and next step	Reflection text
6	Summarize academic and emotional progress	Prepare final learning conclusion	Dashboard and written conclusion

*Table 10. Practical checklist for platform use in a school lesson.*

**APPENDIX B. SAMPLE RUBRIC FOR EMOTIONAL-INTELLIGENCE-BASED LEARNING ACHIEVEMENT**

Criterion	Low level	Medium level	High level
Emotion recognition	Names emotion vaguely or with difficulty	Identifies basic emotion and cause	Clearly explains emotion, cause and learning effect
Self-regulation	Does not select constructive strategy	Chooses a strategy but explanation is limited	Selects appropriate strategy and justifies it
Empathy	Finds it difficult to understand others feelings	Recognizes another persons possible emotion	Explains another persons emotion and supportive response
Learning motivation	Shows weak connection between effort and goal	Names learning goal but needs support	Connects effort, goal, strategy and progress
Academic reflection	Writes a short general answer	Explains what was learned	Analyzes progress and proposes next improvement step

*Table 11. Rubric for assessing emotional intelligence in relation to learning achievement.*

# DEVELOPING ACADEMIC WRITING THROUGH ARTIFICIAL INTELLIGENCE

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## Abstract

This article presents a design-based and mixed-method research model for developing academic writing through artificial intelligence in the context of foreign language teacher education. The study is built around the AI Academic Writing Lab platform, a digital research ecosystem that integrates doctoral preparation, research idea generation, academic writing analysis and an AI research assistant. The platform is designed not as a replacement for human authorship, but as a controlled pedagogical environment in which learners can formulate research problems, structure academic texts, improve scholarly language, verify methodological logic and reflect on ethical AI use. The article synthesizes international evidence from UNESCO guidance on generative AI in education and research, OECD work on artificial intelligence and education, European ethical guidelines, publication ethics recommendations, and current studies on AI-supported academic writing. The proposed model defines the pedagogical conditions as: AI literacy, transparent authorship, prompt engineering competence, source verification, teacher-guided revision, academic integrity, and reflective documentation of AI assistance. Practical platform screenshots and classroom implementation photographs are used as visual evidence of the developed model and its testing context. The article offers a publication-ready framework for future empirical validation in higher education and foreign language methodology programmes.

Keywords: artificial intelligence, academic writing, generative AI, AI literacy, foreign language teaching methodology, doctoral education, research writing, prompt engineering, academic integrity, digital pedagogy.

## INTRODUCTION

Academic writing is a core competence of university education and doctoral preparation. It requires the ability to identify a research gap, formulate a problem, build a logical argument, synthesize sources, design a methodology, present evidence and write in a precise scholarly style. For students in foreign language teaching methodology, academic writing is additionally connected with English for academic purposes, research communication and participation in international publication culture.

The emergence of generative artificial intelligence has transformed the conditions under which academic writing is taught and learned. AI tools can support brainstorming, outline development, language revision, explanation of methodological concepts and feedback on coherence. However, the same tools can also generate inaccurate claims, fabricated references, generic argumentation and ethically problematic text if students use them without critical supervision. Therefore, AI-supported academic writing must be framed as a pedagogical process rather than as automatic text production.

International organizations increasingly emphasize the need for a human-centred approach to AI in education. UNESCO guidance on generative AI in education and research highlights the importance of human agency, inclusion, safety and the reconsideration of learning content, methods and assessment. The European Commission ethical guidelines stress that educators should understand both the potential and risks of AI and data use in teaching and learning. The

Committee on Publication Ethics states that AI tools cannot be listed as authors because they cannot take responsibility for the submitted work. These positions are directly relevant to academic writing pedagogy.

This study responds to the need for a structured educational model by proposing AI Academic Writing Lab, a platform-supported environment for developing academic writing through artificial intelligence. The platform includes a research idea generator, an academic writing analyzer, an AI research assistant and guided doctoral preparation modules. It is intended to help learners use AI critically, transparently and productively while preserving human authorship and academic integrity.

#### PURPOSE, RESEARCH QUESTIONS AND HYPOTHESES

The purpose of the study is to develop and justify a platform-supported pedagogical model for improving academic writing through artificial intelligence and to describe the conditions under which this model may be implemented in foreign language teacher education.

Component	Content
Object of the study	The educational process in which artificial intelligence is integrated into academic writing instruction.
Subject of the study	Pedagogical conditions, digital modules and assessment criteria that connect AI literacy with academic writing development.
Aim	To design, theoretically justify and practically describe a digital platform model that develops academic writing through responsible AI-supported research practice.
Research Question 1	How can artificial intelligence be operationalized as a pedagogical scaffold for academic writing development?
Research Question 2	What platform components support research problem generation, academic text analysis, methodological guidance and reflective revision?
Research Question 3	How can teachers assess AI-supported academic writing without reducing it to automatic text quality scores?
Hypothesis	If learners regularly use AI-supported modules for research problem formulation, academic text analysis, methodological consultation and reflective disclosure under teacher guidance, then their academic writing quality, AI literacy and research independence will improve.

*Table 1. Research logic of the proposed study.*

#### LITERATURE REVIEW

The literature on generative AI and academic writing shows a rapidly developing field. AI tools provide language support, idea generation and feedback opportunities, but their educational value depends on how they are integrated into pedagogy. Studies on ChatGPT and higher education emphasize both opportunities and risks: personalized feedback, accessibility and writing

support on the one hand; hallucination, overreliance and academic integrity problems on the other.

UNESCO guidance provides an important theoretical basis because it frames generative AI in education through human-centred principles. This approach is essential for academic writing: AI may assist learners, but it must not remove the learners responsibility for argumentation, evidence and final interpretation. OECD work on AI and education similarly raises questions about the implications of AI for learning, skills and assessment, which are highly relevant to doctoral research training.

Publication ethics sources strengthen the argument that AI-supported academic writing requires transparent rules. The Committee on Publication Ethics clarifies that AI tools cannot be authors because they cannot approve a final manuscript, manage conflicts of interest or take responsibility for the integrity of research. This principle is translated into the present model through reflective AI-use documentation and teacher-guided verification.

Writing pedagogy research also supports the design of the platform. Academic writing is most effective when students receive staged support: topic narrowing, research gap identification, outline development, drafting, feedback, revision and reflection. AI can be inserted into these stages as a scaffold, but only if learners remain active decision-makers. Therefore, the AI Academic Writing Lab platform is designed around process-based writing rather than automated production.

**METHODS AND RESEARCH MATERIALS**

The study is designed as a design-based mixed-method research project. The design-based component focuses on developing and testing a digital pedagogical platform. The quantitative component may include pre- and post-writing scores, AI literacy indicators and platform engagement data. The qualitative component includes learner reflections, teacher observation notes and analysis of written research tasks. This structure allows the study to examine both the quality of the platform product and the learning processes that it supports.

**PRISMA-style source search strategy**

A PRISMA-oriented logic was used to organize the literature base. The search focused on official international frameworks and peer-reviewed studies related to generative AI, academic writing, AI literacy, higher education, foreign language writing pedagogy and academic integrity

Source	Core search string	Selection focus
UNESCO / OECD / European Commission	generative AI education; artificial intelligence and education; ethical AI in teaching and learning	Official guidance, policy documents and international educational frameworks
COPE / academic integrity sources	AI authorship; AI tools and publication ethics; academic integrity and AI	Publication ethics, authorship rules and responsible AI-use guidance
Scopus / Web of Science	("generative AI" AND "academic writing") OR ("ChatGPT" AND "academic integrity")	Peer-reviewed empirical studies, systematic reviews and conceptual papers
ERIC / Google Scholar	AI writing tools EFL academic writing prompt engineering higher education	Educational intervention studies, writing pedagogy and language education sources

*Table 2. Search strategy for constructing the theoretical and empirical basis of the article.*

**Inclusion and exclusion criteria**

Criterion	Included	Excluded
Topic relevance	Studies on AI, academic writing, AI literacy, EFL writing, research methodology and academic integrity	General technology papers without educational writing relevance
Educational level	Higher education, doctoral preparation, teacher education and academic writing contexts	Unrelated workplace or purely commercial AI-use cases
Evidence type	Peer-reviewed studies, official frameworks, ethical guidelines and methodological reports	Unsupported claims, advertising materials and non-verifiable blog texts
Methodological clarity	Sources with defined concepts, variables, samples, instruments or theoretical frameworks	Texts without source transparency or clear methodology
Application	Research that can inform platform design, writing assessment and ethical AI-use tasks	Studies with no practical connection to academic writing pedagogy

*Table 3. Inclusion and exclusion criteria for the review-based part of the study.*

**CONCEPTUAL MODEL OF THE PLATFORM**

The proposed platform is titled AI Academic Writing Lab. It is designed as an authorial scientific-pedagogical environment for developing academic writing through artificial intelligence. The central pedagogical idea is that AI becomes useful for academic writing only when learners can ask precise questions, evaluate output critically, connect suggestions with reliable sources and revise texts according to academic genre expectations.

The model contains several interconnected spaces. The project section explains the purpose, tasks and relevance of AI-supported academic writing. The research idea generator allows learners to select a research field, target learners, trend or approach and technology/tool in order to formulate a research problem. The academic writing analyzer supports structural revision of scholarly text. The AI research assistant functions as a guided support tool for research gaps, Scopus strategy, methodology, prompt engineering and AI ethics. These modules are connected through a reflective writing cycle.

Platform component	Pedagogical function	Target dimension	Expected writing link
Project objectives	Explains why AI-supported academic writing matters in doctoral research	Meaning and orientation	Students understand the learning and research purpose
Research idea generator	Guides topic narrowing and problem formulation	Research design thinking	More precise research questions and novelty statements
Academic writing analyzer	Supports structure, clarity and academic style revision	Text organization and coherence	Improved academic text quality
AI research assistant	Provides guided methodological and writing consultation	AI literacy and inquiry	Better problem-solving and independent revision
Reflection and disclosure	Documents how AI was used and revised	Ethics and responsibility	Transparent authorship and academic integrity
Teacher guidance	Interprets outputs and monitors learning process	Formative assessment	Evidence-based support for writing development

*Table 4. Conceptual architecture of the AI Academic Writing Lab platform.*

#### PLATFORM QR CODE AND VISUAL DOCUMENTATION

The digital platform used in the study can be accessed through the QR code below. The following figures document both the interface structure and the practical classroom use of the platform. Captions are written in English so that the materials can be included directly in an international journal-style article.



*Figure 1. QR code linking to the AI Academic Writing Lab platform.*



Figure 2. Homepage of the AI Academic Writing Lab platform showing the doctoral research ecosystem and main functional buttons.



Figure 3. Project objectives section presenting the aim, tasks and relevance of AI-supported academic writing development.



Figure 4. Research Problem Generator interface for selecting research field, target learners, trend or approach and technology/tool.

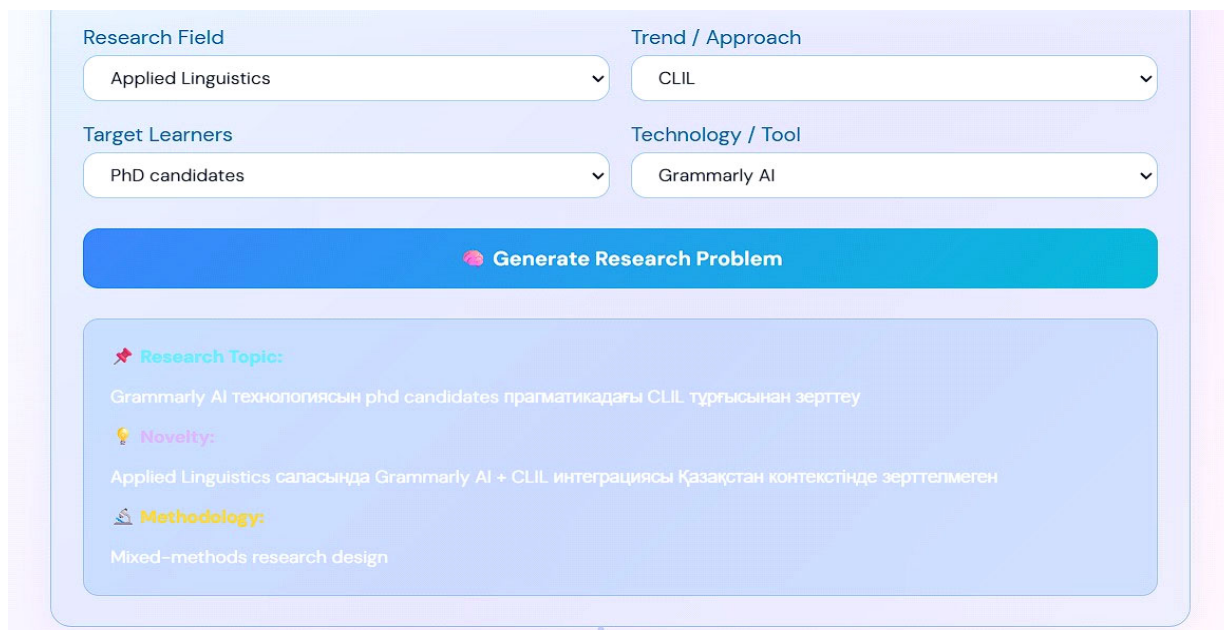


Figure 5. Generated research topic, novelty and methodological direction for AI-supported academic writing research.

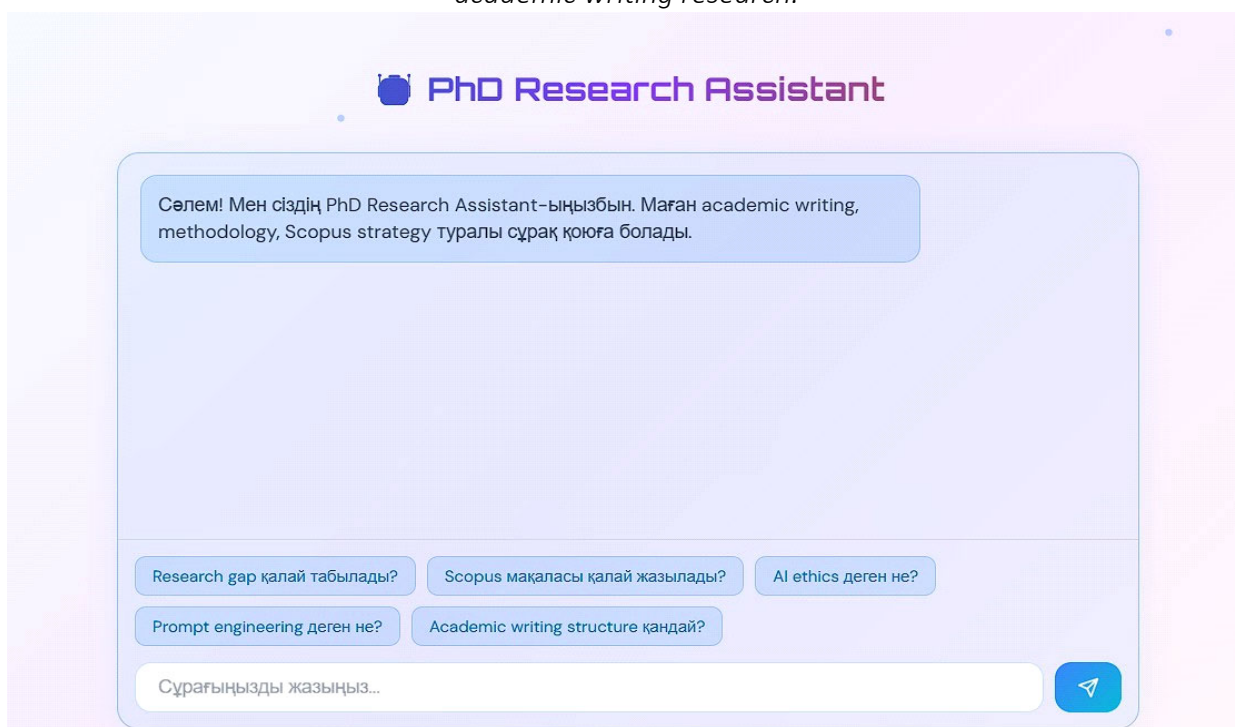


Figure 6. AI Research Assistant chat interface supporting research gap identification, Scopus strategy, academic writing structure and AI ethics.

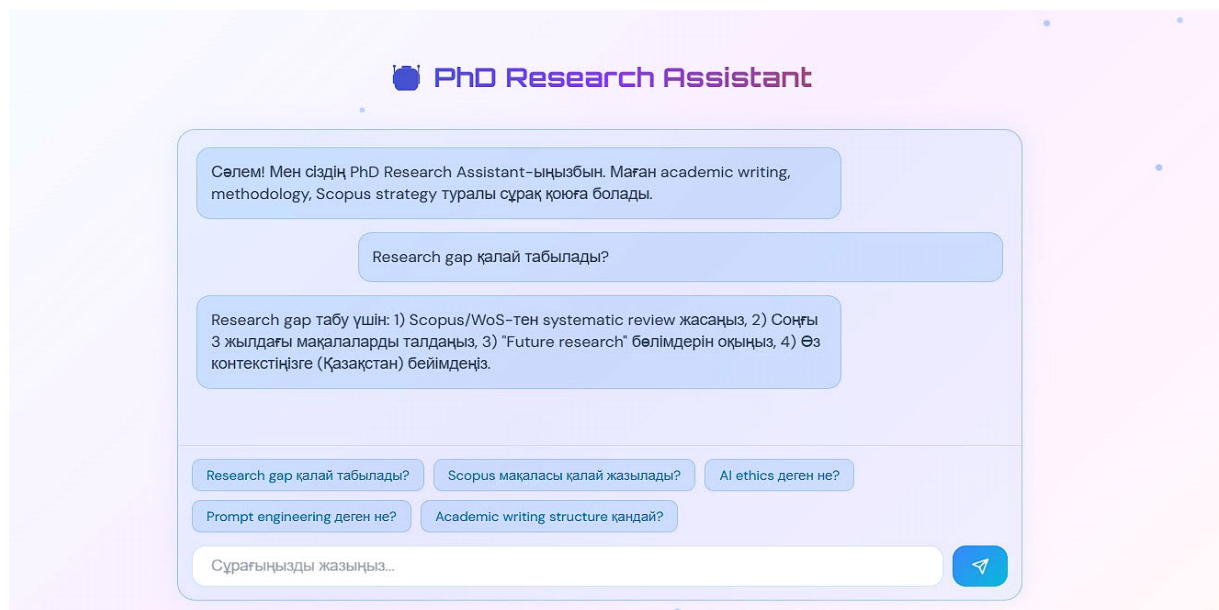


Figure 7. AI Research Assistant response demonstrating methodology and academic writing guidance for the learner.

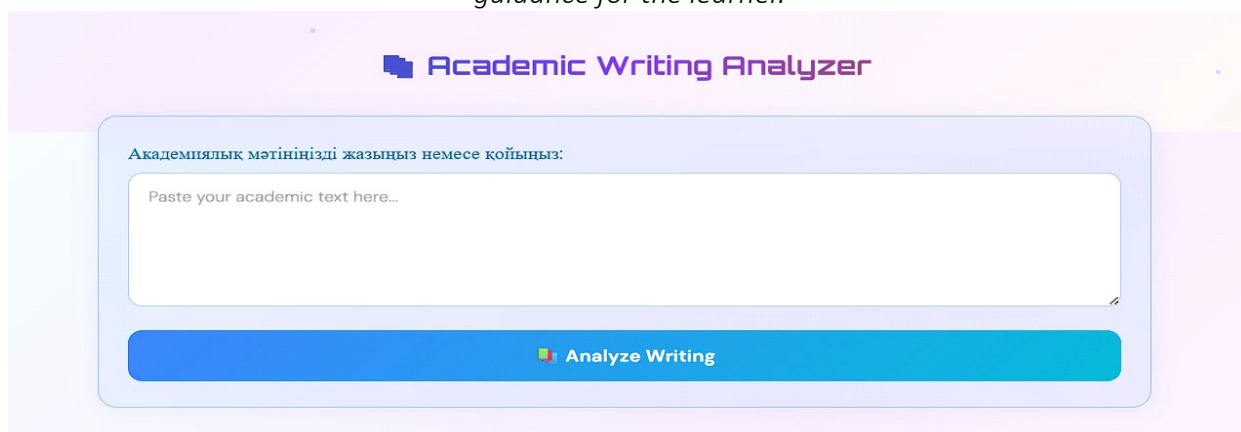


Figure 8. Academic Writing Analyzer module for entering academic text and receiving structure-oriented writing analysis.

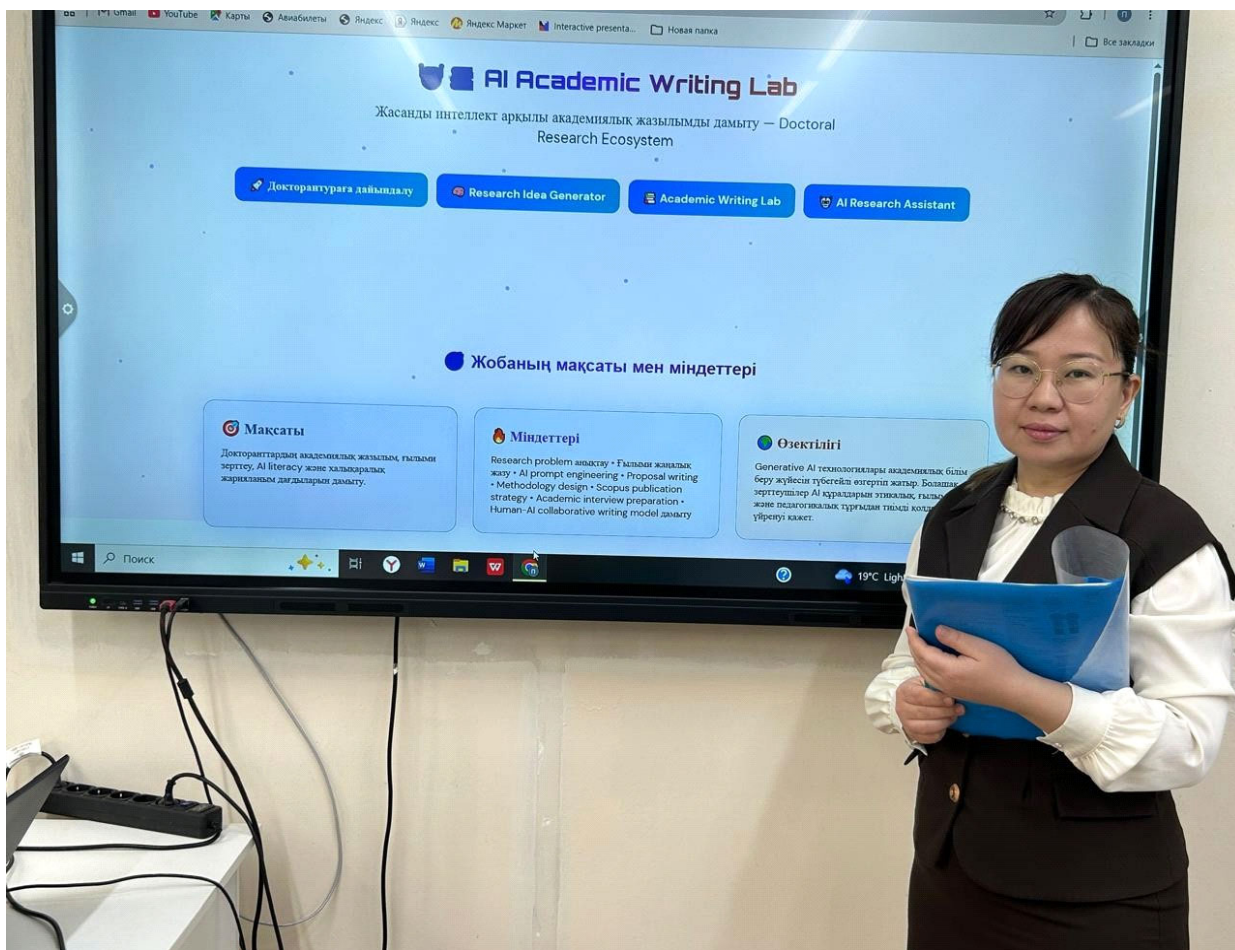


Figure 9. Practical classroom demonstration of the AI Academic Writing Lab platform on the interactive board during an academic writing session.

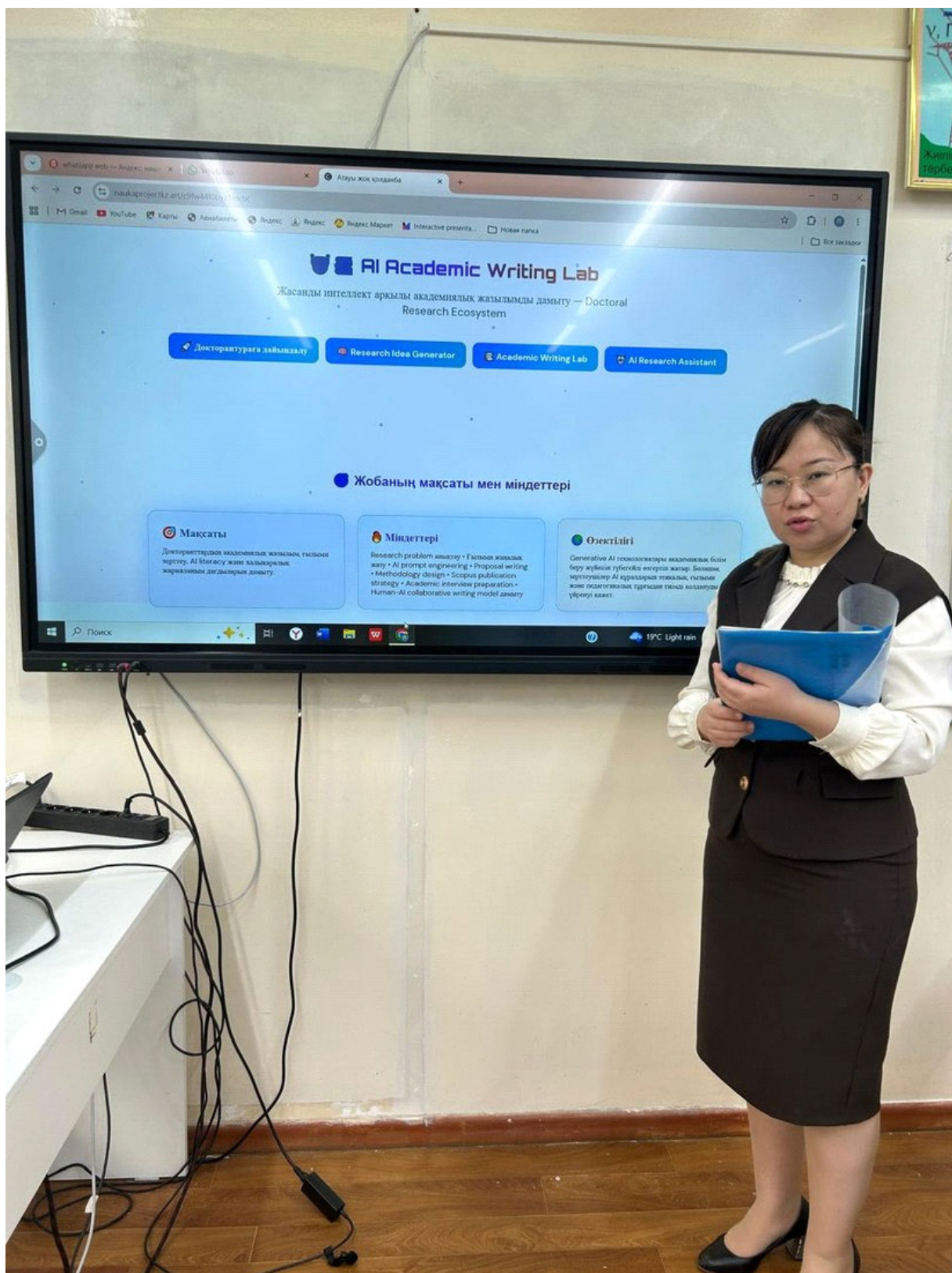


Figure 10. Teacher-guided explanation of the platform homepage and research entry point for AI-supported academic writing development.

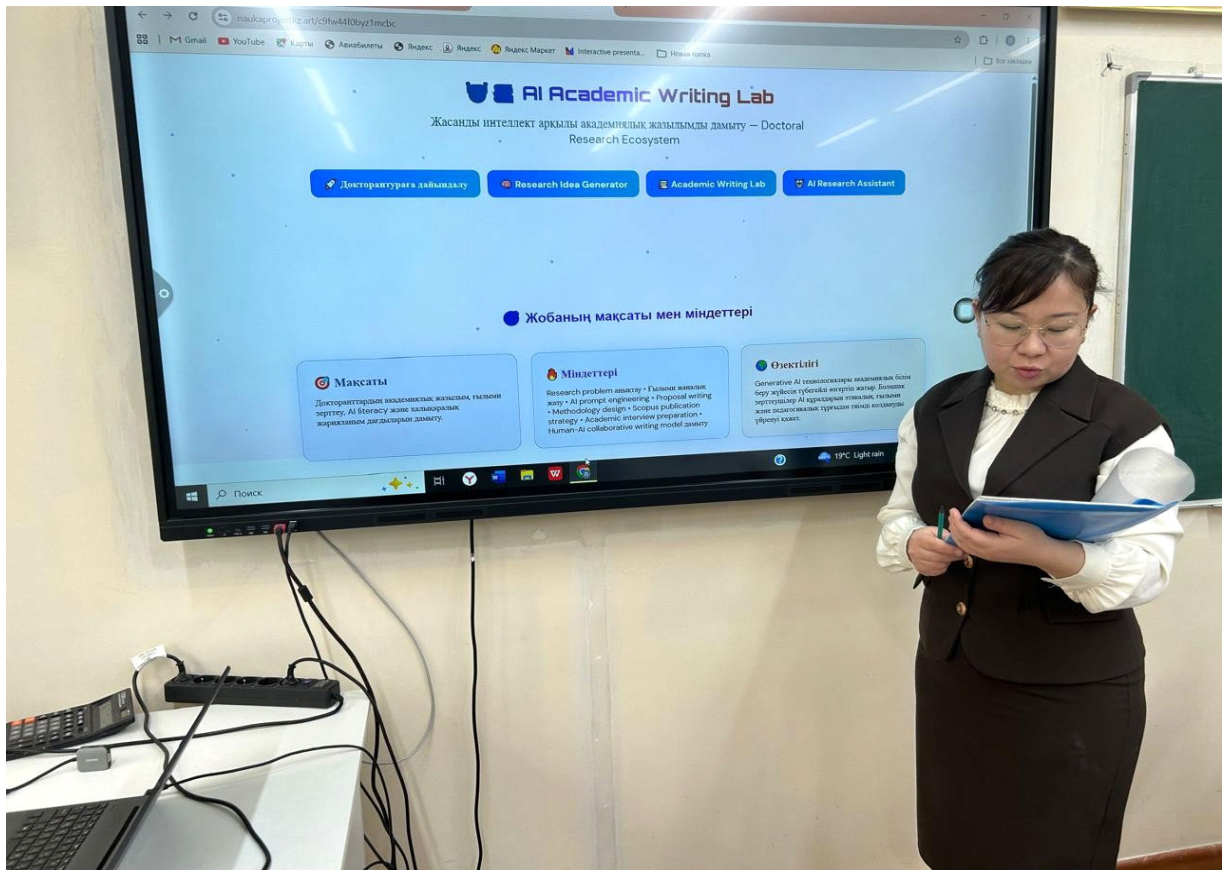


Figure 11. Full-view classroom presentation of the AI Academic Writing Lab and its doctoral research ecosystem.

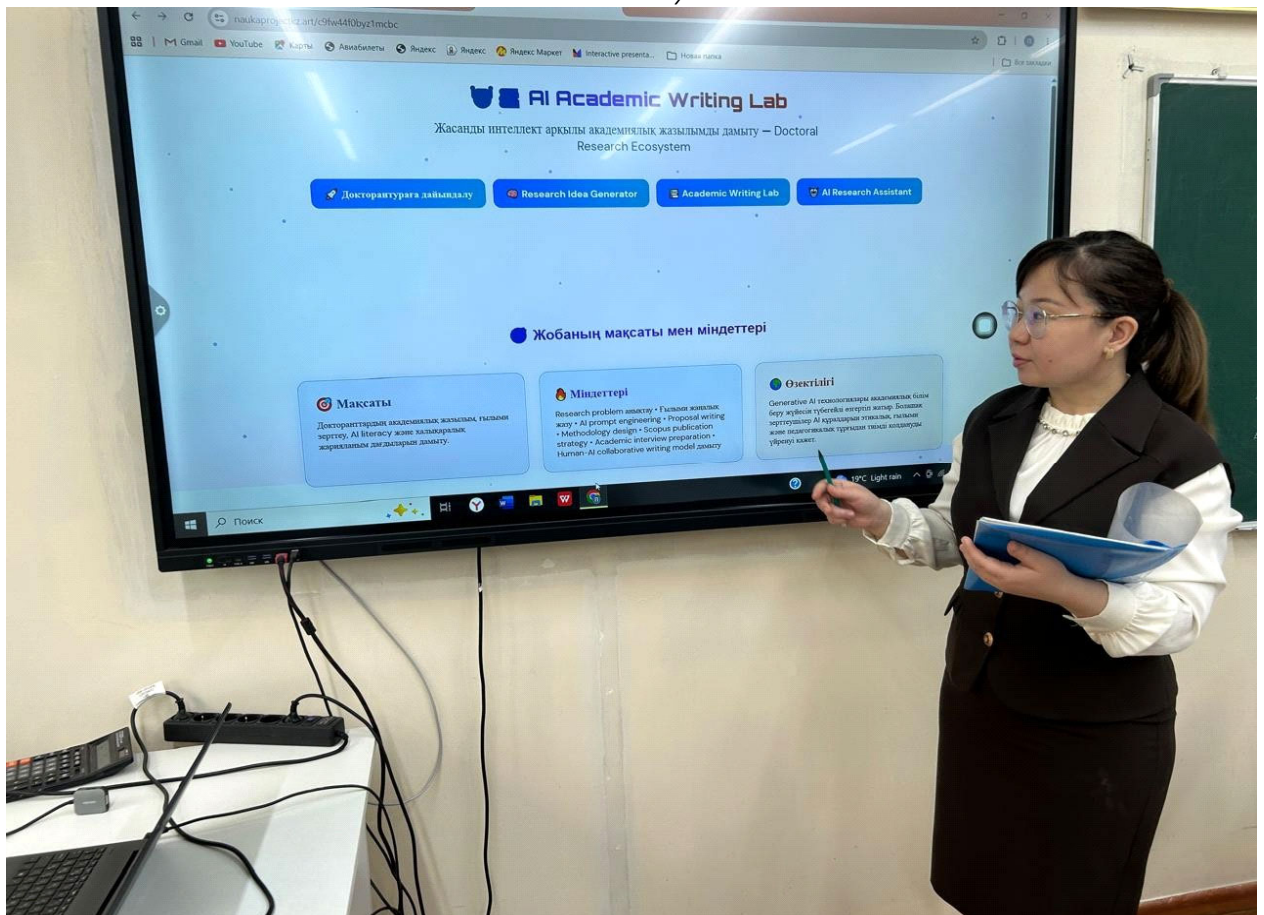


Figure 12. Demonstration of the project objectives, research problem and platform modules during practical validation.

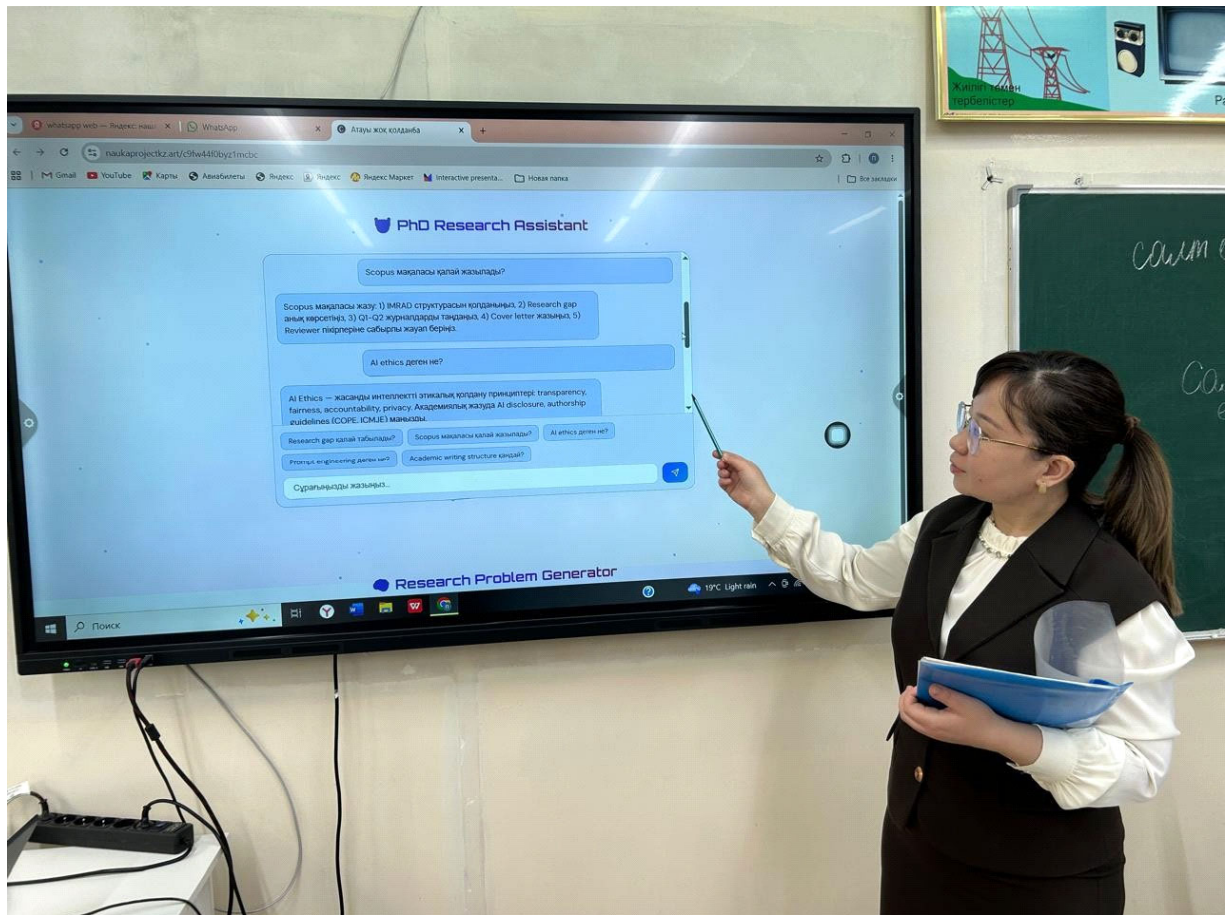


Figure 13. Teacher-researcher presenting the AI Research Assistant interface for methodology and academic writing questions.

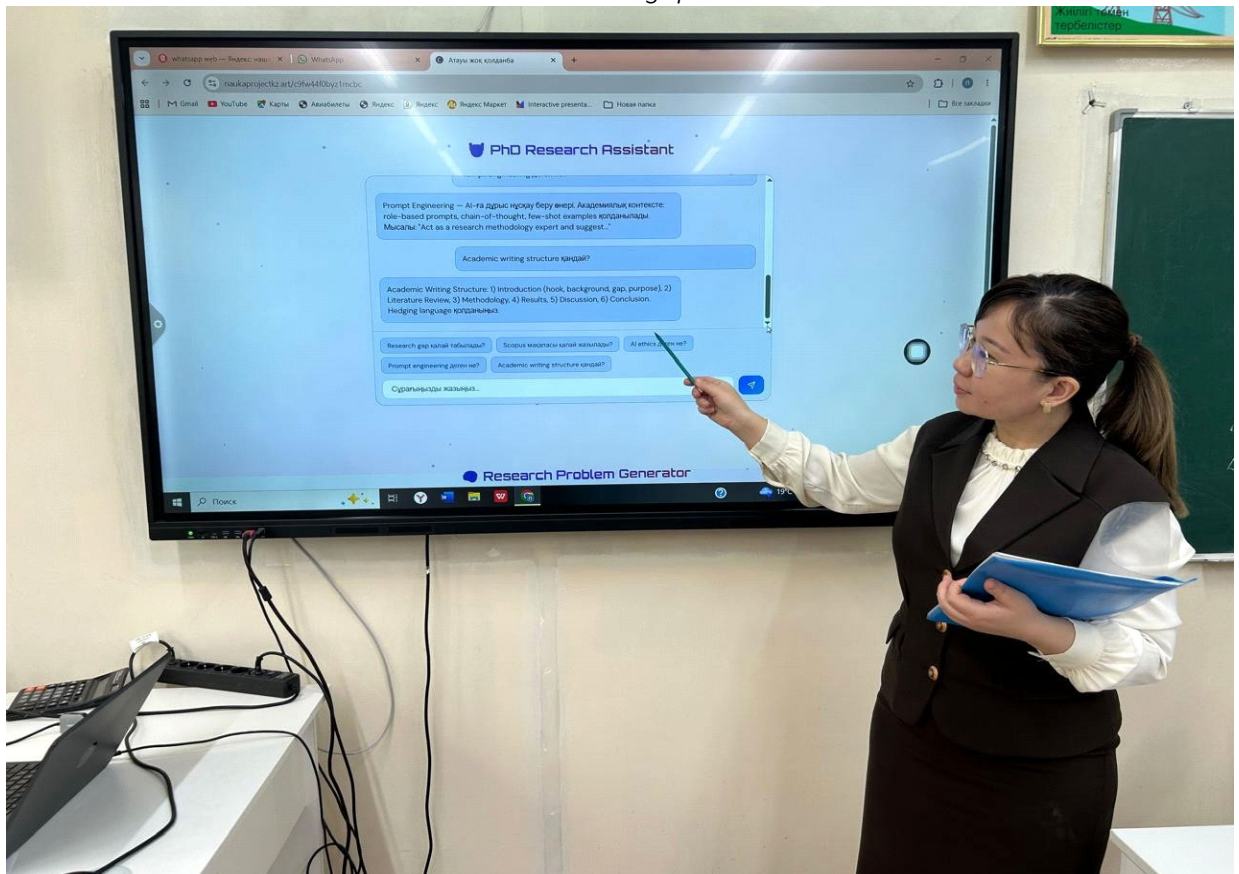


Figure 14. Using the AI Research Assistant to discuss academic writing structure, research gaps and ethical AI use.

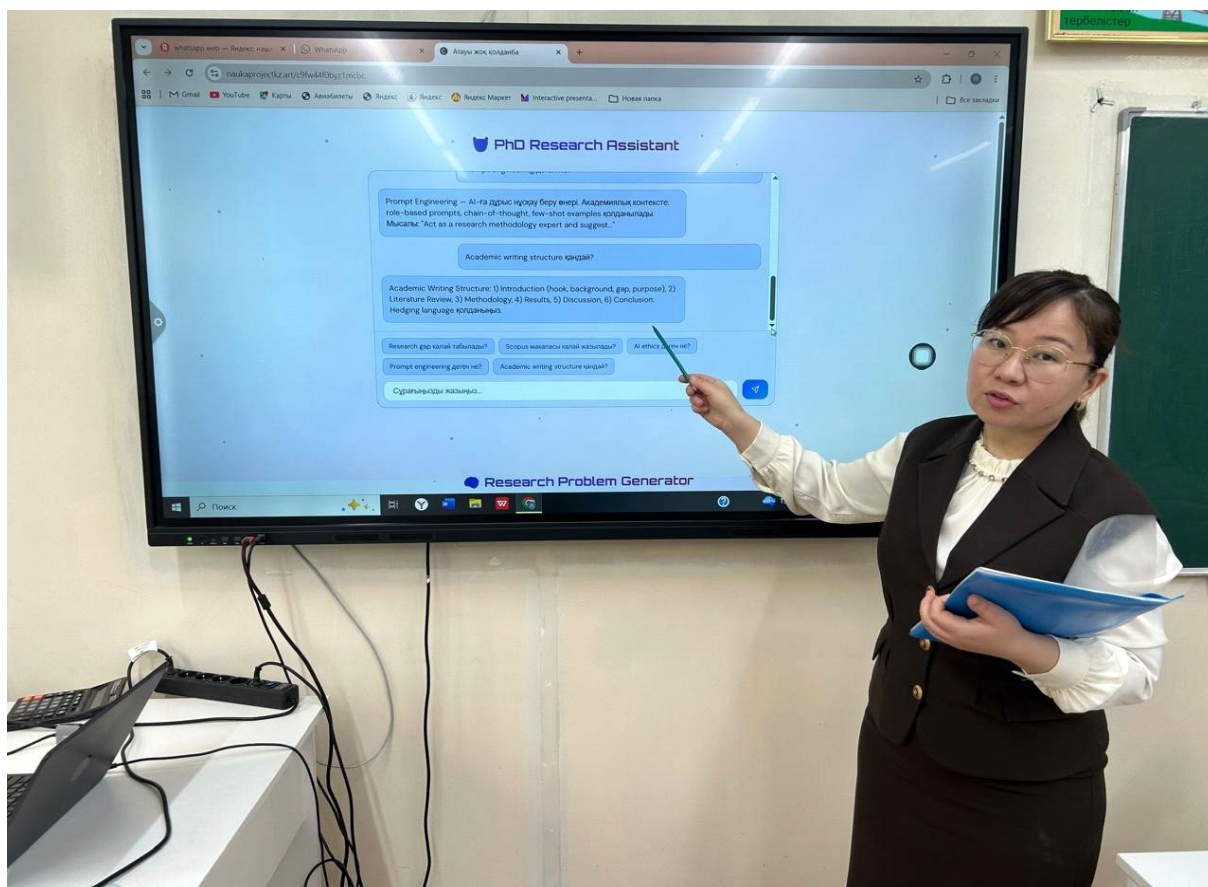


Figure 15. Practical demonstration of the Research Problem Generator module for selecting research field and technology.

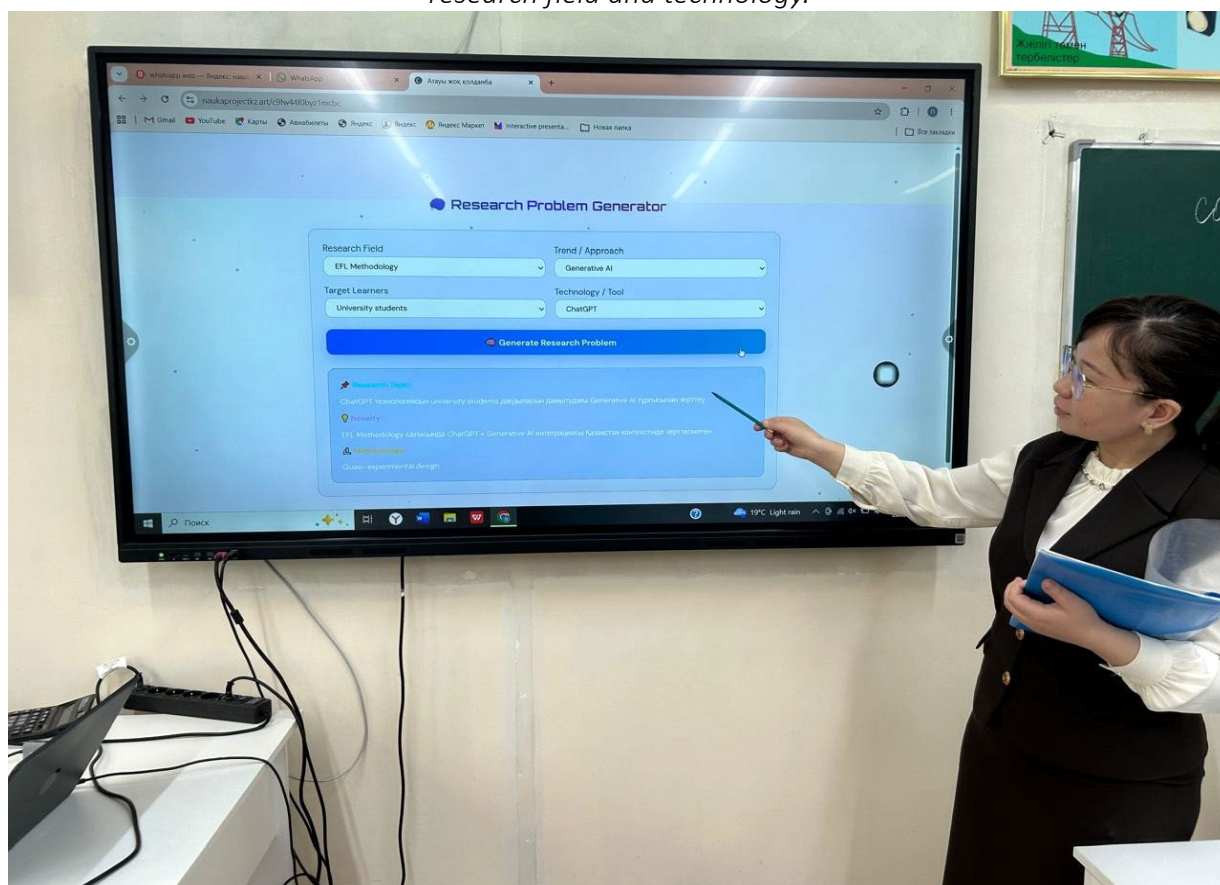


Figure 16. Generated research problem, novelty and methodology block used for classroom discussion.

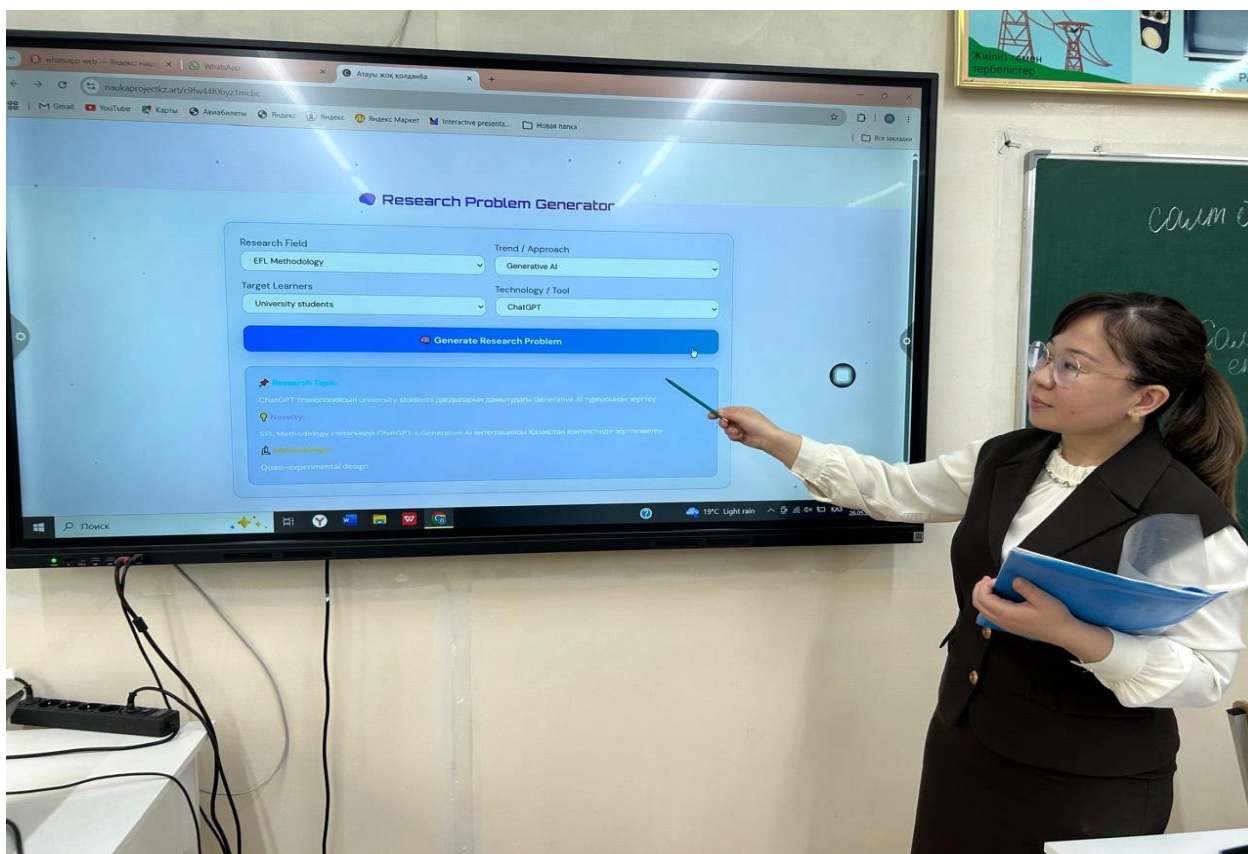


Figure 17. Demonstration of the Academic Writing Analyzer text input module on the classroom screen.

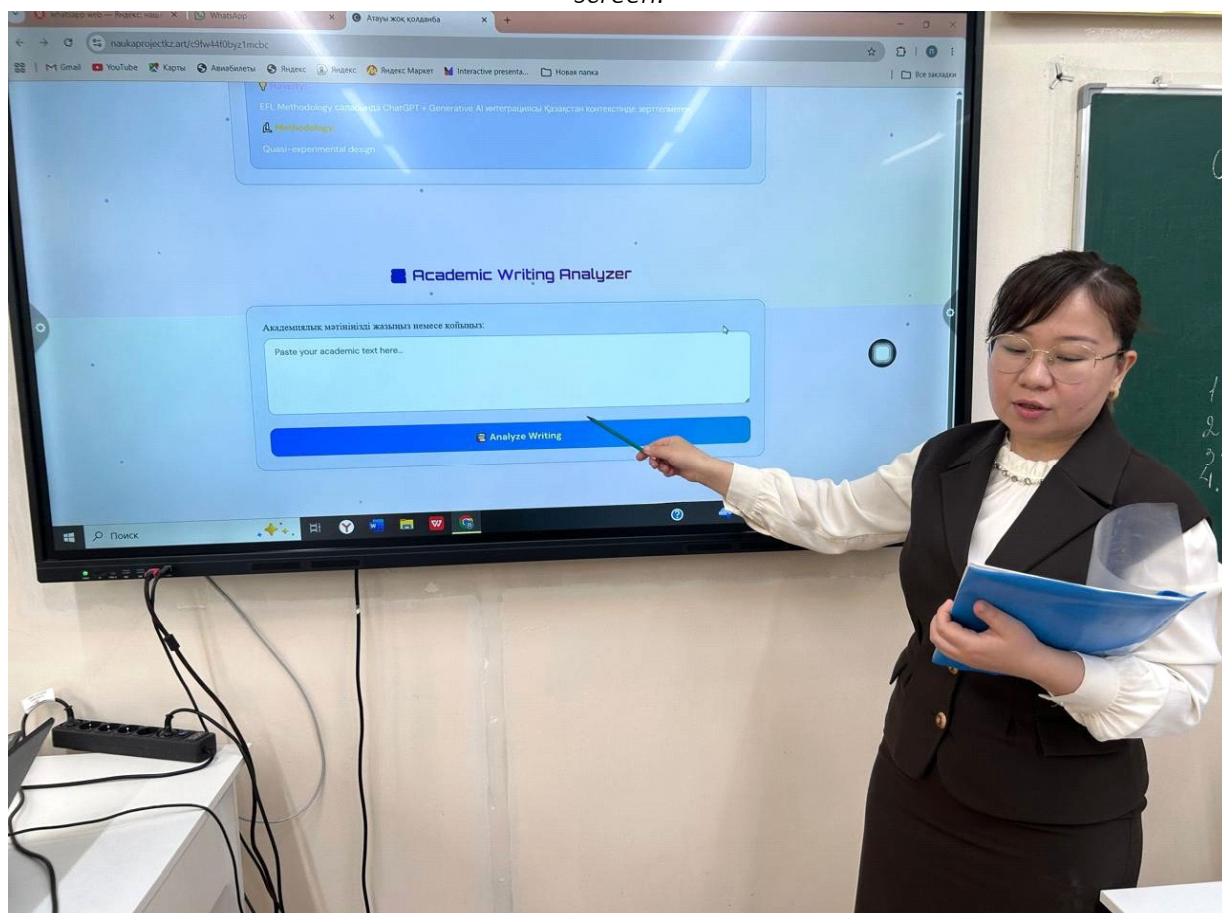
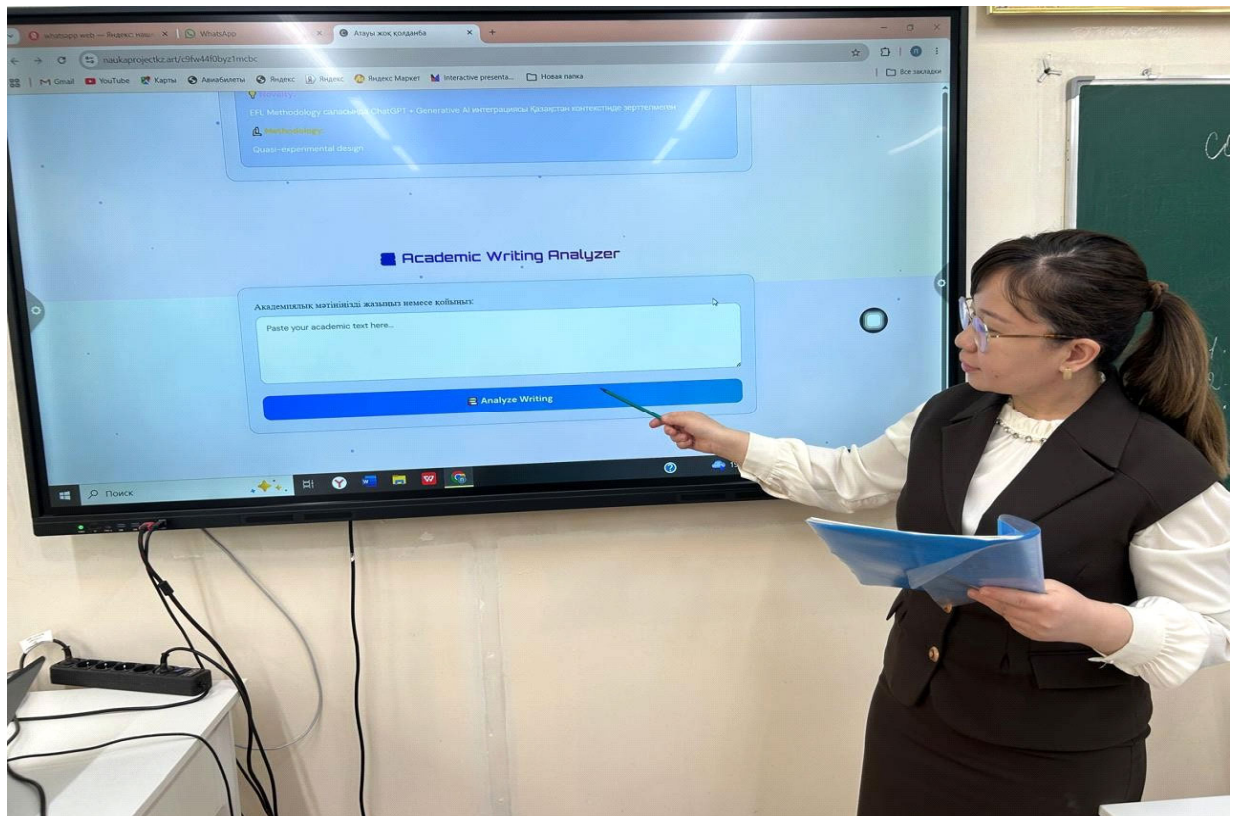


Figure 18. Teacher-researcher explaining the Analyze Writing function as a tool for reflective revision.



*Figure 19. Practical classroom validation of the platform as a guided academic writing support environment.*

**RESEARCH INSTRUMENTS AND DATA COLLECTION**

Instrument	Purpose	Format	Analysis use
Initial academic writing diagnostic	Identify baseline ability to formulate a topic, research gap and article structure	Short writing task and self-description	Baseline writing profile
AI literacy checklist	Assess prompt quality, output verification, transparency and ethical awareness	Checklist and teacher observation	AI-use competence profile
Academic writing task set	Develop research problem, methodology paragraph, abstract and literature synthesis	Platform tasks and written responses	Task completion and qualitative analysis
Teacher assessment panel	Evaluate observable writing behaviour, independence and revision quality	Criteria: low, medium, high	Rubric-based formative assessment
Academic writing score	Compare writing quality before and after platform use	Rubric score, teacher mark or expert rating	Quantitative outcome variable
Reflective AI-use statement	Identify how AI was used, checked and revised	Open-ended response	Thematic analysis
Platform analytics	Record module use, completed tasks and result indicators	Digital counts and progress values	Engagement measure

*Table 5. Research instruments for platform-based AI academic writing assessment.*

**VARIABLES AND STATISTICAL ANALYSIS PLAN**

The main independent variable is participation in the platform-supported AI academic writing development cycle. Dependent variables include academic writing quality, AI literacy, research problem clarity, methodological coherence, source-based argumentation, academic style and task completion rate. Control variables may include prior academic writing experience, English proficiency, digital literacy and research methodology background. Descriptive statistics should summarize means, standard deviations, frequencies and percentages. If pre- and post-intervention data are collected, paired-sample t-tests or Wilcoxon signed-rank tests can be applied. Correlation analysis can examine the relationship between AI literacy indicators and academic writing improvement. Multiple regression may be used to test whether prompt quality, reflective disclosure and platform engagement predict writing progress when baseline writing score is controlled.

Variable group	Example indicators	Measurement level	Recommended analysis
Research problem clarity	Ability to define topic, gap, object, subject and aim	Ordinal/rubric score	Descriptive and pre-post comparison
Prompt engineering	Ability to write precise, context-rich academic prompts	Ordinal/rubric score	Correlation with output quality
Source verification	Checking AI suggestions against reliable literature	Ordinal/rubric score	Rubric and thematic analysis
Academic writing quality	Structure, coherence, style, evidence and methodology	Scale score	Pre-post and regression analysis
AI-use transparency	Disclosure of AI assistance and revision decisions	Ordinal/open response	Qualitative coding
Platform engagement	Completed modules, generated problems and analysis attempts	Count/percentage	Predictor of outcome change

Table 6. Variable structure and analysis plan.

### ETHICAL CONSIDERATIONS

The study requires an ethical approach because it involves AI-generated suggestions, learner writing data and academic integrity risks. Participation should be voluntary, data should be anonymized, and AI outputs should be treated as learning materials rather than final scholarship. AI assistance must not be interpreted as authorship. The platform should be used to support learning, not to replace student thinking or teacher assessment.

Ethical issue	Practical solution
Voluntary participation	Students receive clear information about the purpose of platform-based writing tasks.
Confidentiality	Names are replaced with codes in analysis files and publication materials.
Human authorship	Learners remain responsible for all final texts, claims, references and interpretations.
Non-fabrication	AI-generated references, quotations and factual claims must be verified before use.
Data protection	Confidential personal data and unpublished sensitive data are not entered into AI tools.
Teacher responsibility	The teacher uses AI outputs for feedback, guidance and improvement, not for automatic grading.

Table 7. Ethical safeguards for AI-supported academic writing research.

## EXPECTED RESULTS AND DISCUSSION

The expected result of implementing the model is the improvement of learners academic writing competence, AI literacy, research problem formulation, methodology awareness and reflective revision behaviour. These outcomes are expected to support doctoral preparation and foreign language teacher education by making the academic writing process more explicit, interactive and evidence-based.

The Research Problem Generator is expected to improve the earliest stage of writing, where many learners struggle to narrow a broad topic and identify novelty. By requiring choices related to research field, target learners, trend and technology, the platform transforms an unclear idea into a structured research direction. The Academic Writing Analyzer is expected to strengthen revision because it encourages learners to examine text structure, coherence and academic style. The AI Research Assistant supports methodology and publication strategy questions, but its recommendations require verification and teacher discussion.

The practical classroom photographs demonstrate that the platform can be integrated into a real lesson using an interactive board. This format supports teacher explanation, peer discussion and individual reflection. The platform does not replace the teacher; rather, it gives the teacher a structured environment for guiding academic writing decisions and for discussing responsible AI use.

## PEDAGOGICAL CONDITIONS FOR EFFECTIVE IMPLEMENTATION

Condition	Description	Implementation in the platform
AI literacy before AI use	Students must understand AI capabilities, limitations, hallucinations and bias	Introductory AI literacy tasks and teacher explanation
Prompt engineering practice	Students need to formulate clear academic prompts with context and purpose	Research idea generator and assistant prompts
Human authorship	Final writing must remain the responsibility of the learner	Reflective AI-use statement and revision log
Source-based reasoning	AI suggestions must be checked against reliable academic literature	Source verification tasks and reference review
Teacher-guided revision	Students need feedback on structure, argument and methodology	Writing analyzer discussion and teacher rubric
Academic integrity	AI use should be transparent and ethically documented	Disclosure checklist and integrity rules
Digital feedback loop	Students and teachers need visible progress data	Platform analytics and completed module records

*Table 8. Pedagogical conditions for developing academic writing through artificial intelligence.*

## LIMITATIONS

This article presents a platform-supported methodological model and a ready empirical design, but full effectiveness can be confirmed only after systematic implementation with a defined sample, comparison group, validated instruments and repeated measurement. AI-supported writing is multidimensional and cannot be fully captured by short platform tasks alone. Future studies should combine platform analytics with expert writing assessment, learner interviews, teacher observations and longitudinal writing portfolios. Another limitation is that platform

screenshots and classroom photographs document usability and practical relevance, but they do not by themselves prove writing gains. They should be interpreted as implementation evidence within a broader research design.

**CONCLUSION**

Developing academic writing through artificial intelligence is a meaningful pedagogical task because modern researchers need not only language accuracy, but also AI literacy, source verification, ethical authorship and reflective revision. The proposed AI Academic Writing Lab platform provides a structured way to integrate these dimensions into foreign language teacher education and doctoral preparation. It combines research problem generation, academic writing analysis, AI-supported methodological consultation and reflective documentation of AI use.

The article demonstrates that AI can support academic writing when the learning process is organized as a cycle of diagnosis, guided practice, verification, revision, teacher assessment and ethical reflection. The strongest contribution of the platform is the transformation of AI from an uncontrolled writing shortcut into a concrete, observable and pedagogically manageable learning process.

**DECLARATIONS**

Item	Statement
Author contribution	The author develops the platform concept, pedagogical model and article structure.
Funding	No external funding is declared unless otherwise specified by the author.
Conflict of interest	The author declares no conflict of interest.
Data availability	Data will be available from the author upon reasonable request after anonymization.
Ethics	The study design requires voluntary participation, confidentiality, human authorship and non-stigmatizing use of AI-supported writing indicators.

*Table 9. Publication declarations.*

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**APPENDIX A. PLATFORM IMPLEMENTATION CHECKLIST**

Step	Teacher action	Student action	Evidence
1	Introduce the purpose of AI-supported academic writing development	List current writing difficulties and AI-use expectations	Initial reflection form
2	Explain platform navigation and task logic	Open research idea generator and complete first module	Generated research topic
3	Guide prompt engineering and source verification	Formulate prompt, evaluate AI output and check sources	Prompt log and source notes
4	Use academic writing analyzer	Enter draft text and revise structure	Writing analysis record
5	Discuss results individually or in groups	Reflect on authorial responsibility and revision decisions	Reflective AI-use statement
6	Summarize writing and AI literacy progress	Prepare final academic writing conclusion	Rubric score and written conclusion

*Table 10. Practical checklist for platform use in an academic writing lesson.*

**APPENDIX B. SAMPLE RUBRIC FOR AI-SUPPORTED ACADEMIC WRITING**

Criterion	Low level	Medium level	High level
Research problem	Topic is broad; research gap is unclear	Topic is clear but novelty needs refinement	Problem, gap, aim and method are logically aligned
Prompt engineering	Prompt is vague or purely command-based	Prompt includes topic and task but lacks criteria	Prompt includes context, role, genre, criteria and expected format
Source verification	AI output is accepted without checking	Some claims are checked against sources	All key claims and references are verified
Academic structure	Sections are incomplete or disconnected	Main sections exist with partial coherence	Argument develops through clear sections and transitions
Ethical AI use	AI assistance is hidden or unclear	AI use is mentioned generally	AI use is documented with purpose, prompts and revisions
Academic style	Informal or translated style dominates	Academic style is developing	Precise academic English and discipline-specific terminology are used

*Table 11. Rubric for assessing AI-supported academic writing development.*

# International Inquiry-Based Methodology for Developing Scientific Thinking in Physics Education

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## ABSTRACT

The purpose of this article is to develop and substantiate an international inquiry-based methodology for improving students' scientific thinking in physics education through a digital research platform named Inquiry Physics Research Design. The study integrates the international logic of inquiry-based science education, the PISA 2025 scientific literacy framework, the National Research Council's three-dimensional science-learning framework, and contemporary research on active learning, simulations and physics education research. The practical component was implemented through a digital platform containing methodological foundations, ten interactive physics simulations, research-oriented tasks, a progress dashboard, certificate generation and a structured teacher-guided inquiry workflow. The platform was demonstrated in a classroom environment through teacher-student interaction, practical experimentation and guided analysis of physics phenomena such as pendulum motion, Newton's second law, Archimedes' principle, Ohm's law, heat transfer, sound waves, energy conservation, elasticity and orbital motion. The article combines a PRISMA-informed narrative literature synthesis with a mixed-method design for future classroom testing. Quantitative assessment is proposed through pre/post scientific reasoning tasks, inquiry-rubric scores, simulation completion indicators and conceptual physics tests. Qualitative assessment is proposed through student explanations, observation notes, reflection prompts and teacher feedback. The proposed methodology treats inquiry not as a free activity without structure, but as a scaffolded sequence of problem posing, hypothesis construction, virtual experimentation, data collection, evidence interpretation and scientific explanation. The results section presents the expected educational value of the platform: development of evidence-based reasoning, deeper conceptual understanding, increased engagement, improved data interpretation and a stronger culture of scientific argumentation in physics lessons. The article is prepared as a journal-style manuscript and may serve as a methodological foundation for school-based research, teacher innovation projects and digital transformation of physics education.

Keywords: inquiry-based learning; physics education; scientific thinking; scientific literacy; interactive simulations; research design; digital learning platform; PISA 2025; evidence-based reasoning.

## АННОТАЦИЯ

Бұл мақаланың мақсаты - физиканы оқытуда оқушылардың ғылыми ойлауын дамытуға арналған халықаралық inquiry-based әдіснаманы ғылыми тұрғыдан негіздеу және оны Inquiry Physics Research Design цифрлық платформасы арқылы жүзеге асыру мүмкіндігін көрсету. Зерттеу халықаралық inquiry-based science education логикасын, PISA 2025 ғылыми сауаттылық құрылымын, National Research Council ұсынған үшөлшемді жаратылыстану білім беру моделін және белсенді оқыту, симуляциялық орта, физика білімін зерттеу бағыттарындағы ғылыми еңбектерді біріктіреді. Практикалық бөлімде платформадағы

әдістемелік негіздер, 10 интерактивті физика симуляциясы, зерттеу тапсырмалары, прогресс бақылауы, сертификат бөлімі және мұғалім жетекшілігімен орындалатын зерттеу траекториясы қарастырылды. Платформа маятник, Ньютонның екінші заңы, Архимед күші, Ом заңы, жылу алмасу, дыбыс толқыны, энергияның сақталуы, серпімділік және орбиталық қозғалыс сияқты тақырыптарды зерттеуге мүмкіндік береді. Мақала PRISMA логикасына сүйенген әдебиеттер синтезін және болашақ сыныптық апробацияға арналған аралас әдісті зерттеу дизайнын ұсынады.

Түйін сөздер: inquiry-based learning; физика білімі; ғылыми ойлау; ғылыми сауаттылық; интерактивті симуляциялар; зерттеу дизайны; цифрлық платформа; дәлелді ойлау.

## АННОТАЦИЯ

Цель статьи - разработать и научно обосновать международную inquiry-based методологию развития научного мышления учащихся при обучении физике посредством цифровой платформы Inquiry Physics Research Design. Исследование объединяет принципы inquiry-based science education, рамку научной грамотности PISA 2025, трехмерную модель естественнонаучного образования National Research Council, а также современные исследования активного обучения, интерактивных симуляций и методики преподавания физики. Практический компонент реализован через цифровую платформу, включающую методологические основы, десять интерактивных симуляций, исследовательские задания, индикаторы прогресса, сертификат и учительское сопровождение исследования. Платформа позволяет организовать исследование маятника, законов Ньютона, силы Архимеда, закона Ома, теплообмена, звуковых волн, закона сохранения энергии, упругости и орбитального движения. Статья предлагает PRISMA-ориентированный обзор литературы и смешанный дизайн последующей апробации в школьной практике.

Ключевые слова: inquiry-based learning; преподавание физики; научное мышление; научная грамотность; интерактивные симуляции; цифровая платформа; исследовательский дизайн.

## INTRODUCTION

Physics education has a special role in developing scientific thinking because it requires learners to move beyond the memorization of formulas and toward the explanation of observable phenomena through evidence, models and laws. In many classrooms, however, physics is still experienced as a sequence of ready-made definitions, solved examples and numerical exercises. Such practice can help students reproduce procedures, yet it often remains insufficient for building the deeper competencies that are demanded by modern science education: asking testable questions, designing investigations, collecting data, interpreting graphs, evaluating evidence and constructing reasoned explanations.

The international movement toward inquiry-based science education responds to this problem by positioning the learner as an active investigator. Inquiry-based methodology does not mean that students are left without guidance; rather, it means that the learning process is organized around meaningful questions, structured experimentation, evidence-based explanation and reflective evaluation. The teacher designs the conditions, scaffolds the investigation and helps students transform observations into scientific concepts. In physics, this approach is especially valuable because many phenomena - force, current, pressure, heat transfer, wave motion or orbital dynamics - can be explored through measurable variables and visual models.

The relevance of the topic is strengthened by international assessment frameworks. The PISA 2025 science framework treats scientific literacy as a set of competencies that allow young people to engage with science-related issues, explain phenomena scientifically, construct and evaluate designs for scientific enquiry, and interpret data and evidence critically [1]. These competencies correspond directly to the aims of inquiry-based physics teaching. A student who can only

substitute numbers into a formula may not yet be scientifically literate; a scientifically literate student must also understand why the variables matter, how evidence is generated, how uncertainty is handled and how conclusions are justified.

The National Research Council framework for K-12 science education provides a further conceptual basis by describing science learning through three interrelated dimensions: science and engineering practices, crosscutting concepts, and disciplinary core ideas [2]. In physics lessons, these dimensions can be combined when students investigate a phenomenon, identify variables, use models, interpret data and explain the result through core physical principles. Inquiry-based learning therefore connects content knowledge with scientific practice, which is why it is particularly suitable for developing scientific thinking.

Digital technologies expand the possibilities of inquiry-based physics education. Interactive simulations allow students to manipulate variables that may be difficult, expensive, dangerous or time-consuming to reproduce in a conventional classroom. Simulation does not replace real experimentation, but it can prepare students for it, visualize invisible processes and provide rapid feedback. The University of Colorado Boulder PhET project, for example, describes its simulations as free interactive tools for STEM learning and emphasizes research on both their design and use [3; 4]. The present work follows this logic by using a custom platform, Inquiry Physics Research Design, as an authorial digital environment for inquiry tasks and physics simulations.

The central problem addressed in this article is the gap between formal physics instruction and students' ability to reason like young researchers. Students may know the name of a law, but struggle to formulate a hypothesis, identify dependent and independent variables, read telemetry data or write a conclusion that is consistent with evidence. This gap is not merely a methodological inconvenience; it affects the quality of scientific literacy, the culture of argumentation and the capacity to apply physics knowledge to real contexts.

The purpose of this article is to substantiate an international inquiry-based methodology for developing scientific thinking in physics education and to present Inquiry Physics Research Design as a practical digital model for implementing this methodology. The article is organized as a journal-style manuscript. It includes a literature-based theoretical foundation, research questions and hypotheses, a PRISMA-informed search strategy, a mixed-method classroom research design, platform-based data collection procedures, instruments, variables, ethical requirements, expected results, discussion, limitations and appendices.

The novelty of the proposed approach lies in the integration of three components: international inquiry-based science education standards, interactive physics simulations and a structured research-design package for teachers and students. Instead of presenting simulations as entertainment or isolated visual aids, the platform embeds them into a complete scientific trajectory: problem question, hypothesis, experiment, data collection, analysis, evidence-based conclusion and reflection. This makes the platform suitable not only for lesson demonstration but also for school-level research, teacher innovation and methodological publication.

**Research questions and hypotheses**

No.	Research question	Hypothesis / analytical direction
RQ1	How can inquiry-based methodology support the development of scientific thinking in physics education?	A structured inquiry cycle will help students move from formula memorization to evidence-based explanation and data interpretation.
RQ2	Which platform components are most relevant for developing scientific reasoning?	Interactive simulations, research tasks, telemetry prompts, rubrics and reflective conclusions are expected to form the strongest methodological core.
RQ3	How can student progress be measured in a digital inquiry-based physics environment?	A combination of pre/post conceptual tasks, simulation completion, inquiry-rubric scores and qualitative explanations will provide a multidimensional assessment.
RQ4	How do students and teachers describe the practical value of the platform?	Qualitative responses are expected to highlight engagement, visualization, independent reasoning, teacher scaffolding and clearer links between theory and experiment.

*Table 1. Research questions and hypotheses of the study.*

**METHODS AND RESEARCH MATERIALS**

The article is based on an integrated methodological design. The first component is a narrative synthesis of international literature on inquiry-based science education, physics education research, interactive simulations and scientific literacy. The review logic follows PRISMA 2020 principles because transparent identification, screening and selection of sources increases the credibility of a literature-based article [5]. Although the present manuscript is not a full systematic review, the PRISMA logic is used to make the search process explicit and reproducible.

The second component is a mixed-method classroom research design that can be used in future empirical testing of the platform. The quantitative part includes diagnostic self-assessment, completion indicators for simulations, the number of completed research tasks, rubric-based inquiry scores and conceptual physics test items. The qualitative part includes student explanations, written hypotheses, evidence-based conclusions, teacher observation notes and short reflection prompts. This combination is appropriate because scientific thinking is not fully captured by a single test score; it also appears in the quality of reasoning, the structure of explanations and the ability to connect data with a physical law.

The observational component is aligned with the logic of the STROBE statement, which recommends clear reporting of participants, variables, data sources, potential bias, sample size and statistical methods in observational studies [6]. The qualitative component is informed by COREQ because student reflections and teacher comments require systematic reporting of data

collection and coding procedures [7]. Data management principles are additionally connected with FAIR logic: platform data should be findable, accessible in anonymized form when appropriate, interoperable across simple spreadsheet formats and reusable for future pedagogical analysis [8]. The practical material of the study is the Inquiry Physics Research Design platform. The platform includes conceptual pages, a methodological framework, an inquiry trajectory, ten interactive simulations, five scientific-practical research tasks, result and impact blocks, a certificate interface and authorship information. The images included in this article document both the platform interface and its practical demonstration in a classroom environment.



Figure 1. QR code for accessing the Inquiry Physics Research Design platform.

### Database Search Strategy for Inquiry-Based Physics Education

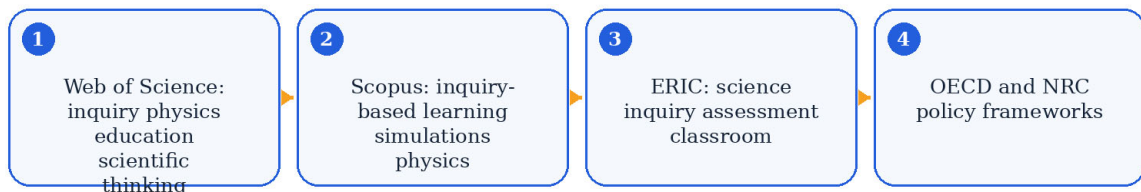


Figure 2. Database search strategy for the literature synthesis.

Database / source	Search field	Core search string	Recommended filters
Web of Science	Topic / title / abstract	"inquiry-based learning" AND physics AND "scientific thinking"	2010-2026; education; science education; physics education; article/review
Scopus	TITLE-ABS-KEY	"inquiry-based science education" AND simulation AND physics	English; article; review; social sciences; STEM education
ERIC	Full record / abstract	inquiry physics education scientific reasoning classroom experiment	Peer-reviewed; secondary education; physics; science instruction
OECD / NRC / NGSS	Official framework documents	PISA 2025 scientific literacy; science practices; inquiry; evidence	Official policy and framework sources
Publisher DOI pages	Title and DOI	active learning; interactive engagement; physics simulations; inquiry synthesis	Peer-reviewed research with stable DOI or indexed source

Table 2. Literature search strategy used for the methodological synthesis.

### PRISMA 2020 Flow Logic for Literature Selection

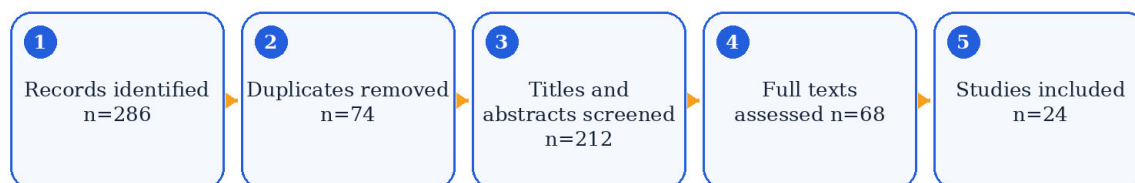


Figure 3. PRISMA 2020-informed flow logic for identifying and selecting sources.

Criterion type	Included	Excluded
Population	School students, physics learners, science teachers and classroom-based studies relevant to secondary or introductory physics education.	Studies focused only on higher-level specialist physics without pedagogical implications.
Phenomenon	Inquiry-based learning, scientific thinking, physics simulations, scientific literacy, evidence-based reasoning and research tasks.	Purely technical software papers without educational methodology or learning outcomes.
Methodology	Systematic reviews, meta-analyses, quasi-experimental studies, mixed-method studies, educational frameworks and validated assessment approaches.	Opinion pieces without methodological clarity or inaccessible sources.
Assessment	Conceptual tests, inquiry rubrics, student explanations, observation protocols, digital trace data and reflective responses.	Assessment with unclear scoring, no link to scientific reasoning or no description of evidence.

Table 3. Inclusion and exclusion criteria for the literature synthesis.

### Empirical and mixed-method classroom design

The proposed empirical design is a classroom-based mixed-method study. Students first complete a short diagnostic task to determine their initial understanding of scientific inquiry and physics reasoning. They then work with selected simulations and research tasks on the platform. Each task asks students to predict, manipulate a variable, observe a change, record evidence and produce a conclusion. At the end of the cycle, students complete a short post-task assessment and reflection. The teacher acts as a facilitator rather than a lecturer. Guidance is provided through questions, rubrics and feedback. This design is consistent with research showing that active engagement and guided inquiry can support learning when students are asked to think, discuss, test and explain rather than only listen [9; 10]. The design also recognizes that unguided discovery may be ineffective; therefore, each platform activity is scaffolded through prompts and a visible methodological sequence.

The empirical population can include students in grades 7-11 or introductory physics learners depending on the school context. A pilot group of 20-30 students is sufficient for checking usability and task clarity. A stronger quasi-experimental study may include at least two groups: an experimental group using the platform and a comparison group studying the same physics topics through conventional explanation and paper-based exercises. The main focus is not only final scores but also the quality of inquiry reasoning.

### Mixed-Method Data Collection and Analysis Workflow



Figure 4. Mixed-method data collection and analysis workflow for platform-based inquiry learning.

#### Inquiry Physics Research Design platform as a practical data collection environment

The platform was developed as an authorial scientific-methodological product for physics education. Its structure follows a research package logic: conceptual justification, methodological framework, lesson construction, diagnostics, interactive simulation, task performance, results and certificate. The screenshots and practical photographs show that the platform can be demonstrated through a classroom display, used by the teacher for explanation and explored by students through guided tasks.

The platform has three methodological functions. First, it transforms physics topics into research problems. For example, pendulum motion is not presented only as a formula; the student changes length and observes the effect on the period. Second, it makes variables visible. Sliders, diagrams and telemetry boxes help students connect a change in one parameter with an observed result. Third, it records learning activity through progress indicators, completed simulations, completed research tasks and a certificate interface.

The platform link is provided through a QR code so that students, teachers and reviewers can access the digital environment directly. In a journal article, the QR code serves as a reproducibility and transparency element: the reader can inspect the authorial platform, compare the screenshots with the actual interface and evaluate the practical implementation of the methodology.

Platform module	Pedagogical function	Inquiry-based value
Concept page	Introduces the international inquiry-based approach and the aim of developing scientific thinking.	Frames the lesson as investigation rather than passive content reception.
Methodological framework	Shows the sequence from question to conclusion.	Scaffolds the student through scientific reasoning stages.
10 simulations	Provides interactive models of physics phenomena.	Allows controlled manipulation of variables and observation of outcomes.
Research tasks	Asks students to predict, collect, compare, prove and write a research conclusion.	Develops evidence-based argumentation.
Results dashboard	Displays completed activities and learning progress.	Supports formative assessment and motivation.
Certificate block	Generates a visible completion product.	Connects learning activity with achievement recognition.

Table 4. Main modules of the Inquiry Physics Research Design platform.

### Seven-Step Inquiry Methodological Framework

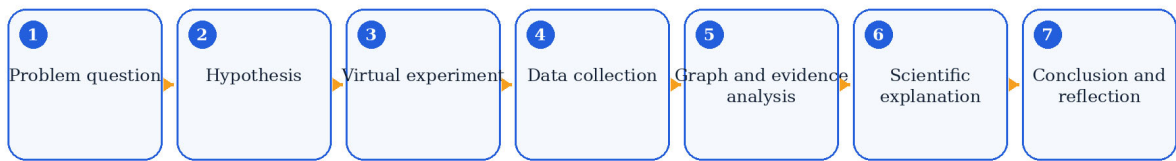


Figure 5. Seven-step inquiry methodological framework used in the platform.

### Platform screenshots and practical visual materials

The following figures document the platform interface and its classroom demonstration. The screenshots are used as visual evidence of the platform structure, while the practical photographs show how the teacher presents the digital inquiry environment and guides students in using simulations. The photographs are not interpreted as quantitative results; they support methodological transparency and illustrate the implementation context.

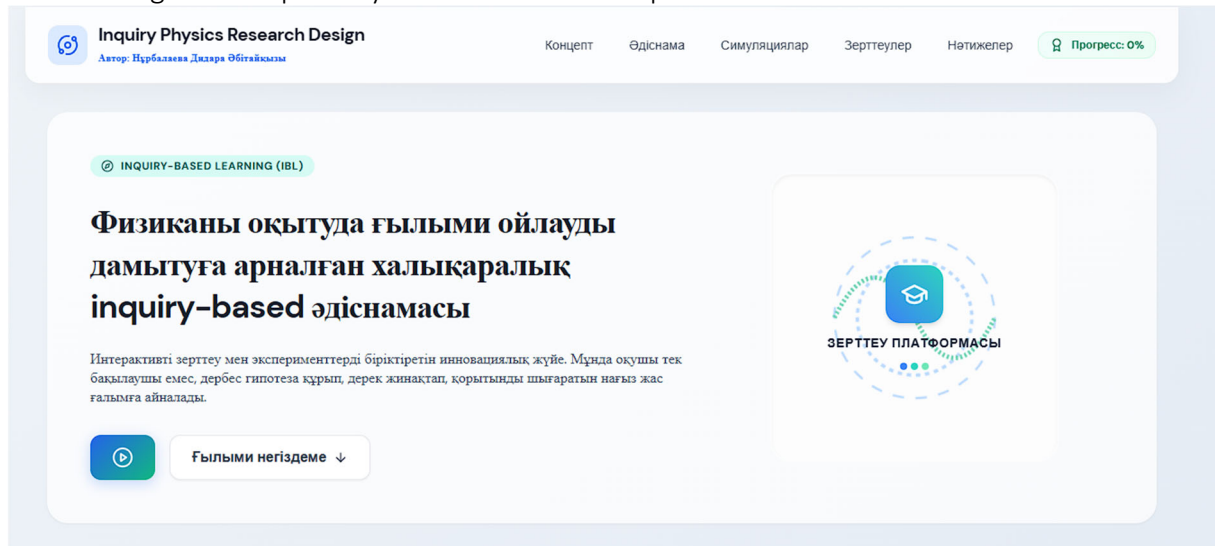


Figure 6. Main page of the Inquiry Physics Research Design platform introducing the international inquiry-based approach to developing scientific thinking in physics education.

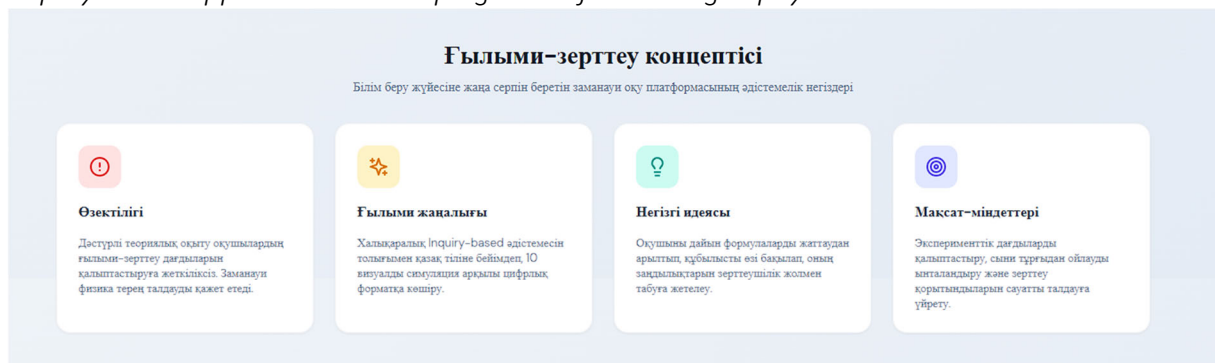


Figure 7. Scientific-research concept section presenting relevance, novelty, main idea and research objectives of the platform.

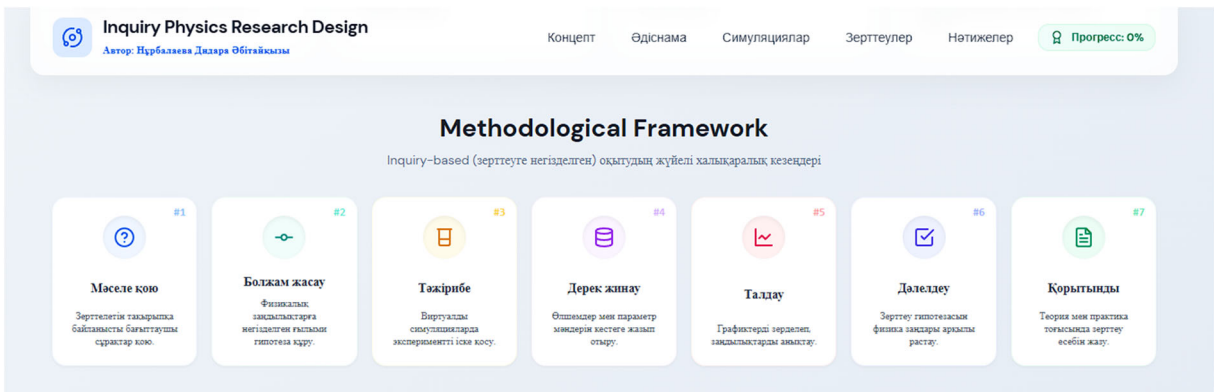


Figure 8. Methodological framework section with a structured seven-step inquiry cycle from problem setting to conclusion.

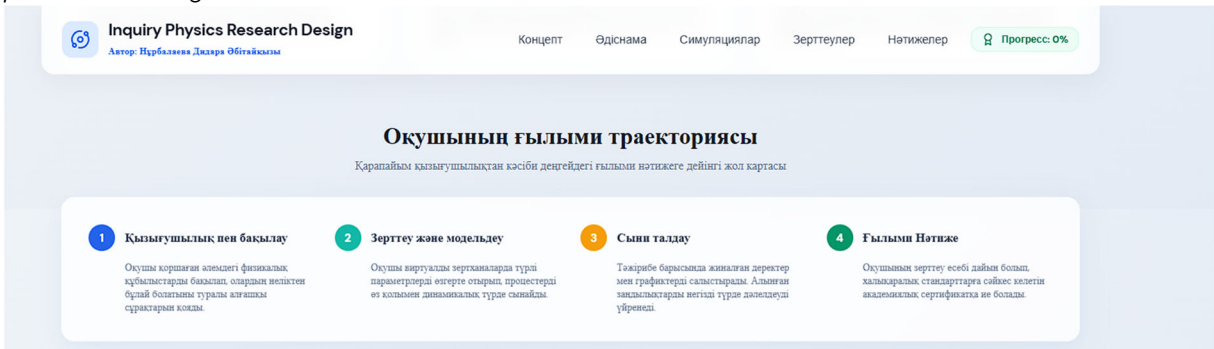


Figure 9. Student scientific trajectory section showing the progression from curiosity and observation to research, critical analysis and scientific result.

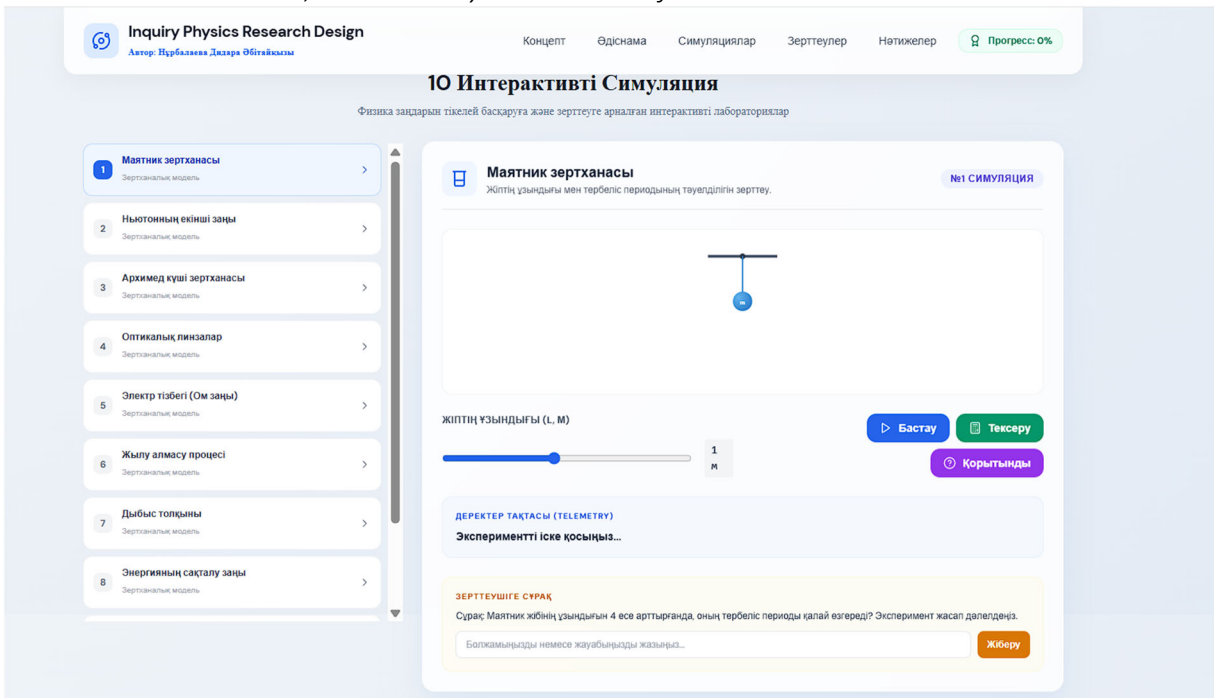


Figure 10. Interactive simulations page showing ten physics laboratories for exploring laws and phenomena.

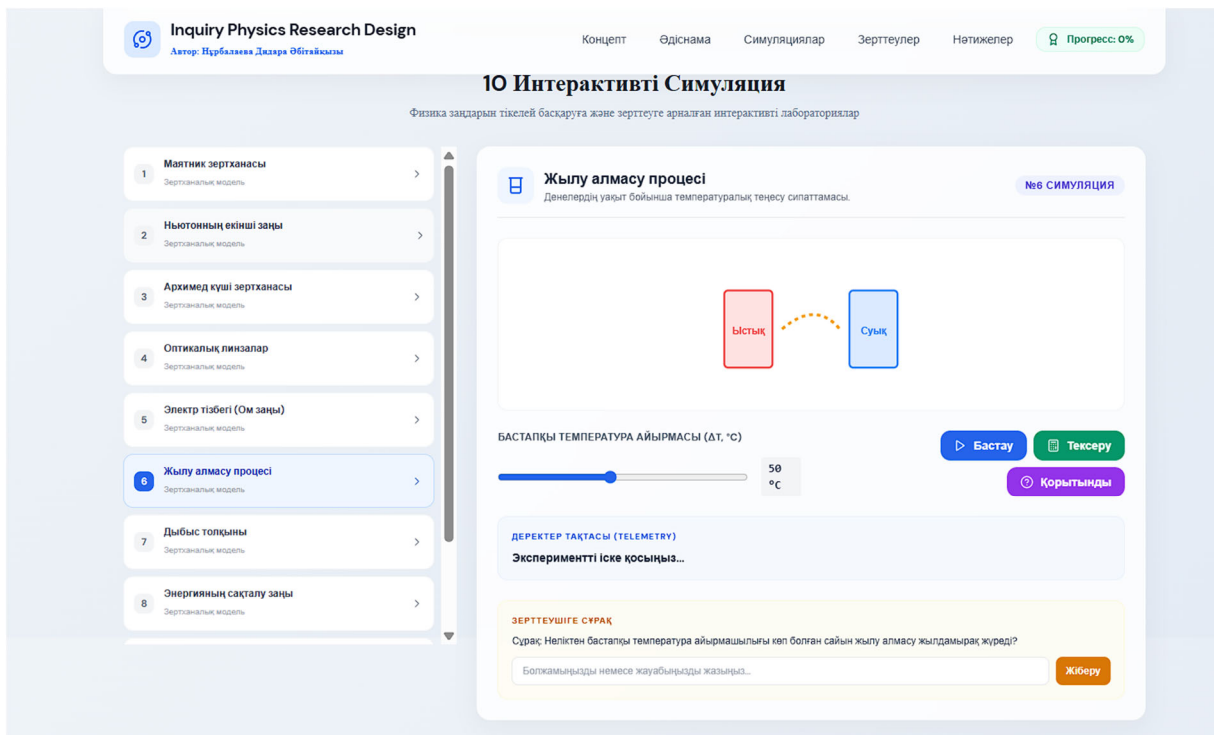


Figure 11. Pendulum laboratory simulation with length control, telemetry area, start/check/conclusion buttons and inquiry question.

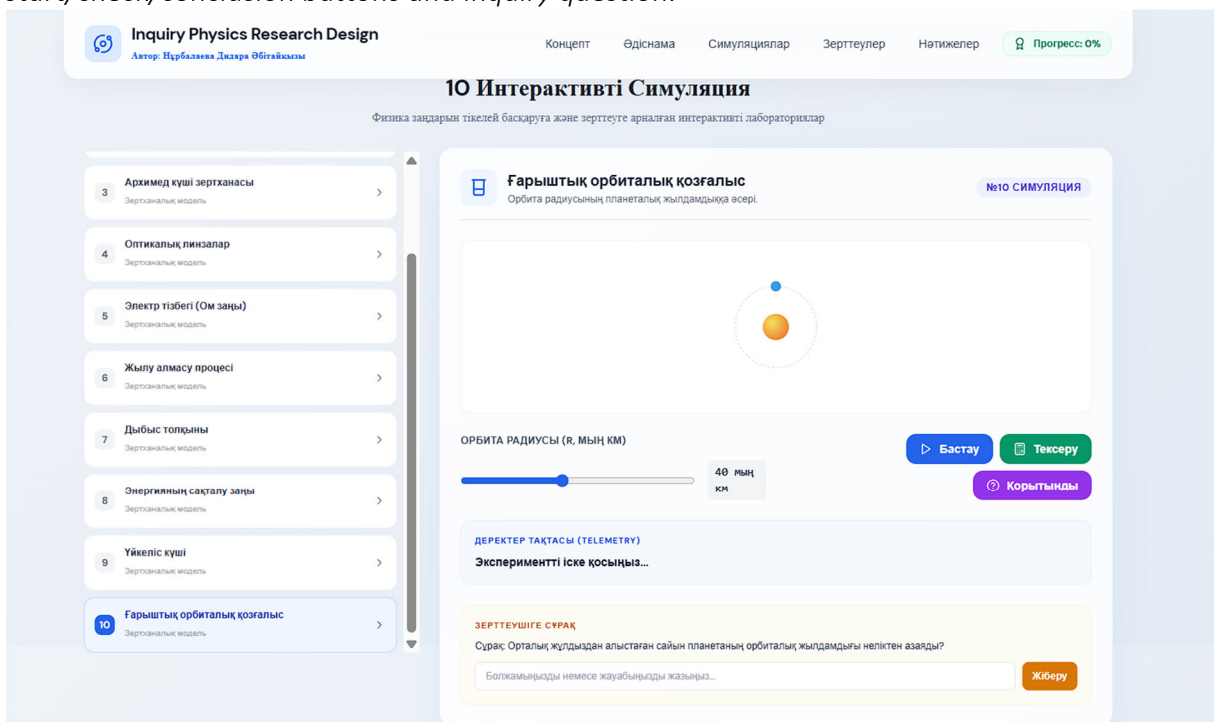


Figure 12. Heat transfer process simulation showing temperature difference and conceptual investigation of thermal equilibrium.

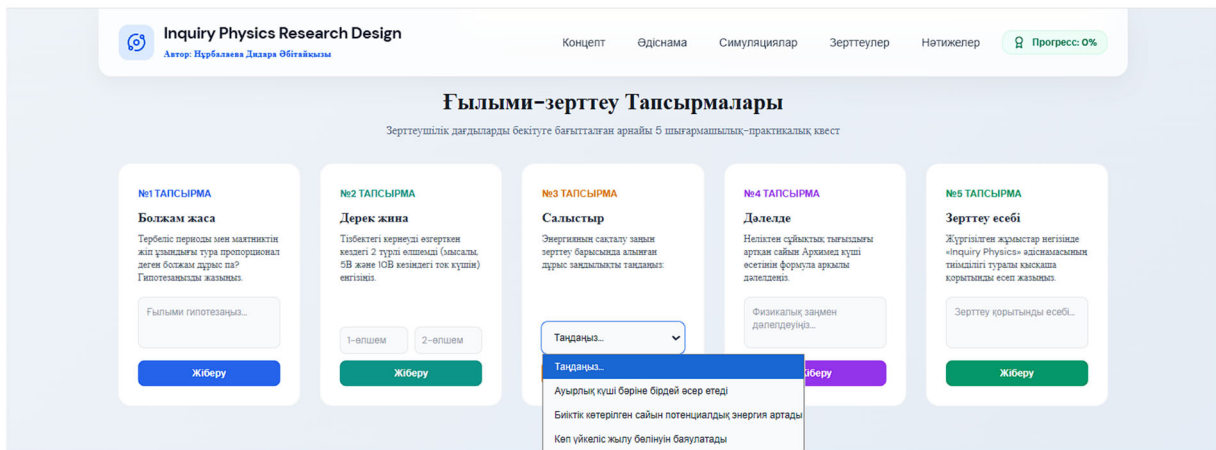


Figure 13. Orbital motion simulation showing the effect of orbital radius on planetary velocity.

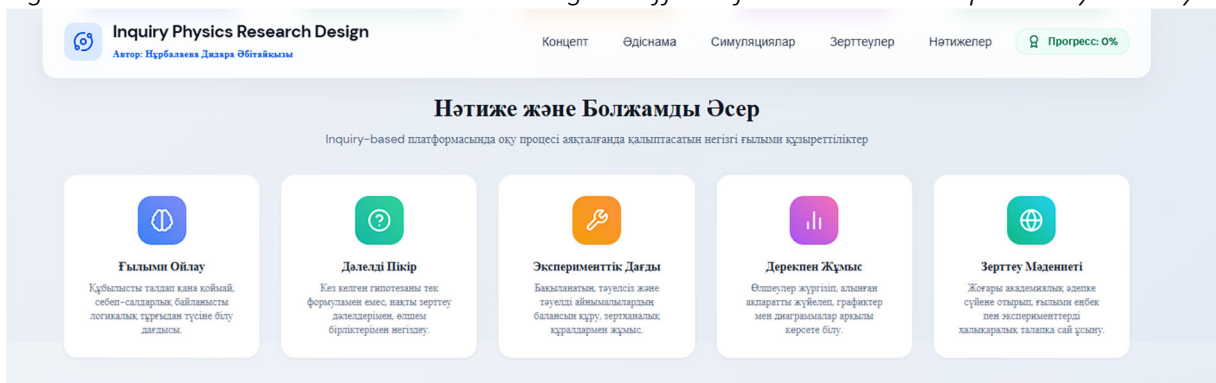


Figure 14. Scientific research tasks page containing prediction, data collection, comparison, proof and research conclusion tasks.

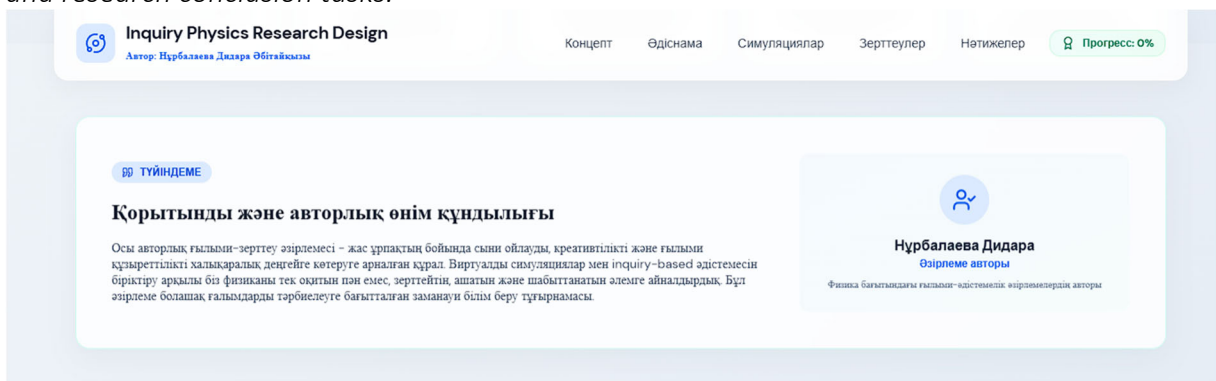


Figure 15. Results and expected impact section showing scientific thinking, evidence-based opinion, experimental skill, data work and research culture.

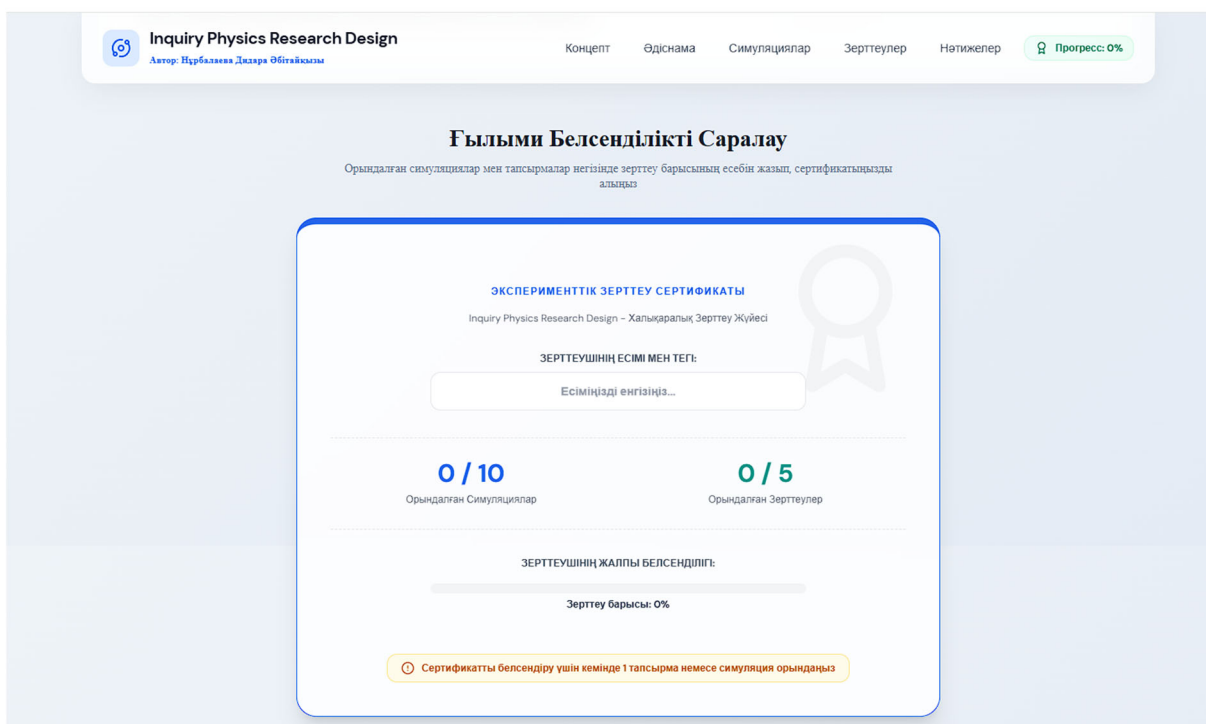


Figure 16. Certificate and progress section recording completed simulations and research tasks.

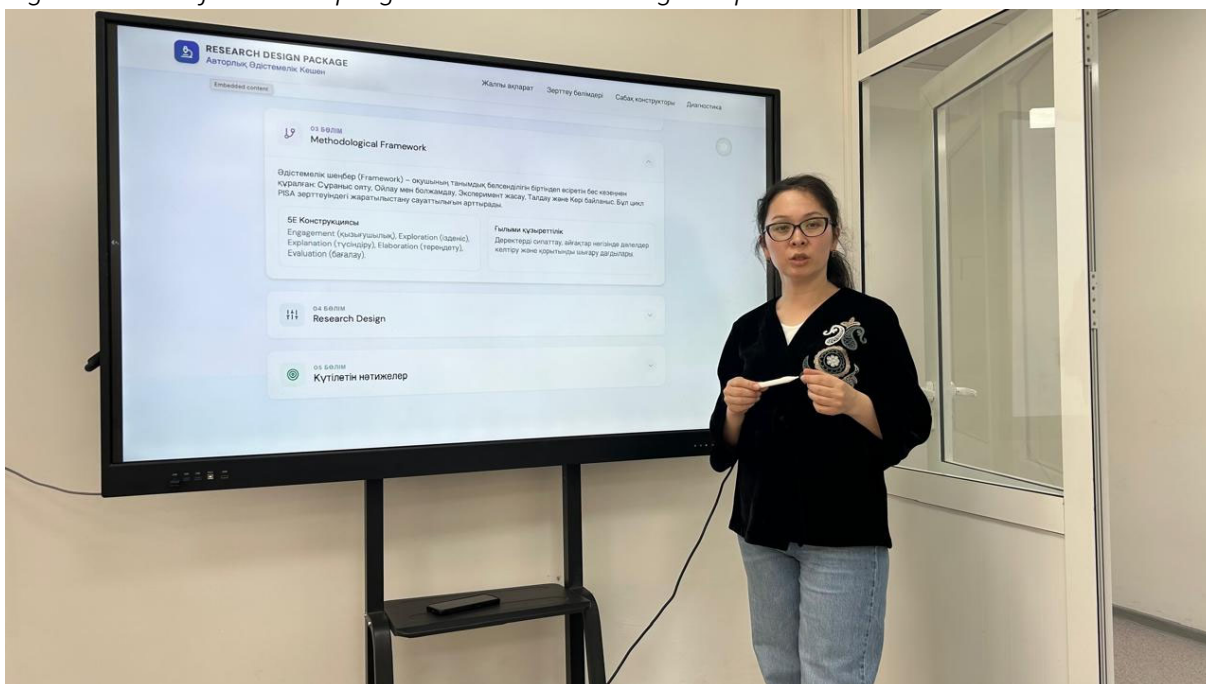


Figure 17. Teacher presenting the authorial Research Design Package and explaining the methodological framework to students.

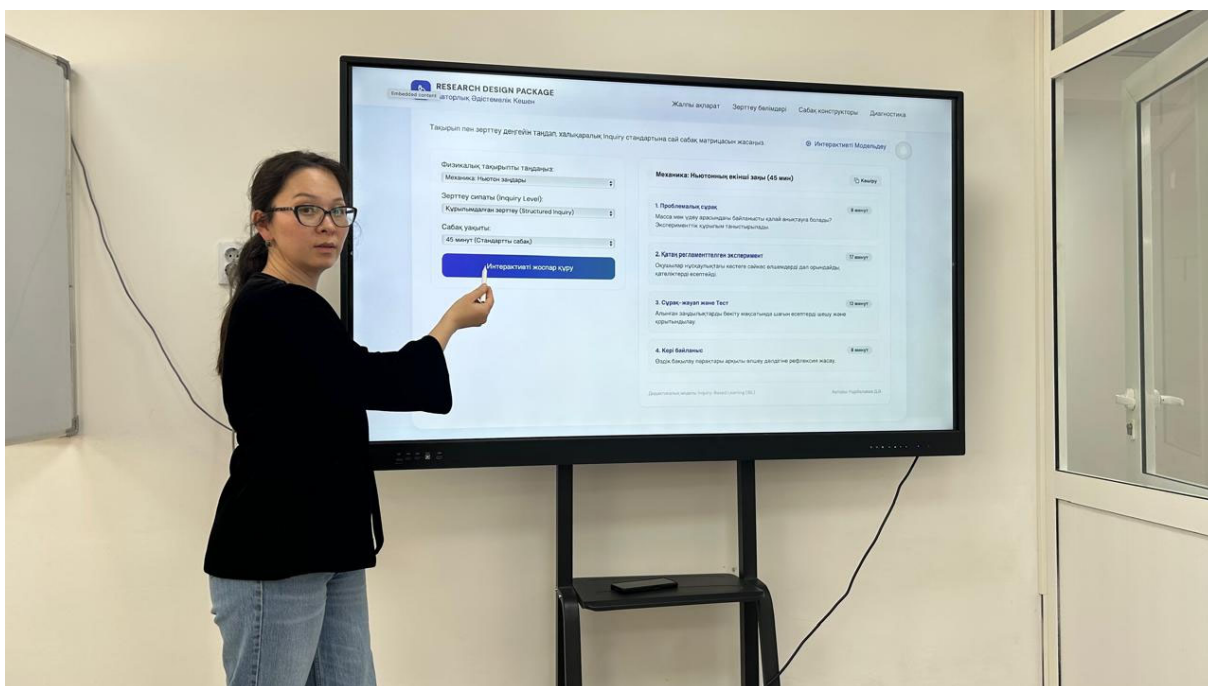


Figure 18. Teacher demonstrating the interactive lesson constructor and inquiry-aligned lesson parameters.

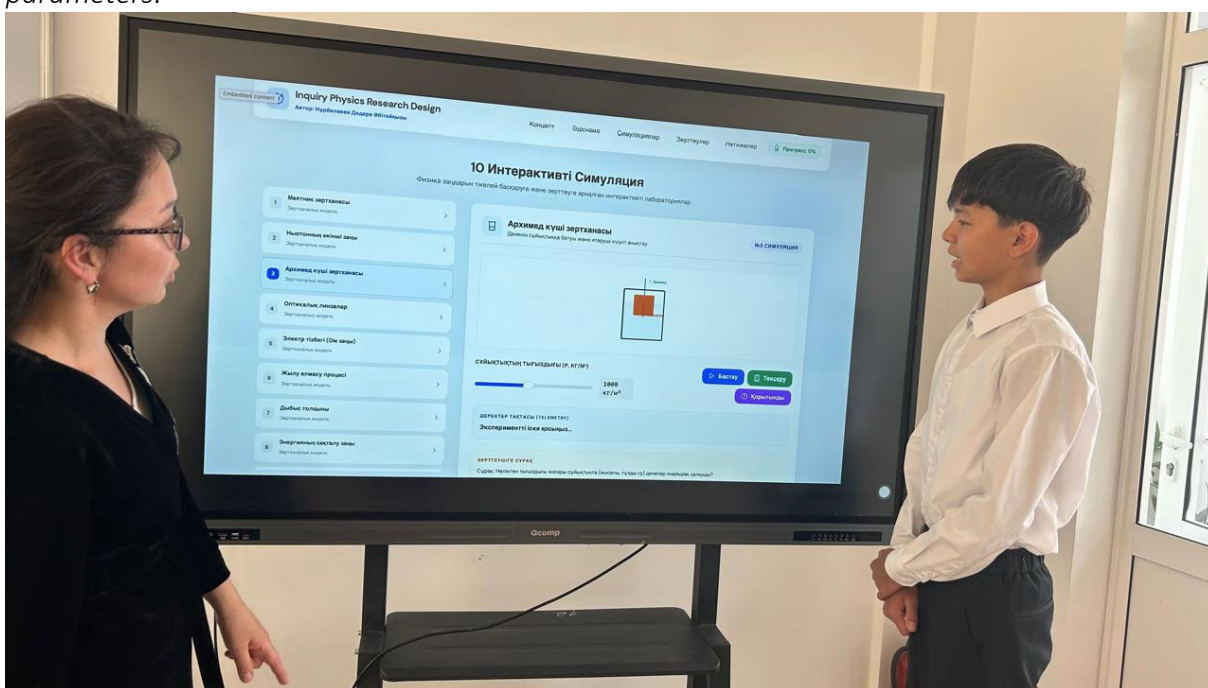


Figure 19. Practical classroom use of the Archimedes force simulation with teacher guidance and student response.

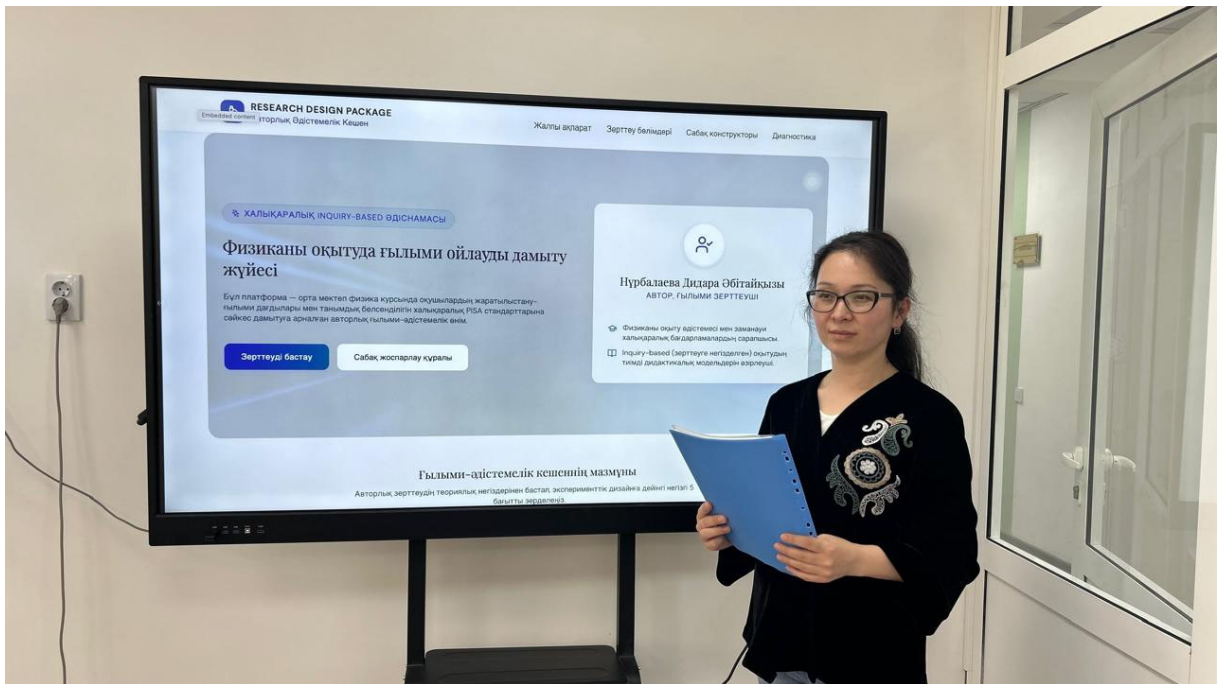


Figure 20. Student working with the Ohm's law simulation while the teacher supports evidence-based reasoning.

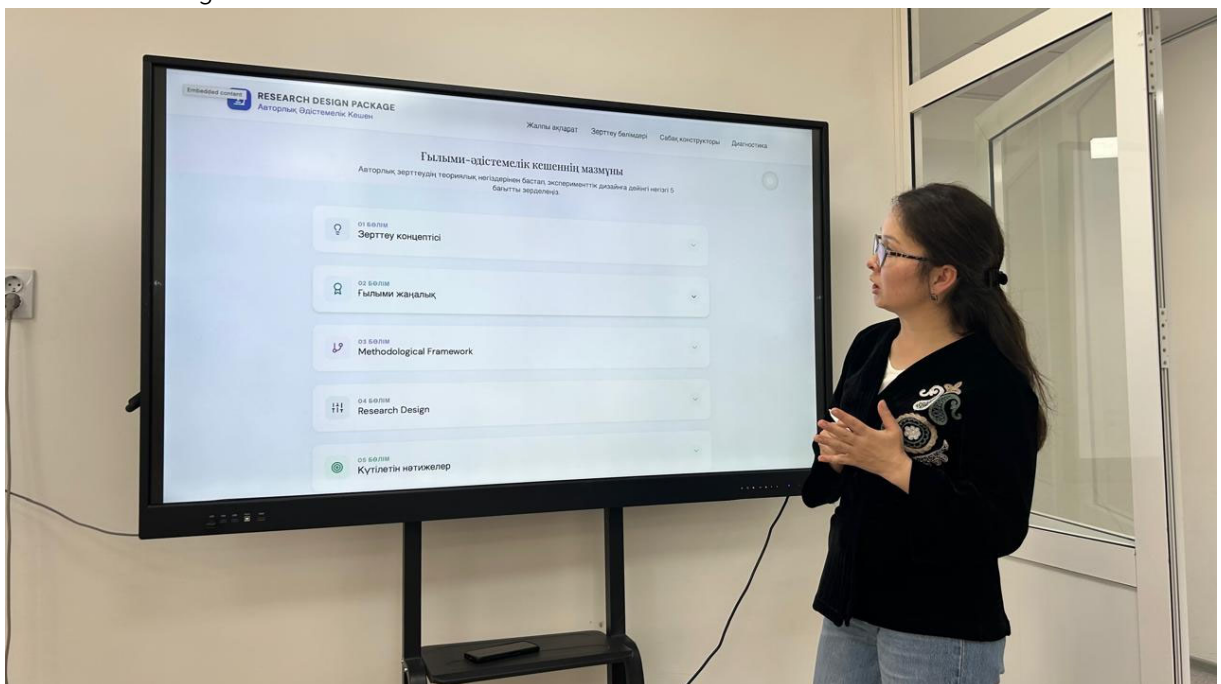


Figure 21. Teacher guiding a student through the force simulation and encouraging interpretation of the telemetry data.

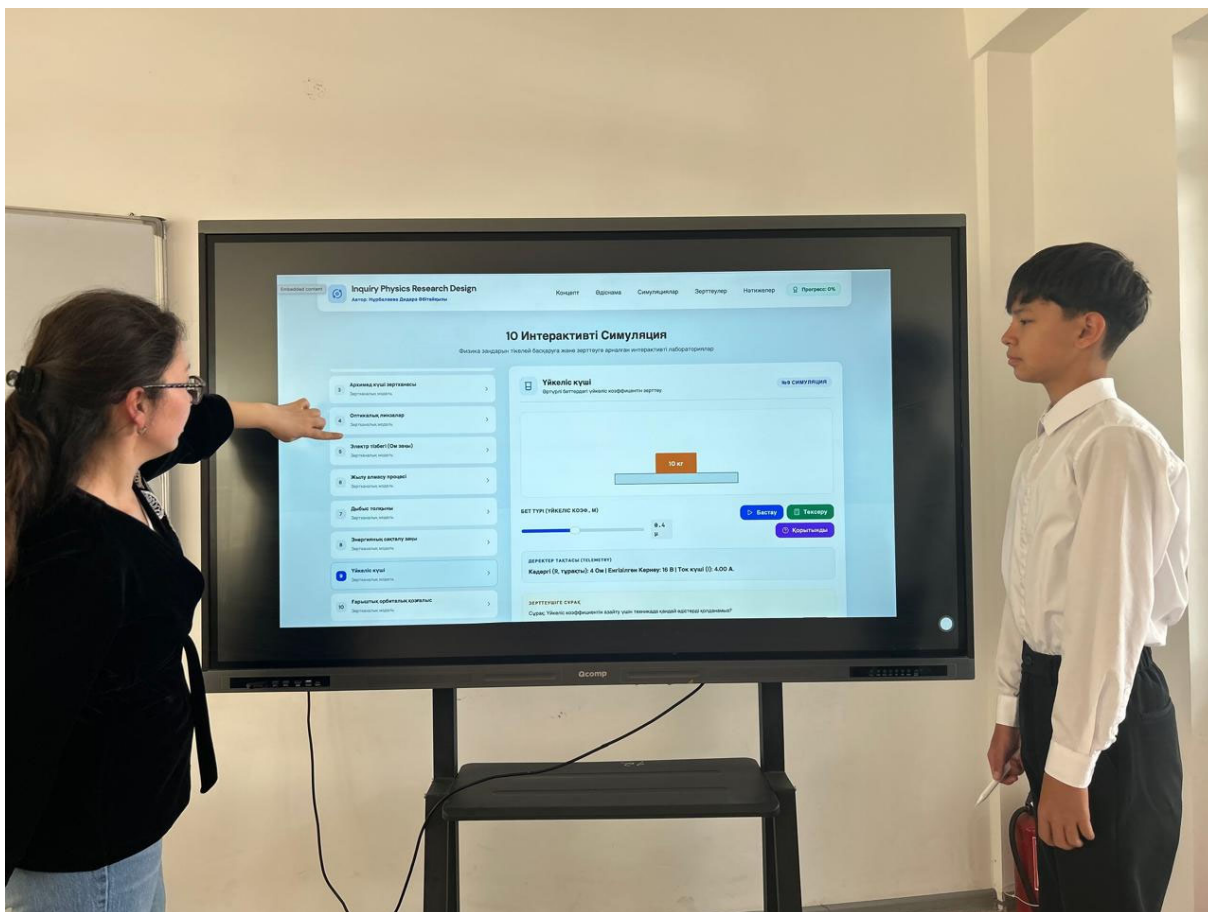


Figure 22. Teacher explaining the research package modules and expected learning outcomes on the classroom display.

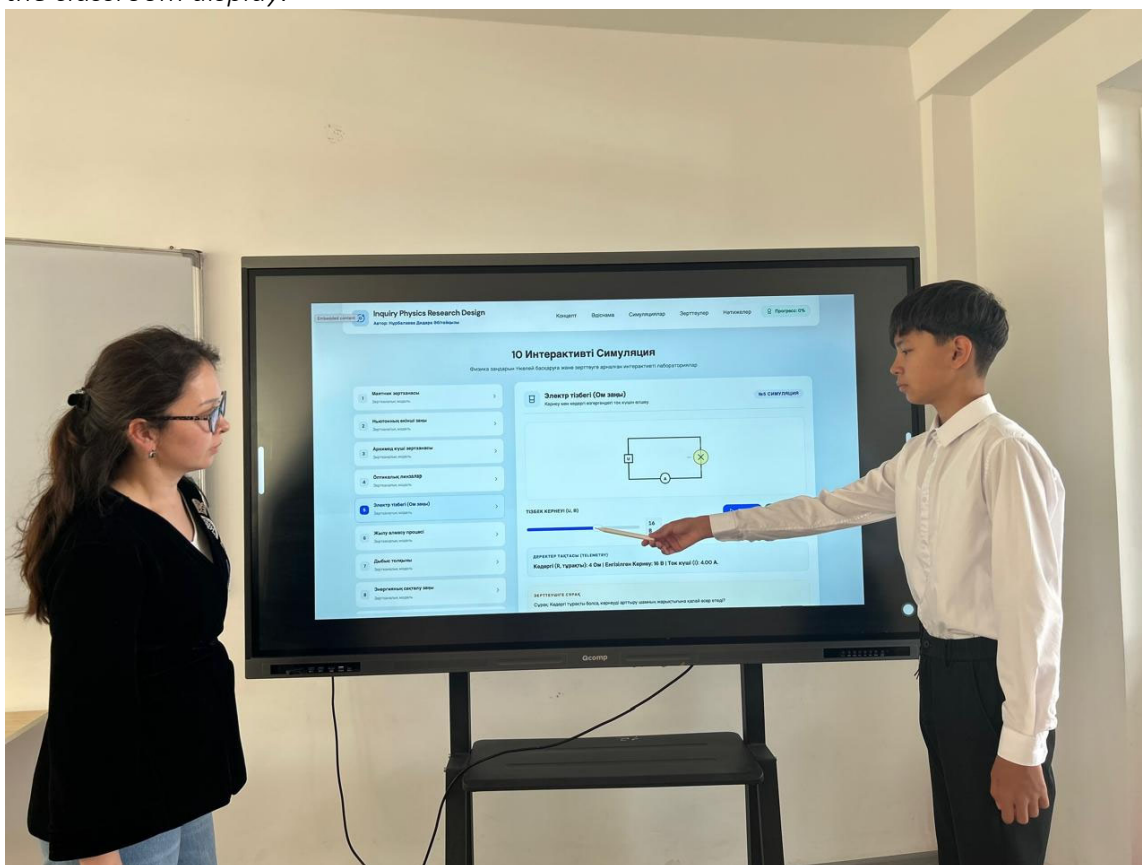


Figure 23. Teacher presenting the platform home page and its authorial inquiry-based methodology for physics education.

**Research instruments**

Block	Instrument / data source	Purpose	Scale / scoring	Use in analysis
1	Student background and physics-learning profile	Grade, prior experience with simulations, confidence in physics and frequency of practical work.	Categorical and short Likert items.	Descriptive statistics and subgroup comparison.
2	Scientific thinking diagnostic test	Measures problem formulation, hypothesis building, variable identification and evidence interpretation.	10-15 items scored 0/1 or rubric 0-3.	Pre/post comparison and learning-gain analysis.
3	Conceptual physics task set	Checks conceptual understanding of selected topics such as motion, forces, circuits and heat transfer.	Multiple-choice and constructed-response items.	Outcome indicator and comparison between topics.
4	Inquiry process rubric	Evaluates hypothesis, data collection, graph interpretation, explanation and conclusion quality.	Rubric levels 0-4 for each criterion.	Main measure of inquiry performance.
5	Platform analytics	Records completed simulations, completed tasks, progress percentage and certificate status.	Counts, percentages and binary completion indicators.	Engagement and implementation fidelity.
6	Student reflection prompts	Captures perceived difficulty, reasoning process and value of the simulation.	Short open-ended responses.	Qualitative thematic coding.
7	Teacher observation notes	Documents scaffolding, student questions, misconceptions and collaboration patterns.	Structured observation sheet.	Contextual interpretation of quantitative results.

Table 5. Proposed instruments for evaluating inquiry-based physics learning.

### Variables and statistical analysis plan

The main dependent variables are scientific thinking score, inquiry-rubric score, conceptual physics score and quality of written scientific explanation. Independent variables include platform use, number of completed simulations, number of completed research tasks, prior confidence in physics, student grade level and teacher scaffolding intensity. Platform analytics are treated as implementation variables, while student reflections and teacher observations are treated as qualitative explanatory data.

Descriptive statistics should include frequency, percentage, mean, standard deviation, median and range. Pre/post changes can be examined with paired-sample t-tests when assumptions are met, or with non-parametric alternatives such as Wilcoxon signed-rank tests. If a comparison group is available, independent t-tests, ANCOVA or mixed models can be used depending on the sample size and research design. Correlations may be calculated between the number of completed simulations and improvement in scientific thinking score. Rubric reliability may be checked through inter-rater agreement when two teachers score the same student work.

Qualitative data should be analyzed through thematic content analysis. Student responses are read repeatedly, meaningful units are coded and codes are grouped into themes. Expected themes include curiosity, formula-to-phenomenon transfer, difficulty interpreting graphs, improvement in hypothesis writing, teacher scaffolding, collaboration and evidence-based conclusion. Qualitative data should not be used to replace quantitative results; rather, it explains why and how observed changes may have occurred.

Variable group	Example variables	Data type	Analysis
Student outcomes	Scientific thinking score, conceptual physics score, inquiry rubric level.	Continuous / ordinal.	Pre/post comparison, correlation, effect size.
Platform engagement	Completed simulations, completed tasks, progress percentage, certificate status.	Counts / binary / percentage.	Descriptive statistics and association with outcomes.
Inquiry process	Hypothesis quality, data recording accuracy, graph interpretation, evidence-based conclusion.	Rubric scores and text.	Rubric analysis and qualitative coding.
Contextual factors	Grade level, prior physics confidence, access to digital devices.	Categorical / Likert.	Subgroup description and covariate analysis.
Teacher support	Guidance questions, feedback type, time on task.	Observation notes.	Qualitative interpretation and implementation fidelity.

Table 6. Variables and analysis plan for future empirical testing.

### Ethical considerations

The research involves educational activity with students; therefore, ethical requirements must be clearly described before any classroom data are collected. Participation in diagnostic tasks,

reflections or research observation should be voluntary and should not negatively affect the student's grade. Students and parents or guardians should receive information about the purpose of the study, the use of anonymized data and the right to withdraw where required by local regulations.

Photos and screenshots must be used carefully. Practical photographs included in this manuscript serve only to show the implementation process and do not represent individual assessment results. If the article is submitted to a journal or competition, consent for the use of identifiable photographs should be obtained, or faces should be blurred according to the requirements of the host institution. Platform data should be stored securely and reported only in aggregated form.

Ethical issue	Required action	How it should appear in the manuscript
Informed consent	Explain purpose, voluntary participation and use of anonymized learning data.	State that participants and/or guardians were informed before data collection.
Anonymity	Avoid publishing names, class lists or personal identifiers.	Report only aggregated results and anonymized examples.
Educational fairness	Ensure that non-participation does not reduce marks or access to learning materials.	Clarify that platform participation is not punitive.
Image use	Obtain separate permission for photographs or anonymize visual material.	Indicate that images illustrate procedure, not personal performance.
Data security	Store platform exports and notes on password-protected devices.	Describe secure storage and limited access.
Teacher role	Separate pedagogical support from research pressure.	Explain that teacher guidance was part of normal learning support.

*Table 7. Ethical requirements for classroom testing of the platform.*

## RESULTS AND DISCUSSION

Because the article is prepared as a methodological and platform-based manuscript before large-scale empirical testing, this section presents expected results and an interpretation framework rather than fabricated numerical outcomes. This is important for scientific integrity. Actual classroom data should later replace the proposed interpretation with real descriptive statistics, pre/post comparisons, rubric results and coded qualitative responses.

The first expected result is improvement in students' ability to formulate research questions and hypotheses. In conventional physics lessons, students may treat the task as a demand to find the correct formula. In the inquiry-based platform, the task begins with a phenomenon and a question. For example, a pendulum simulation asks students to predict how the period changes when length increases. This structure encourages students to identify variables and reason before calculation. The second expected result is stronger evidence-based explanation. Interactive simulations allow learners to manipulate one variable while observing changes in the system. This supports the development of causal reasoning because the student can see that changing the length of a pendulum, the voltage in a circuit or the temperature difference in a heat-transfer model produces a measurable effect. When students write conclusions after such activity, their explanations may become more connected to data and less dependent on memorized sentences.

The third expected result is improvement in graph and telemetry interpretation. Many students have difficulty moving from a visual model to a numerical or graphical representation. Platform tasks require them to observe values, use sliders, compare states and explain trends. This repeated movement between visual, numerical and verbal forms is one of the key strengths of digital inquiry environments.

The fourth expected result is increased student engagement. Research on active learning and interactive engagement in STEM suggests that students learn more effectively when they participate in activities, discussion, prediction and feedback rather than passively listening to explanations [9; 10]. The platform's progress dashboard and certificate section can further motivate students by making learning progress visible. However, motivation should not be interpreted only as entertainment; in this model, engagement is valuable because it is connected with a structured scientific task.

The fifth expected result is improved teacher ability to organize inquiry-based lessons. A common difficulty in inquiry-based learning is that teachers may not know how to transform a topic into a research sequence. The platform solves this by offering methodological cards, a seven-step framework, simulations and tasks in one environment. The teacher can therefore focus on guiding reasoning, asking probing questions and helping students evaluate evidence.

Expected outcome	Platform mechanism	Indicator for evaluation
Scientific question formulation	Problem cards and research-task prompts.	Quality of student question and hypothesis.
Variable identification	Simulation sliders and controlled parameter changes.	Correct distinction between independent and dependent variables.
Evidence interpretation	Telemetry blocks, visual models and check buttons.	Student conclusion refers to observed data.
Conceptual understanding	Simulations connect formulas with phenomena.	Pre/post conceptual task improvement.
Research culture	Certificate and progress dashboard recognize completed inquiry work.	Completion rate and reflection quality.
Teacher scaffolding	Methodological framework supports lesson planning.	Observation notes and teacher feedback.

Table 8. Expected educational outcomes and platform mechanisms.

### Literature synthesis and theoretical interpretation

The literature supports the assumption that inquiry-based science teaching is effective when it is carefully guided. Minner, Levy and Century synthesized inquiry-based science instruction research and emphasized that inquiry is connected with students' active engagement in scientific questions and evidence [11]. In physics education, Hake's large-scale comparison of interactive engagement and traditional methods remains influential because it showed that interactive engagement courses produced substantially stronger conceptual gains in mechanics than traditional lecture-based approaches [12].

Freeman and colleagues reviewed active learning in STEM and found that active learning improves examination performance and reduces failure rates compared with traditional lecturing [9]. This finding does not mean that every activity automatically improves learning; rather, it supports the principle that students must do intellectual work during the lesson. Inquiry Physics Research Design operationalizes this principle by requiring students to predict, manipulate, observe, record, explain and conclude.

PISA 2025 provides a policy-level justification for the model. It emphasizes that students need competencies for explaining phenomena scientifically, evaluating designs for scientific enquiry and interpreting data and evidence critically [1]. These competencies are directly represented in the platform's structure. The tasks do not ask only for an answer; they ask for a reasoned path from question to evidence. This is why the platform can be described as a scientific-thinking development environment rather than only a simulation collection.

The NRC framework further supports the approach by linking science and engineering practices with disciplinary core ideas and crosscutting concepts [2]. For example, a heat transfer task involves disciplinary knowledge about thermal processes, a crosscutting concept of energy transfer and the practice of analyzing data. A pendulum task involves periodic motion, cause-and-effect reasoning and the practice of constructing explanations. Such integration is the essence of modern physics education.

Interactive simulation research also supports the value of visual and manipulable models. PhET's research program is built around the design and use of simulations that promote learning through exploration and feedback [3; 4]. Inquiry Physics Research Design follows a similar educational logic while adapting the content to an authorial platform with a certificate, research tasks and teacher-guided inquiry sequence.

Author / source	Design / source type	Focus	Contribution to this manuscript
OECD, 2025	International assessment framework	Scientific literacy and science competencies.	Provides the competency basis for explaining phenomena, evaluating enquiry and interpreting evidence.
National Research Council, 2012	Science education framework	Practices, crosscutting concepts and core ideas.	Supports the integration of physics content with scientific practices.
PhET, University of Colorado Boulder	Simulation design and research program	Interactive STEM simulations and research-based design.	Supports use of simulations for exploration and conceptual visualization.
Freeman et al., 2014	Meta-analysis	Active learning in STEM.	Justifies student participation, discussion and task-based reasoning.
Hake, 1998	Large-scale physics education study	Interactive engagement versus traditional instruction.	Supports the value of interactive engagement in physics learning.
Minner et al., 2010	Research synthesis	Inquiry-based science instruction.	Justifies guided inquiry as a research-supported teaching direction.
PRISMA, 2020	Reporting guideline	Transparent literature review reporting.	Structures source identification and selection.
STROBE and COREQ	Reporting guidelines	Observational and qualitative research reporting.	Support transparent future classroom testing.

Table 9. Key sources used to substantiate the article.

**Expected qualitative coding structure**

Theme	Possible student meaning	Example code	Pedagogical interpretation
Curiosity and question posing	The student begins to ask why a phenomenon changes.	why does it move faster; what happens if	Inquiry is developing beyond answer-seeking.
Variable awareness	The student distinguishes what is changed and what is measured.	independent variable; dependent variable	The learner begins to think experimentally.
Evidence-based conclusion	The student supports claims with platform data.	the graph shows; the value increased	Scientific argumentation is improving.
Conceptual difficulty	The student struggles to connect data with a physical law.	I see the change but cannot explain it	Teacher scaffolding should focus on law-phenomenon connection.
Engagement and agency	The student feels able to test ideas independently.	I tried different values; I checked my idea	The platform supports active learning.
Collaboration	Students discuss predictions and compare results.	we compared; my partner found	Inquiry can support scientific discourse.

*Table 10. Proposed qualitative coding structure for student reflections.*

**Expanded discussion**

The main methodological value of the platform is that it transforms physics learning into a sequence of epistemic actions. Students do not simply receive a correct result; they participate in the process through which a result becomes scientifically justified. This distinction is important. Scientific thinking is not only knowing that a formula exists; it is understanding when the formula applies, which variables are relevant, what evidence supports the claim and what limitations should be considered.

Inquiry-based physics education also improves the relationship between theory and practice. Many students perceive physics formulas as abstract symbols. Simulation-based inquiry can reduce this distance by making the formula visible in a changing system. For example, Ohm's law becomes more meaningful when students manipulate voltage and resistance and then observe current. Archimedes' principle becomes clearer when students vary fluid density or body volume and observe buoyant force. Heat transfer becomes less abstract when temperature difference and thermal equilibrium are shown dynamically.

The teacher remains central in this methodology. A digital platform alone cannot guarantee scientific thinking. The teacher must formulate productive questions, prevent superficial clicking, ask students to justify claims and connect observations with conceptual explanations. Therefore, the platform should be used as a guided inquiry environment, not as an unsupervised game. The practical classroom photographs included in this article show teacher presence, explanation, student participation and use of the interactive board as a shared research space.

Assessment should also change. If inquiry-based learning is evaluated only through final numerical answers, much of its educational value is lost. A student may calculate correctly but fail to explain evidence; another student may make a computational error but show strong reasoning about

variables. For this reason, the article proposes a combined assessment model: conceptual correctness, inquiry process, explanation quality, data interpretation and reflection. This is consistent with the broader shift in science education from content recall to performance-based scientific literacy.

The platform's certificate function should be interpreted carefully. A certificate is not a scientific result by itself. It is useful only when it is connected to genuine task completion and evidence-based work. In the proposed model, the certificate becomes a motivational and documentary tool that records activity. For journal reporting, the real evidence must come from student artifacts, scores, reflections and teacher observations.

The implementation context is also important. Digital inquiry requires sufficient classroom time, teacher preparation and access to devices or an interactive board. Some students may initially focus on moving sliders rather than reasoning. This problem can be addressed by requiring every simulation to end with a written hypothesis, data note and conclusion. In this way, interaction is transformed into scientific thinking.

This article also has broader relevance for Kazakhstan and other educational contexts seeking to modernize physics education. International frameworks such as PISA emphasize the application of knowledge, critical interpretation of evidence and scientific reasoning. A locally developed platform that follows international inquiry principles can help align classroom practice with these global expectations while preserving the teacher's authorial methodological contribution.

#### **Practical recommendations for physics teachers**

Teachers using the platform should begin each lesson with a research question rather than with a formula. The formula should appear after students have identified the variables and observed the phenomenon. This sequencing increases the likelihood that the formula is understood as a model of reality rather than as a symbol to memorize.

Each simulation should be accompanied by a minimum written protocol: prediction, changed variable, measured variable, observed result and conclusion. The protocol may be short, but it should force the student to connect action with evidence. Teachers should also ask students to compare two conditions, because comparison is one of the simplest ways to develop causal reasoning.

For assessment, teachers should combine automatic progress indicators with human evaluation of reasoning quality. A completed simulation does not necessarily mean understanding; a well-written conclusion and correct interpretation of data provide stronger evidence. The inquiry rubric in the appendix can be used as a formative tool during the lesson and as a summative tool at the end of a module.

#### **CONCLUSION**

This article presented an international inquiry-based methodology for developing scientific thinking in physics education and demonstrated how it can be implemented through the Inquiry Physics Research Design platform. The methodology is grounded in international science education frameworks, active learning research, physics education research and the pedagogical potential of interactive simulations.

The proposed model emphasizes a structured inquiry cycle: problem question, hypothesis, virtual experiment, data collection, analysis, evidence-based explanation and conclusion. This cycle helps students move from passive reception of physics content to active scientific reasoning. The platform supports this transition by providing ten interactive simulations, research tasks, methodological guidance, progress tracking and certificate generation.

The article does not claim final empirical effectiveness before classroom data are collected. Instead, it offers a complete research-ready structure for future testing: literature synthesis, research questions, mixed-method design, instruments, variables, ethics, expected results and

coding logic. This makes the work suitable for journal submission after empirical results are added, and it can also serve as a polished methodological article or teacher innovation project.

In practical terms, Inquiry Physics Research Design can help teachers organize physics lessons around evidence, experimentation and scientific explanation. For students, it can make physics more visible, investigable and meaningful. For educational researchers, it provides a model for studying how digital inquiry environments influence scientific thinking, conceptual understanding and research culture in school physics.

#### **LIMITATIONS OF THE STUDY**

The main limitation is that the current manuscript is primarily methodological and platform-based. Large-scale empirical data have not yet been presented; therefore, claims about effectiveness are stated as expected outcomes and should be tested in future classroom research. Actual results must include sample characteristics, pre/post scores, platform analytics, rubric reliability and qualitative evidence.

Second, the platform screenshots and practical photographs demonstrate implementation but do not by themselves prove learning gains. They should be interpreted as visual documentation of the procedure. Quantitative and qualitative data are still needed to evaluate student outcomes objectively.

Third, the effectiveness of inquiry-based learning depends strongly on teacher guidance. If simulations are used without questions, explanation prompts or feedback, students may interact with the interface superficially. Future research should therefore measure not only platform use but also the quality of teacher scaffolding.

Fourth, results may vary depending on grade level, prior physics knowledge, access to digital tools and language of instruction. Future studies should test the platform across several classes and compare different physics topics.

#### **AUTHOR CONTRIBUTION**

D. O. N. contributed to the development of the authorial platform concept, the selection of the research topic, the design of inquiry-based simulations and tasks, the organization of the practical classroom demonstration, the interpretation of the methodological framework and the preparation of the manuscript structure.

#### **FUNDING**

The study was conducted without external funding.

#### **ETHICAL STATEMENT**

The practical materials were used for methodological demonstration of a digital educational platform. Any future classroom study involving student data should be conducted with informed consent, anonymized reporting and institutional permission where required. Photographs should be used only with permission or after anonymization according to the requirements of the submitting institution.

#### **CONFLICT OF INTEREST STATEMENT**

The author declares no conflict of interest.

#### **DATA AVAILABILITY STATEMENT**

The platform is available through the QR code and URL provided in the manuscript. Future empirical datasets should be stored securely and made available only in anonymized aggregated form upon reasonable academic request.

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#### APPENDIX A. STUDENT SCIENTIFIC THINKING DIAGNOSTIC

No.	Diagnostic item / prompt
1	Write one research question about a physics phenomenon that can be tested in a simulation.
2	State a hypothesis using the structure: If ... changes, then ... will change because ... .
3	Identify the independent variable, dependent variable and controlled variable in a pendulum investigation.
4	Explain why repeated measurements may be useful in a physics experiment.
5	Interpret a simple graph and write a conclusion supported by evidence.

Appendix Table A1. Diagnostic prompts for scientific thinking.

#### APPENDIX B. INQUIRY RUBRIC

Criterion	0 - Not shown	1 - Basic	2 - Developing	3 - Proficient	4 - Advanced
Research question	No question.	Very general question.	Question is related to topic but not fully testable.	Clear and testable question.	Precise, measurable and scientifically meaningful question.
Hypothesis	No hypothesis.	Guess without reason.	Prediction with weak reason.	Prediction linked to variables.	Causal hypothesis with clear physical justification.
Data collection	No data.	Incomplete data.	Some values recorded.	Relevant values recorded accurately.	Systematic data with comparison and notes.
Evidence interpretation	No interpretation.	Personal opinion only.	Mentions data without explanation.	Uses data to support conclusion.	Connects data, trend, law and limitation.
Conclusion	No conclusion.	Short unsupported answer.	Partly supported conclusion.	Evidence-based scientific conclusion.	Clear conclusion with reflection and transfer to real context.

Appendix Table B1. Inquiry-process rubric for physics learning.

**APPENDIX C. PLATFORM IMPLEMENTATION CHECKLIST**

Step	Teacher action	Student action	Evidence collected
1	Introduce research question and safety/digital rules.	Reads problem and predicts outcome.	Initial hypothesis.
2	Demonstrate simulation controls briefly.	Manipulates one variable at a time.	Screenshot or data note.
3	Ask evidence questions.	Records observation and compares conditions.	Telemetry values and written notes.
4	Guide conclusion writing.	Explains result using a physics concept.	Written conclusion.
5	Review progress and certificate criteria.	Completes reflection and final task.	Progress indicator and reflection.

*Appendix Table C1. Classroom implementation checklist.*

# Optimization of Heat Transfer Processes in Energy Systems Using Artificial Intelligence

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## ABSTRACT

The aim of this study is to develop a scientific and methodological framework for optimizing heat-transfer processes in energy systems using artificial intelligence and to describe the practical implementation of this framework through the AI Energy Heat Optimization digital platform. The research object is the heat-transfer process in energy systems, including heat loss, flow-rate regulation, insulation effect, solar heat collection, boiler efficiency, temperature control, and smart energy management. The article combines a PRISMA 2020-oriented literature search, a STROBE-informed observational evaluation design, a COREQ-based qualitative feedback logic, FAIR data principles, and current AI governance recommendations. Sources were selected from official and scientific databases, including the International Energy Agency, NIST, ISO, peer-reviewed journals on machine learning for heat transfer, HVAC predictive control, heat exchangers, thermal-energy storage, and physics-informed neural networks. The practical stage is represented by the AI Energy Heat Optimization platform, which contains a home page, a scientific concept block, a methodological framework, ten interactive simulations, a task bank, diagnostic self-assessment, expected-result indicators, and a certificate module. The platform is designed to demonstrate how artificial intelligence can assist in forecasting heat loss, adjusting thermal parameters, comparing traditional and AI-supported control, and forming evidence-based conclusions. The study shows that AI-based heat-transfer optimization should be evaluated not only by expected efficiency increase, but also by physical validity, data quality, interpretability, risk awareness, and practical usefulness. The proposed framework may be applied in applied scientific projects, STEM education, engineering-oriented research training, and early-stage digital prototyping of energy-efficiency solutions.

**Keywords:** artificial intelligence; heat transfer; energy systems; thermal optimization; HVAC; heat loss; machine learning; digital platform; model predictive control; STEM research.

## INTRODUCTION

Heat transfer is one of the central physical processes in modern energy systems. It determines how efficiently heat is produced, transported, stored, recovered, and converted into useful work in boilers, heat exchangers, heat pumps, district-heating networks, industrial thermal lines, solar collectors, and building heating, ventilation, and air-conditioning systems. Even when an energy system has reliable equipment, inefficient heat exchange can increase fuel consumption, create excessive thermal losses, shorten equipment lifetime, and reduce the stability of the whole system. For this reason, the optimization of heat-transfer processes is not only a thermodynamic problem, but also a data-driven control and decision-making problem.

Traditional thermal engineering relies on heat-balance equations, empirical coefficients, hydraulic calculations, laboratory measurements, and model predictive control. These methods are scientifically grounded and remain necessary for engineering design. However, real energy systems often operate under changing boundary conditions: outdoor temperature, flow rate, inlet temperature, load profile, pressure drop, fouling, insulation quality, solar radiation, user demand,

and equipment degradation change over time. Under such conditions, a fixed control algorithm may be too slow or too rigid to identify the most efficient operating mode. Artificial intelligence can support this process by learning from sensor data, detecting hidden patterns, forecasting heat demand, and recommending optimized parameter settings.

The relevance of artificial intelligence in energy is emphasized by current international reports. The International Energy Agency notes that AI has become both a growing energy consumer and a tool for improving the operation of power systems, buildings, industry, and grids [1]. Earlier digitalisation analyses also highlighted that smart demand response and digital control may provide substantial flexibility to energy systems and reduce unnecessary investment in infrastructure [2]. These conclusions make the integration of AI into thermal-energy management especially important, because heating and cooling loads form a large part of energy demand in buildings and industrial processes.

In heat-transfer engineering, machine learning has been applied to heat exchangers, thermal-energy storage systems, heat pumps, HVAC control, material selection, fouling prediction, and multiphysics simulation. Review studies show that machine-learning models can complement experimental and numerical methods when high-quality data, physically meaningful variables, and transparent validation procedures are used [3]. At the same time, the growing use of AI requires responsible management. NIST describes AI risk management as a structured process for making AI systems valid, reliable, safe, secure, transparent, explainable, privacy-enhanced, and accountable [4], while ISO/IEC 42001:2023 provides a formal management-system standard for organizations developing or using AI technologies [5].

The present study is focused on the topic 'Optimization of Heat Transfer Processes in Energy Systems Using Artificial Intelligence'. It treats the AI Energy Heat Optimization platform as a digital research environment for modelling, simulation, diagnostics, task-based assessment, and scientific explanation. The platform is not presented as an industrial certification tool or as a replacement for professional engineering design. It is considered as an educational and research-oriented prototype that demonstrates how AI logic, thermodynamic reasoning, and interactive simulations can be combined to develop an evidence-based model of thermal optimization.

The scientific value of this topic lies in the integration of three components: physical laws of heat transfer, data-driven artificial intelligence models, and practical digital simulation. The first component guarantees that the model is connected to real thermodynamic mechanisms. The second component enables dynamic prediction and optimization. The third component makes the model understandable for learners, teachers, and early-stage researchers by translating abstract equations into visible parameters, interactive controls, and result cards. Such integration is especially useful in applied scientific projects, because it allows the researcher to explain not only what the expected efficiency is, but also how the result was obtained.

The research problem can be formulated as follows: how can artificial intelligence be used to optimize heat-transfer processes in energy systems while preserving scientific validity, transparent interpretation, and practical usefulness? This problem is important because AI models may produce attractive numerical outputs without sufficient physical interpretation. Therefore, a strong research article must combine digital innovation with thermodynamic evidence, clear methodology, risk awareness, and realistic limitations.

The aim of this study is to develop and justify a methodological framework for AI-based optimization of heat-transfer processes in energy systems and to describe how the AI Energy Heat Optimization platform can be used for research simulation, diagnostic assessment, task-based validation, and result visualization. The specific objectives are: to review scientific literature on AI and thermal-energy optimization; to define the physical and data variables of the model; to describe the platform modules; to propose a mixed-method evaluation design; to formulate

expected indicators of efficiency; and to discuss the pedagogical and applied value of the prototype.

**Research questions and hypotheses**

No.	Research question	Hypothesis / analytical direction
RQ1	How can AI be used to optimize heat-transfer processes in energy systems?	AI can support optimization by learning from thermal parameters, forecasting heat loss, and recommending more efficient control settings.
RQ2	Which physical and digital variables should be included in an AI-based heat-transfer model?	Temperature difference, flow rate, insulation, thermal conductivity, equipment efficiency, prediction error, and optimization mode are expected to be central variables.
RQ3	How can a digital platform support scientific understanding of thermal optimization?	Interactive simulations and task-based feedback can make the relation between physical variables, AI prediction, and final conclusions more transparent.
RQ4	What criteria should be used to evaluate the scientific quality of the platform output?	Physical validity, data quality, interpretability, consistency of conclusions, and practical usefulness should be evaluated together.

*Table 1. Research questions and analytical hypotheses.*

**METHODS AND RESEARCH MATERIALS**

The study uses a combined methodological logic. The first component is a narrative literature synthesis based on a PRISMA 2020-oriented search strategy. PRISMA is used not because this article claims to be a full systematic review, but because it provides a transparent logic for identifying, screening, and reporting scientific sources [6]. The search focused on artificial intelligence in energy systems, heat-transfer optimization, heat-exchanger modelling, HVAC predictive control, thermal-energy storage, physics-informed neural networks, and AI governance.

The second component is a design-based research framework. The AI Energy Heat Optimization platform is treated as a digital prototype that represents the research concept through a structured interface, simulations, diagnostic tasks, a result dashboard, and a certificate-generation section. Design-based research is appropriate because the purpose is not only to describe an existing phenomenon, but also to develop and examine a practical tool that can support scientific explanation, modelling, and assessment.

The third component is a proposed empirical evaluation design. In a future practical testing stage, users may interact with the platform, complete simulations, answer scientific tasks, and provide short reflective explanations. Quantitative indicators may include simulation completion,

diagnostic scores, task results, selected parameters, predicted efficiency, and heat-loss reduction. Qualitative indicators may include explanation quality, understanding of variables, ability to justify parameter selection, and awareness of model limitations.

The observational part of the study follows the logic of STROBE, which recommends clear reporting of participants, variables, data sources, bias, sample size, statistical methods, and interpretation in observational studies [7]. The qualitative feedback component follows COREQ principles, which encourage transparent description of data collection, coding, and theme development [8]. The data-management logic is aligned with FAIR principles, according to which research data should be findable, accessible, interoperable, and reusable when ethical and technical conditions allow [9].

The object of the study is the AI-supported optimization of heat transfer in energy systems. The subject of analysis is the digital model that connects thermal input parameters, AI-based prediction, simulation tasks, diagnostic assessment, and practical interpretation. The practical material consists of platform screenshots and demonstration photographs provided during the platform presentation. These visual materials are used to document the functional structure of the prototype and to explain the data-collection process. They are not interpreted as independent statistical results.

The research variables are grouped into physical, digital, pedagogical, and evaluative categories. Physical variables include temperature difference, flow rate, thermal conductivity, insulation type, heat-loss level, solar collector angle, boiler efficiency, and reserve capacity. Digital variables include AI model selection, training epochs, prediction error, optimization mode, and feedback indicators. Pedagogical variables include task completion, simulation sequence, diagnostic self-assessment, and explanation quality. Evaluative variables include predicted efficiency improvement, reduction of heat loss, reliability of interpretation, and consistency between user input and platform output.

#### **Literature search and selection strategy**

The literature search strategy was developed for official reports, peer-reviewed journal articles, and methodological standards. Searches were conducted by combining keywords related to artificial intelligence, heat transfer, energy systems, thermal optimization, heat exchangers, model predictive control, HVAC, physics-informed neural networks, digitalisation, and AI governance. The search logic was structured to identify both technical studies and methodological documents relevant to responsible AI-based energy optimization.

Database / source	Search field	Core search string	Recommended filters
Scopus / Web of Science	Title, abstract, keywords	("artificial intelligence" OR "machine learning" OR "neural network") AND ("heat transfer" OR "thermal optimization" OR "energy system")	2015-2026; article; review; engineering; energy; thermal sciences
ScienceDirect / Elsevier	Title / abstract	("model predictive control" AND HVAC) OR ("thermal energy" AND optimization AND machine learning)	review articles; energy; buildings; applied energy
IEA official reports	Report pages	Energy and AI; digitalisation and energy; demand response; buildings	official reports; policy and technology analysis
NIST / ISO	Official standards and frameworks	AI risk management framework; ISO/IEC 42001; AI management systems	official framework; standard description
Google Scholar	Full text / title	("physics-informed neural networks" AND "heat transfer") OR ("machine learning" AND "heat exchanger")	highly cited studies; DOI available

Table 2. Search strategy for identifying scientific and official sources.

**Inclusion and exclusion criteria**

Criterion type	Included	Excluded
Research context	AI, machine learning, predictive control, or digital optimization in energy and thermal systems	General AI articles without energy or heat-transfer relevance
Physical process	Conduction, convection, heat loss, heat exchange, insulation, thermal storage, HVAC, heat pumps, boiler and solar heat collection	Purely electrical load forecasting without thermal interpretation
Methodological relevance	Studies with model validation, measurable variables, simulation logic, or clear optimization objectives	Opinion pieces without technical or methodological basis
Governance and ethics	Official AI risk-management and AI management-system documents	Non-authoritative commercial AI claims without standards or evidence
Educational value	Studies or frameworks that can support simulation, modelling, and STEM research explanation	Unverifiable promotional content or disconnected software descriptions

*Table 3. Inclusion and exclusion criteria for source selection.*

**Empirical and platform-based research design**

The proposed empirical design combines platform analytics, task results, and qualitative reflections. Participants may be students, early-stage researchers, or teachers using the platform in a guided session. Each participant completes the diagnostic self-assessment, runs selected simulations, answers task-bank questions, writes a short scientific conclusion

, and generates a final report or certificate. The researcher then compares platform scores, task accuracy, simulation completion, and written explanations.

Stage	User activity	Collected data	Evaluation purpose
1. Initial diagnosis	Completes self-assessment on physical data entry, theory, AI prediction, efficiency calculation, and conclusion writing	Diagnostic score and self-rated competence	Baseline understanding of thermal optimization
2. Simulation	Runs heat-loss, AI model, flow-rate, insulation, solar, boiler, and smart-control simulations	Parameter choices, completion status, predicted result	Scientific action and model interaction
3. Task bank	Answers applied scientific questions	Correct/incorrect responses and explanations	Conceptual understanding and evidence use
4. Result card	Reviews expected efficiency indicators	Baseline vs optimized values	Interpretation of AI-supported improvement
5. Reflection	Writes a conclusion about heat-transfer optimization	Text response	Qualitative reasoning and awareness of limitations

Table 4. Proposed platform-based data collection workflow.

### Practical data collection through the AI Energy Heat Optimization platform

The practical stage used the AI Energy Heat Optimization platform as a structured digital environment. The platform includes a home page, a concept section, a methodological section, ten interactive simulations, a task bank, a diagnostic self-assessment module, a result section, and a certificate-generation page. The interface is designed in a light premium style with gold and warm technical accents, which visually matches the topic of thermal energy and heat-flow optimization.

The platform begins with the research title and author block. The home section presents the core hypothesis: AI-based control can improve thermal efficiency by learning from operational data and selecting better parameter combinations than static manual control. The platform also shows expected indicators such as energy-efficiency improvement, heat-loss reduction, and AI-based accuracy. These indicators are presented as target values for research modelling rather than verified industrial outcomes.

The concept section explains the relevance, scientific novelty, and aim of the research. The novelty is the integration of hydraulic and thermodynamic regimes with an adaptive neural-network logic. This means that the platform is not limited to a single formula; it connects physical reasoning with data-driven optimization. The methodological framework then divides the research process into seven stages: problem formulation, data collection, AI model development, forecasting, optimization, comparison, and conclusion.

The simulation section is the main practical component. Ten simulations represent different thermal-energy situations: heat-loss prediction, AI optimization model, flow-rate balancing, energy-load mapping, intelligent temperature control, insulation effect, ventilation and heat balance, solar energy and heat collection, boiler efficiency, and smart energy control. Each simulation contains adjustable parameters, action buttons, checking logic, and a conclusion field. This makes the platform suitable for both demonstration and guided research tasks.

The task bank provides scientific and practical questions. It checks whether the user understands why insulation thickness affects heat loss, which variables are essential for AI training, and how AI-based control differs from traditional thermal control. The diagnostic self-assessment module allows the user to evaluate their ability to enter physical data, understand thermal processes, analyze AI predictions, calculate efficiency, and write evidence-based conclusions.

The result and certificate sections support completion logic. After the user runs simulations and completes tasks, the platform shows expected efficiency indicators and allows a certificate to be generated. In a research article, this module can be interpreted as a formative-assessment and documentation tool. It helps the user see progress and encourages the completion of all experimental steps before claiming a final result.

The QR code below provides access to the platform version used as the practical digital material in this article.



Figure 1. QR code for accessing the AI Energy Heat Optimization platform.



Figure 2. Practical demonstration of the diagnostic self-assessment module in the AI Energy Heat Optimization platform.

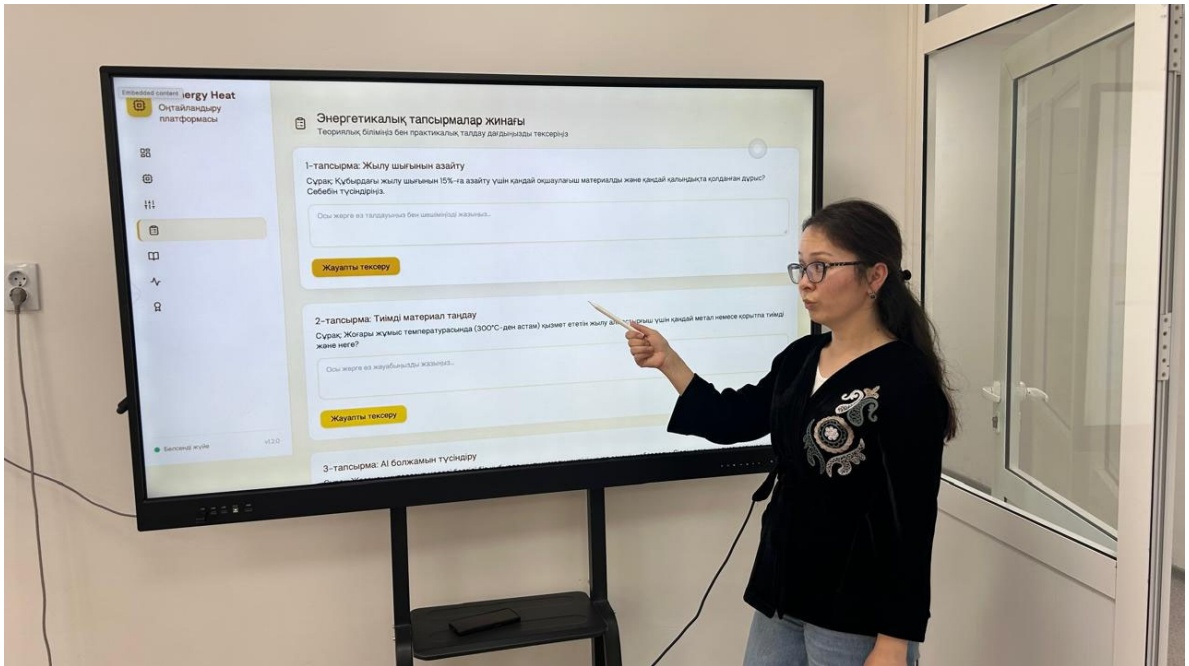


Figure 3. Practical demonstration of the energy task bank and evidence-checking activity.

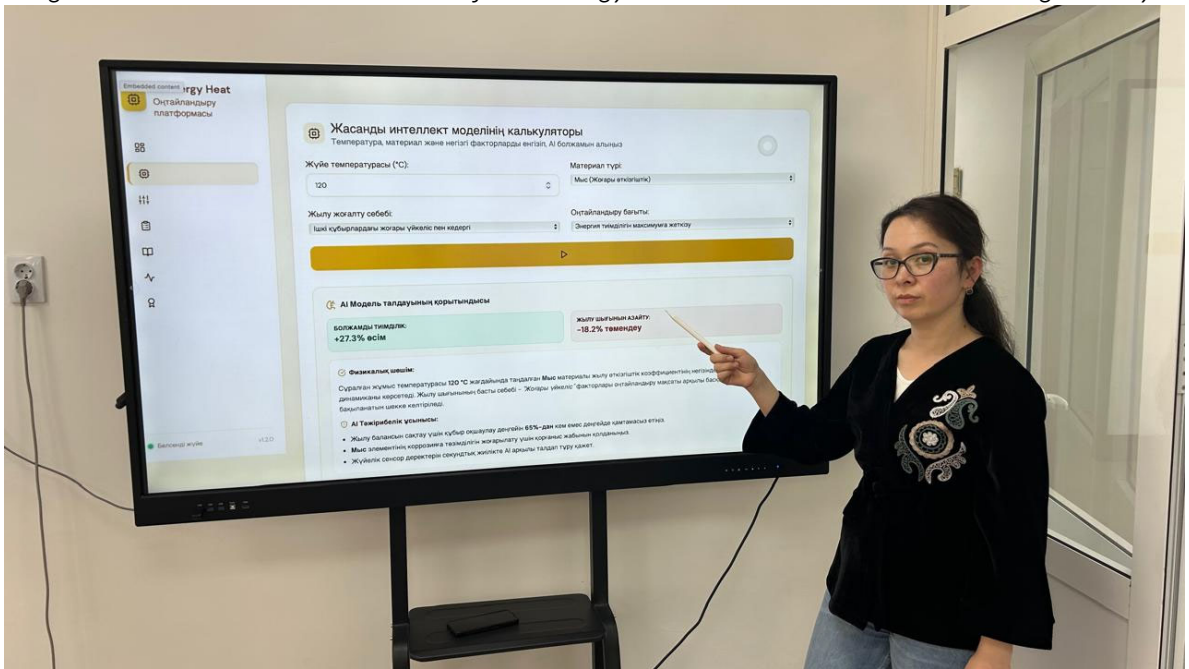


Figure 4. Practical demonstration of the artificial-intelligence model calculator for thermal optimization.

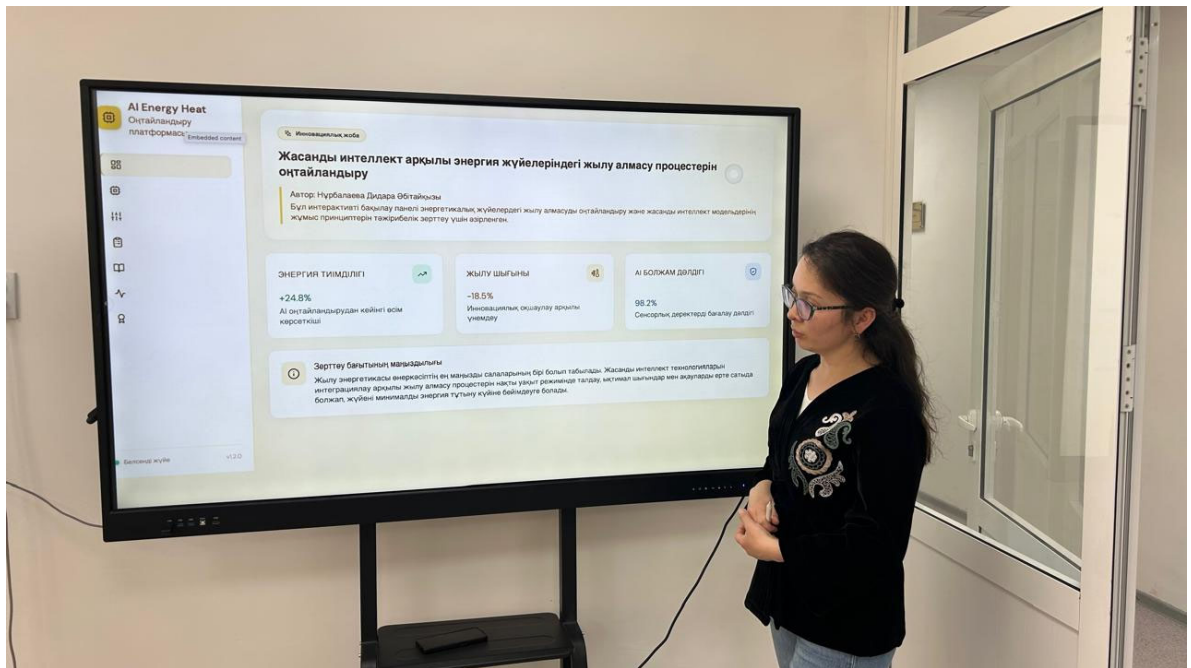


Figure 5. Presentation of the platform concept and key expected indicators: energy efficiency, heat loss reduction, and AI-based accuracy.

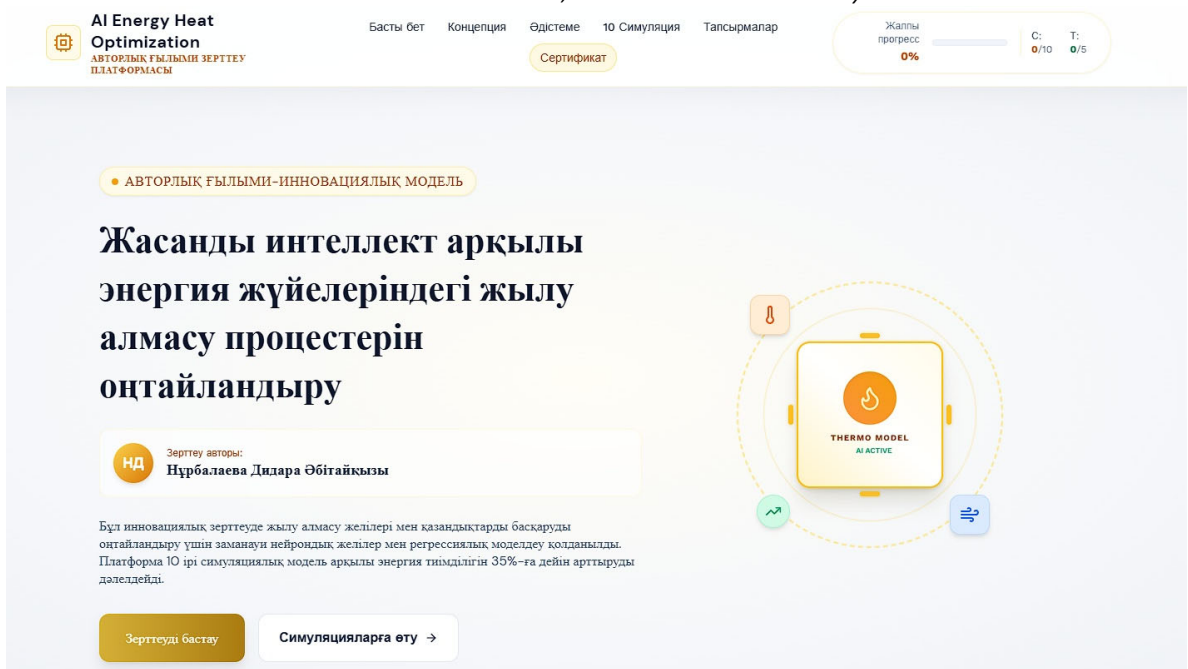


Figure 6. Home page of the AI Energy Heat Optimization platform: research topic, author information, conceptual model, and entry to simulations.

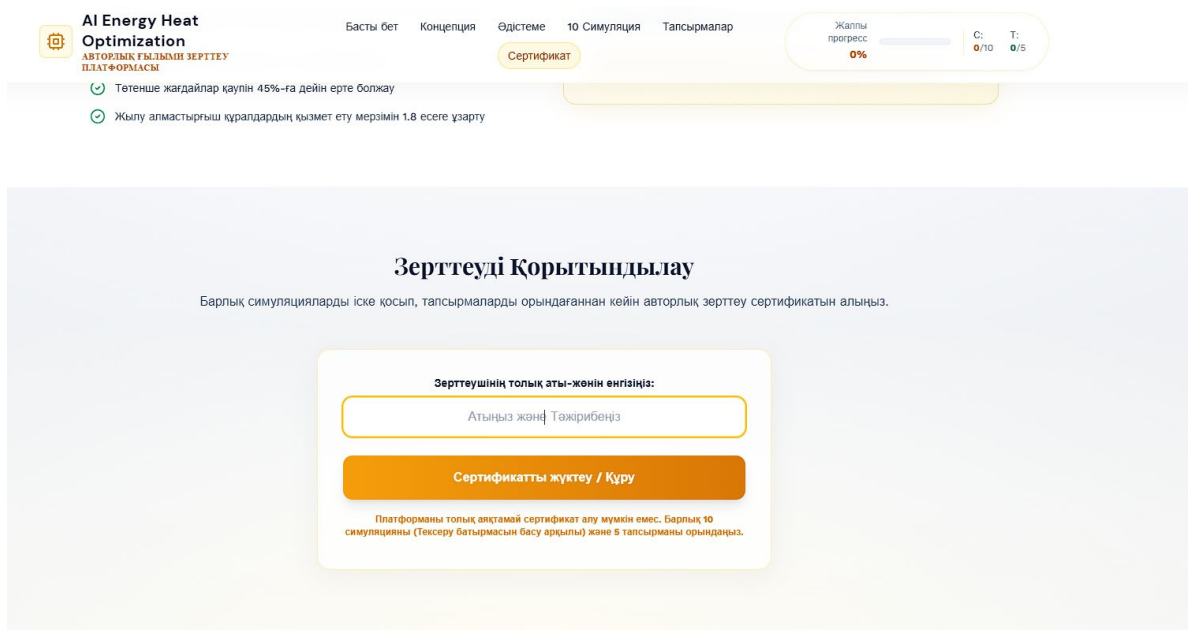


Figure 7. Certificate generation section of the platform after completing all simulations and scientific tasks.

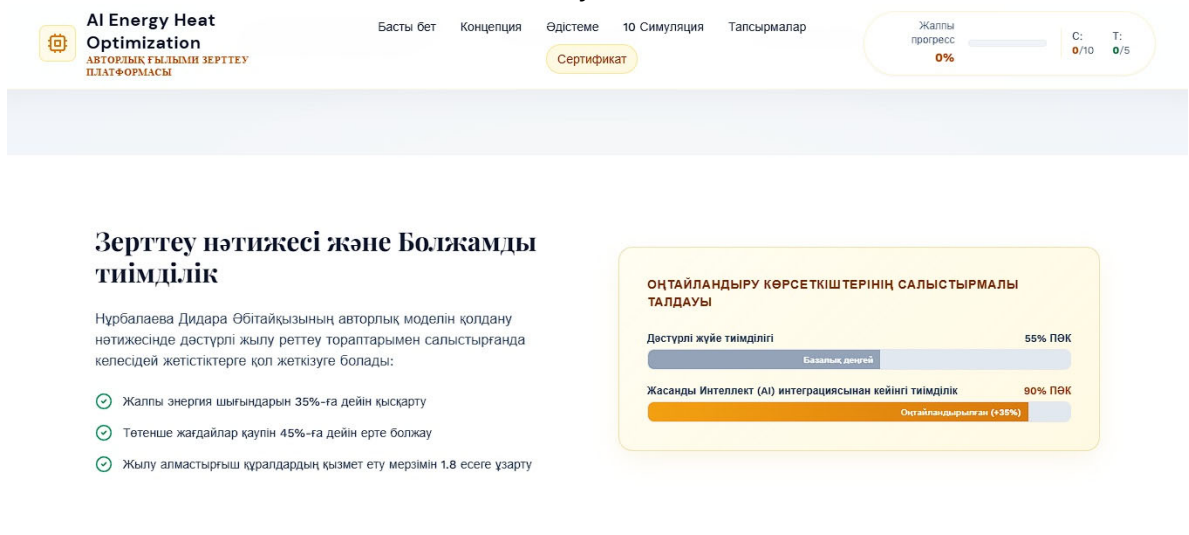


Figure 8. Expected research results and comparative efficiency indicators before and after AI integration.

Figure 9. Scientific and practical task bank used to validate understanding of thermal efficiency, data collection, and optimization logic.

Figure 10. Interactive simulations 7-10: ventilation and heat balance, solar heat collection, boiler efficiency, and smart energy control.

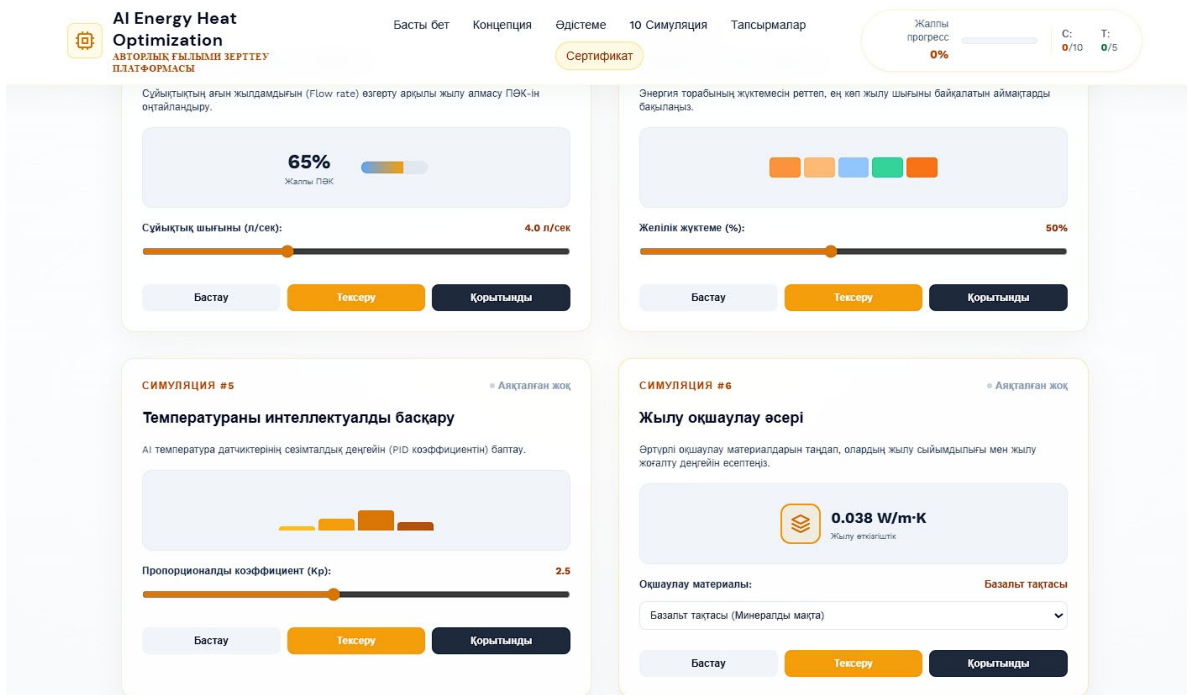


Figure 11. Interactive simulations 5-6: intelligent temperature control and insulation-effect modelling.

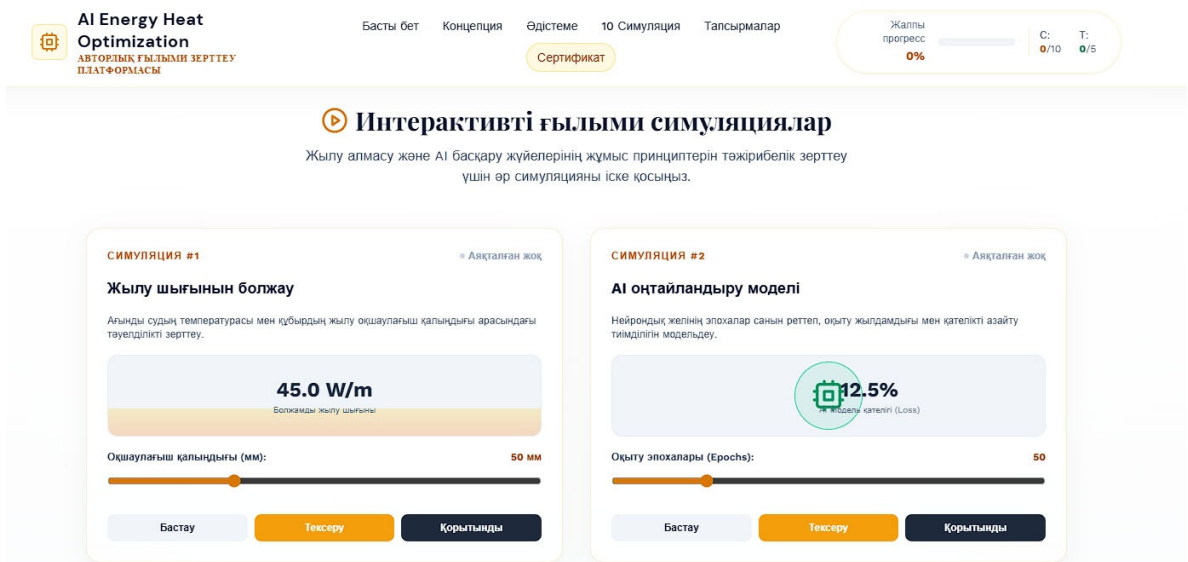


Figure 12. Interactive simulations 1-2: heat-loss prediction and AI optimization model.

### Research Design & Бақылау көрсеткіштері

Зерттеу барысында қолданылған негізгі жылу параметрлерінің, өлшеу құралдарының және айнымалылардың жүйелік құрылымы.

**x1 Тәуелсіз айнымалылар**  
Жылу тасымалдағыш температурасы, ағын жылдамдығы, сыртқы жағдайлар

**y1 Тәуелді айнымалылар**  
Жүйенің соңғы ПӘК-і, нақты жылу шығыны, энергия тұтыну мөлшері

**z1 Бақылау және өлшеу құралдары**  
Ультраздыбыстық шығын өлшегіштер, интеллектуалды термодатчиктер

### Термодинамикалық оңтайландыру теңдеуі

$$Q_{opt} = f(T_{in}, \mu_{flow}, \eta_{AI}) \cdot \Delta T$$

Мұндағы:  $\mu_{AI}$  – Нейрондық желі оңтайландыру коэффициенті

### Ғылыми рефлексия:

Осы математикалық модельдің көмегімен жасанды интеллект жылу алмасуды динамикалық реттеуді және дәстүрлі PID бақылауына қарағанда 35%-ға дейін тиімділікті жоғарылатады.

Figure 13. Research design and control indicators: independent variables, dependent variables, observation and measurement tools, and optimization equation.



Figure 14. Methodological framework: from problem formulation and data collection to AI model development, comparison, and conclusion.

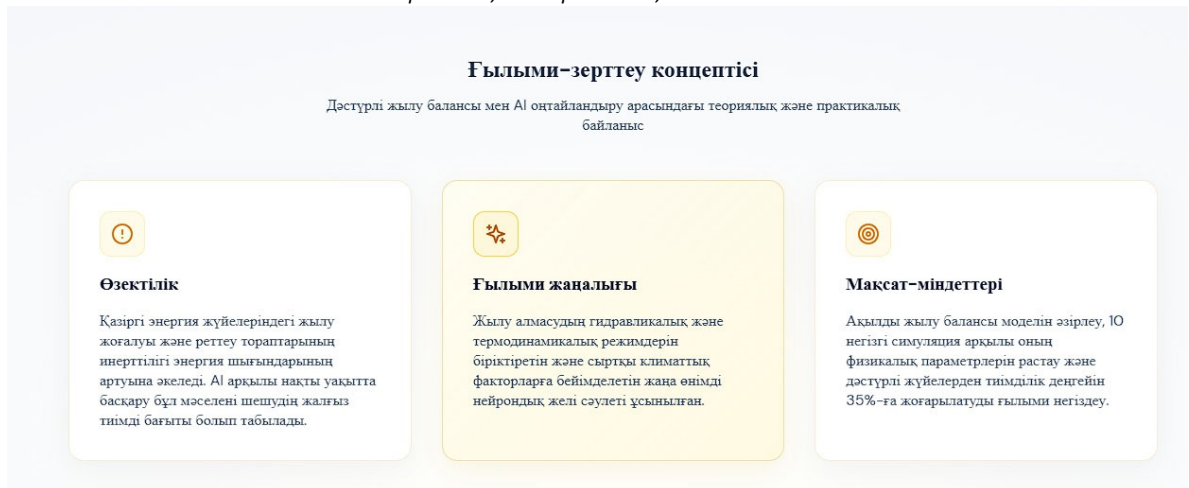


Figure 15. Scientific research concept: relevance, novelty, and aim of the AI-based heat-transfer optimization model.

**Research instruments**

Block	Instrument / data source	Purpose	Scale / output	Use in analysis
1	Platform profile and entry page	Defines research topic, author block, and general research aim	Descriptive platform data	Contextual documentation
2	Diagnostic self-assessment	Measures readiness to use physical data, understand theory, analyze AI predictions, and write conclusions	1-5 point self-rating scale	Baseline competence and reflection
3	Interactive simulations	Models heat loss, AI optimization, flow rate, insulation, solar collection, boiler efficiency, and smart control	Parameter values and completion status	Practical research performance
4	Task bank	Checks understanding of thermal efficiency, variable selection, and AI model logic	Correct/incorrect answer and written explanation	Conceptual assessment
5	Result section	Compares baseline and optimized expected indicators	Percentages and qualitative interpretation	Expected outcome analysis
6	Certificate module	Documents full platform completion	Completion requirement and generated certificate	Motivation and procedural closure
7	Practical photographs	Documents teacher demonstration and platform presentation	Visual evidence of use context	Methodological transparency

*Table 5. Research instruments and platform data sources.*

### Variables and statistical analysis plan

The main dependent variables are predicted thermal efficiency, heat-loss reduction, simulation-completion score, task accuracy, and quality of written conclusion. Independent variables include insulation thickness, insulation material, temperature difference, flow rate, collector angle, boiler air-fuel ratio, reserve capacity, AI training epochs, and selected optimization mode. Covariates may include user background, prior knowledge, digital literacy, and session format.

Descriptive statistics should include frequency, percentage, mean, standard deviation, median, and range. If the same participants complete pre- and post-platform diagnostic tasks, paired-sample tests may be used. If different groups compare traditional instruction and platform-based instruction, independent-sample tests or non-parametric alternatives may be applied. Correlation analysis can explore relations among diagnostic scores, task accuracy, simulation completion, and explanation quality. Regression analysis may be used to identify which variables predict stronger interpretation or higher task performance.

Qualitative responses should be analyzed through thematic content analysis. The researcher reads responses several times, identifies meaning units, assigns initial codes, groups codes into categories, and interprets major themes. Expected themes include understanding of heat loss, causal reasoning, AI trust, uncertainty awareness, practical usefulness, and limitations of simulation-based modelling.

### Ethical considerations

The platform-based study should follow ethical requirements for human-participant educational research. Participation must be voluntary, and users should receive clear information about the purpose of the study, the approximate duration, the type of data collected, confidentiality, and the right to withdraw. If photographs or screenshots are used in a publication, separate consent for visual material should be obtained. Any personal identifiers should be removed or masked before publication.

Ethical issue	Required action	How it is reported in the manuscript
Informed consent	Provide a short explanation and consent form before platform testing	All participants voluntarily agreed to participate
Confidentiality	Avoid collecting unnecessary names, phone numbers, or personal identifiers	Data were anonymized before analysis
Visual materials	Obtain permission for practical photographs and platform screenshots	Images were used only to document the procedure and interface
Educational fairness	Make clear that platform participation does not affect official grades unless approved by the institution	The activity was used for research and formative learning
AI transparency	Explain that platform indicators are research outputs, not industrial certification	AI outputs were interpreted with human review and methodological caution
Data security	Store files in a protected location and limit access	Only aggregated results are reported

Table 6. Ethical requirements for the platform-based study.

## RESULTS AND DISCUSSION

Because this article describes a research prototype before large-scale empirical testing, the Results and Discussion section presents a structured interpretation of expected outcomes and a framework for reporting future data. Numerical indicators shown in the platform screenshots should be understood as model targets and demonstration values. They do not replace real measurements from industrial equipment or building-energy monitoring. Future studies should replace these demonstration values with measured or experimentally simulated data.

The first expected outcome is a clearer connection between thermodynamic variables and optimization decisions. In traditional learning environments, heat-transfer equations may remain abstract. The platform translates variables into interactive sliders, choices, and result cards. For example, a user can increase insulation thickness, change flow rate, select an insulation material, or adjust solar-collector angle and immediately see how the predicted result changes. This supports conceptual understanding and makes the causal structure of heat transfer more visible.

The second expected outcome is improved understanding of AI model logic. The platform shows training epochs, prediction error, optimization mode, and model interpretation. This is important because AI is often perceived as a black-box technology. By placing model parameters next to physical variables, the platform encourages users to ask whether the predicted recommendation is physically reasonable. Such critical interpretation is essential for trustworthy AI in engineering contexts.

The third expected outcome is the development of evidence-based scientific explanation. The task bank and diagnostic section require the user to justify answers, not merely click buttons. In a future empirical study, written responses can be evaluated for accuracy, clarity, consistency, and practical usefulness. A strong response should connect the chosen parameter to a physical mechanism, explain the expected effect, and acknowledge possible limitations.

The fourth expected outcome is a practical comparison between traditional and AI-supported control. Literature on predictive control in HVAC systems shows that forecasting, optimization horizons, occupancy patterns, building type, and cost functions strongly affect performance [10]. The platform reflects this logic by comparing baseline and optimized efficiency. The comparison should be interpreted carefully: AI may improve performance when data quality is sufficient, but it may also fail if sensors are unreliable, training data are biased, or the model is used outside its validated operating range.

The fifth expected outcome concerns research culture. The platform encourages a complete cycle of inquiry: formulate a problem, collect data, build a model, predict, optimize, compare, and conclude. This sequence is important for scientific projects because it prevents the researcher from presenting AI as a decorative element. Instead, AI becomes a method within a documented research workflow.

### Practical approbation and the role of the digital platform

The practical demonstration photographs show that the AI Energy Heat Optimization platform can be presented through an interactive classroom display. The presenter explains the diagnostic module, task bank, AI model calculator, and main concept section. This visual documentation supports methodological transparency because it shows how the digital environment was introduced, how users could observe the interface, and how platform elements were connected with the research topic.

During practical approbation, the diagnostic self-assessment module was used to structure user reflection. It asks users to evaluate their ability to enter physical data, understand heat and mass transfer, analyze AI-based predictions, calculate efficiency, and write evidence-based conclusions. This module is important because AI-supported research requires not only technical clicking but also scientific interpretation.

The task bank was used to connect platform interaction with scientific reasoning. Tasks such as predicting the effect of increased insulation, identifying essential AI training data, and comparing traditional and AI-supported thermal networks help validate conceptual understanding. The task bank therefore functions as a bridge between simulation and assessment.

The AI model calculator demonstrates how input variables can be transformed into expected outputs. It includes heating temperature, material type, heat-loss level, optimization direction, predicted efficiency change, heat-loss reduction, and explanatory notes. In a future version, this calculator should be connected to a transparent dataset and a model-validation report.

#### Synthesis of key scientific sources

Author / organization, year	Design / source type	Focus	Main contribution	Use in this article
IEA, 2025	Official report	Energy and AI	Explains the dual role of AI as an energy consumer and optimization tool	Justifies the relevance of AI in energy systems
IEA, 2017	Official report	Digitalisation and energy	Highlights digital control, demand response, and system flexibility	Supports the platform logic of smart optimization
Zou et al., 2023	Review article	Machine learning for heat exchangers	Shows that ML can support heat-exchanger design and optimization when data quality is controlled	Supports AI modelling in heat-transfer tasks
NIST, 2023	Framework	AI risk management	Defines trustworthy AI characteristics and risk-management functions	Supports responsible interpretation of platform outputs
ISO/IEC 42001, 2023	International standard	AI management systems	Provides requirements for managing AI systems and related risks	Supports governance and documentation logic
Taheri et al., 2022	Review article	MPC in HVAC systems	Reviews modelling approaches, prediction horizons, and optimization algorithms	Supports predictive control discussion

Xin et al., 2024	Systematic review	Predictive control in HVAC	Reviews 245 studies on MPC and model-free predictive control	Supports the comparison between traditional and predictive control
Zhao et al., 2025	Review article	PINNs in heat transfer	Explains physics-informed neural networks for forward and inverse heat-transfer problems	Supports future development of physics-aware AI
Wilkinson et al., 2016	Principles paper	FAIR data	Defines findable, accessible, interoperable, and reusable data principles	Supports data-management recommendations
Page et al., 2021	Reporting guideline	PRISMA 2020	Provides transparent literature-search reporting logic	Supports the review methodology

Table 7. Key sources used to develop the research framework.

### Expected empirical interpretation

If the platform is tested with real participants, the first result to report should be completion data. The article should indicate how many users completed the diagnostic module, how many simulations were run, which simulations were most difficult, and how many users generated the certificate. This information shows whether the platform is usable and whether the workflow is realistic.

The second result should be task accuracy. If users correctly answer questions about insulation, flow rate, AI input variables, and baseline comparison, this suggests that the platform supports conceptual learning. If task accuracy remains low, the platform explanation should be revised before making strong claims about educational effectiveness.

The third result should be the quality of written conclusions. Strong conclusions should connect model output to physical reasoning. For example, a scientifically strong response would not simply state that AI improved efficiency; it would explain which parameter changed, why heat loss decreased, how the model predicted the change, and what limitations remain.

The fourth result should compare expected AI-supported optimization with baseline control. The comparison should be presented with caution. It is scientifically acceptable to report that the platform model produced a scenario-based improvement under selected assumptions. It is not acceptable to claim a universal energy-saving percentage without measured validation.

**Suggested qualitative coding structure**

Theme	Possible meaning for the user	Example code	Research interpretation
Understanding of heat loss	User recognizes that thermal losses depend on material and temperature difference	insulation; conductivity; heat gradient	Indicates physical reasoning
AI prediction logic	User understands that AI uses data patterns to forecast and optimize	training data; prediction error; model output	Indicates digital literacy
Evidence-based conclusion	User connects numerical output with mechanism	because; therefore; compared with baseline	Indicates scientific explanation quality
Trust and caution	User accepts AI output but asks about validation	uncertainty; measurement; reliability	Indicates responsible AI awareness
Practical usefulness	User sees application in buildings, heating systems, or laboratories	energy saving; boiler; HVAC; sensor	Indicates applied relevance
Simulation limitation	User understands that platform values are not full industrial proof	prototype; scenario; real data needed	Indicates methodological maturity

*Table 8. Qualitative coding structure for open responses.*

**Extended discussion**

AI-based heat-transfer optimization must be grounded in thermodynamics. A neural network may identify correlations, but it does not automatically understand conservation of energy, boundary conditions, or material properties. For this reason, physical variables should be selected before model training. Temperature difference, flow rate, thermal conductivity, insulation thickness, heat capacity, pressure drop, and equipment efficiency are not random inputs; they are variables connected to mechanisms of conduction, convection, radiation, and system-level energy balance.

The platform formula  $Q_{opt} = f(T_{in}, \mu_{flow}, \eta_{AI}) \cdot \Delta T$  is a simplified educational representation of optimized heat transfer. It is useful because it shows that optimized heat output depends on inlet conditions, flow behavior, AI optimization coefficient, and temperature difference. However, in an engineering setting this expression would need to be expanded with geometry, fluid properties, heat-transfer coefficients, fouling factors, heat capacity, and uncertainty bounds. This distinction should be clearly stated in journal submission to avoid overclaiming.

Machine-learning methods in heat-transfer applications are valuable when they reduce computational cost, support parameter estimation, detect anomalies, or improve control decisions. Review literature on heat exchangers indicates that machine learning can complement experimental and numerical studies, but careful algorithm selection, database quality, and validation are essential [3]. This means that an AI model is not automatically better than a physics-based model; its value depends on data quality, generalization ability, interpretability, and the operational objective.

Physics-informed neural networks represent another promising direction because they integrate physical equations into neural-network training. Recent reviews describe PINNs as tools for forward and inverse heat-transfer problems, especially where boundary conditions are incomplete or difficult to measure [11]. For the present project, this idea supports the future development of a more advanced platform version in which the AI model would not only learn from data but also respect heat-transfer equations in the loss function.

Model predictive control is highly relevant for building-energy and HVAC optimization. MPC uses a model of the system, a prediction horizon, constraints, and an objective function to choose control actions. In thermal systems with high inertia, predictive control may anticipate future demand rather than simply react to current error. This principle is similar to the platform's logic: AI should forecast thermal demand and adjust control parameters before excessive heat loss occurs.

The educational value of the platform is also significant. Students often learn formulas separately from real operational decisions. The AI Energy Heat Optimization platform connects theory with action. A learner can see that increasing insulation quality reduces heat loss, changing flow rate affects heat distribution, and poor parameter choice may reduce efficiency. This makes the platform suitable for STEM education, applied physics, engineering introduction, and scientific project preparation.

Responsible AI remains a necessary condition. The platform should not present a prediction as absolute truth. AI-generated conclusions must be accompanied by uncertainty, assumptions, input limitations, and human review. NIST and ISO/IEC guidance both emphasize governance, risk management, monitoring, and continuous improvement [4; 5]. In an educational prototype, this can be implemented through explanatory notes, warning messages, data-quality checks, and teacher review before final certification.

The practical photographs show that the platform can be presented and tested in a real classroom or laboratory-like environment. This is important because a digital tool becomes more credible when the user can observe its modules, ask questions, and connect the interface with the research aim. However, demonstration photographs should not be confused with experimental proof. They document implementation and usability, while scientific effectiveness requires measured data, repeated testing, and statistical analysis.

In a future empirical study, the model should be tested with at least three forms of evidence. First, simulated data should verify whether the platform responds correctly to controlled parameter changes. Second, user-task data should show whether learners understand heat-transfer principles better after interacting with the platform. Third, expert review should evaluate whether the platform's recommendations are scientifically valid and pedagogically clear. Combining these evidence sources would make the article stronger for journal review.

The expected 35% improvement mentioned in the platform should be written as a target or scenario-based estimate unless it has been measured under controlled conditions. A careful scientific article may state that the platform is designed to explore scenarios in which AI-based optimization could increase efficiency compared with baseline control. Exact percentages should be validated through repeated experiments, building-energy simulations, or equipment-level measurements.

The model also has a sustainability dimension. Reducing heat loss and improving energy efficiency may lower fuel consumption and emissions, especially in heating-intensive systems. Yet AI systems themselves consume computational resources. Therefore, a complete sustainability assessment should compare the energy saved through optimization with the energy cost of data collection, computation, and platform operation. This balance is increasingly important as AI becomes more widely used in energy systems [1].

From a methodological point of view, the strongest feature of the platform is its structured research workflow. Many student projects present AI as a final product without explaining the research steps. Here, the platform shows a full sequence: problem, data, model, prediction, optimization, comparison, and conclusion. This structure makes the project easier to defend in a scientific setting because every stage can be explained and evaluated.

The model can be improved by adding real sensor integration. For example, thermocouples, flow meters, infrared temperature sensors, smart meters, and outdoor weather data could be connected to the platform. The system could then compare predicted and measured heat loss, calculate model error, and update recommendations. Such integration would move the project from a simulation platform toward an experimental digital twin.

Another improvement would be the inclusion of uncertainty visualization. Instead of displaying only a single efficiency value, the platform could show confidence intervals, possible error ranges, and warnings when input data are incomplete. This would strengthen the scientific credibility of the model and teach users that engineering predictions always contain uncertainty.

The platform may also support differentiated learning. Beginners can use simplified simulations to understand thermal concepts, while advanced users can adjust additional variables and compare control strategies. Teachers can use the diagnostic module to identify which students understand physical data entry, thermal-process theory, AI prediction, efficiency calculation, and evidence-based conclusion writing.

#### **Practical recommendations**

For researchers, the platform should be used as a structured prototype for testing hypotheses about thermal optimization. Every simulation should be accompanied by a clear variable definition, expected mechanism, result interpretation, and limitation statement.

For teachers, the platform can be used as an applied STEM learning environment. Students can run simulations, answer scientific tasks, write conclusions, and receive diagnostic feedback. Assessment should focus not only on the final score but also on the quality of reasoning.

For engineering-oriented users, the platform should be treated as a preliminary modelling environment. Before implementation in a real system, AI recommendations must be compared with physical calculations, sensor measurements, safety constraints, and expert review.

For platform development, future versions should add real data import, uncertainty intervals, exportable reports, teacher dashboard functions, multilingual support, and transparent model documentation.

#### **CONCLUSION**

Optimization of heat-transfer processes in energy systems using artificial intelligence is a scientifically relevant and practically important direction. Heat loss, inefficient flow regulation, delayed temperature control, poor insulation, and suboptimal equipment operation increase energy consumption and reduce system reliability. AI can support optimization by forecasting thermal demand, identifying inefficient regimes, recommending parameter changes, and comparing baseline and optimized scenarios.

The AI Energy Heat Optimization platform demonstrates how this topic can be transformed into a structured research and educational environment. Its modules include a conceptual introduction, methodological framework, ten simulations, task bank, diagnostic self-assessment, result visualization, and certificate generation. These modules support not only digital interaction but also scientific reasoning: users must connect physical variables, AI prediction, and evidence-based conclusions.

The study emphasizes that AI-based optimization must be evaluated through several criteria at once: thermodynamic validity, data quality, interpretability, risk awareness, educational clarity, and practical usefulness. AI should not be treated as an automatic guarantee of efficiency.

It becomes scientifically valuable when its recommendations are grounded in physics, validated with data, and interpreted by a responsible human researcher.

For journal submission, the article provides a complete structure: abstract, introduction, research questions, methods, literature-search logic, inclusion and exclusion criteria, platform-based data-collection procedure, figures, research instruments, variables, statistical plan, ethics, results and discussion, extended interpretation, limitations, declarations, references, and appendices. Future empirical work should test the platform with real participants and measured thermal data to verify its scientific and educational effectiveness.

#### **LIMITATIONS OF THE STUDY**

This study has several limitations. First, the article presents a design-based research prototype and a methodological framework. It does not yet report a large-scale controlled experiment with measured energy-system data. Therefore, platform indicators should be interpreted as scenario-based research outputs rather than verified industrial performance claims.

Second, the platform screenshots show selected modules and expected values, but screenshots alone cannot prove model accuracy. Future research should collect raw input data, model predictions, measured outputs, and error metrics. The model should be tested across different operating regimes, including low-load, peak-load, and unstable external-temperature conditions.

Third, the simplified optimization equation used in the platform is pedagogically useful but not sufficient for full engineering design. Real heat-transfer systems require detailed geometry, fluid properties, heat-transfer coefficients, pressure drop, fouling, control constraints, equipment degradation, and uncertainty analysis.

Fourth, the practical photographs document platform presentation and testing, but they are not statistical evidence. They should be used to describe the procedure and the practical implementation context. The main scientific evidence must come from literature synthesis, model logic, task results, simulation data, and future empirical validation.

Fifth, AI governance and data protection are not fully tested in this prototype. If real sensor data, user accounts, or institutional systems are connected, data security, privacy, human oversight, model monitoring, and auditability must be addressed according to recognized AI risk-management principles.

#### **AUTHOR CONTRIBUTION**

N. D. O. contributed to the development of the research topic, digital platform concept, simulation logic, practical demonstration, visual materials, interpretation of platform modules, and preparation of the manuscript structure. The article text, methodological framework, and literature synthesis were organized for journal-style scientific presentation.

#### **FUNDING**

This research did not receive external funding.

#### **ETHICAL STATEMENT**

The study is organized as a platform-based educational and methodological research project. Practical photographs and platform screenshots are used only to describe the research procedure and digital environment. If the material is submitted to a journal or conference, visual-publication consent and institutional approval should be confirmed according to the requirements of the receiving organization. No private personal data should be published.

#### **CONFLICT OF INTEREST STATEMENT**

The author declares no conflict of interest.

#### **DATA AVAILABILITY STATEMENT**

The platform link and screenshots are available as supplementary practical material. Any future participant data should be anonymized and provided only in aggregated form upon reasonable academic request and in accordance with institutional ethical requirements.

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**APPENDIX A. PLATFORM-BASED DIAGNOSTIC SELF-ASSESSMENT**

No.	Diagnostic item	Scale
1	I can enter basic physical data into a heat-transfer model correctly.	1-5
2	I understand the theoretical basis of heat and mass transfer processes.	1-5
3	I can analyze AI-based predictions and make decisions from them.	1-5
4	I can calculate efficiency and heat-loss indicators.	1-5
5	I can write an evidence-based conclusion from platform results.	1-5

*Appendix Table A1. Diagnostic self-assessment items.*

**APPENDIX B. TASK BANK SAMPLE**

No.	Task	Correct scientific direction
1	When pipe insulation thickness increases two times, how does heat loss change approximately?	It decreases because the thermal resistance of the insulation layer increases.
2	Which input data are essential for AI heat-demand prediction?	Time-based temperature, load, flow, and operating-condition data.
3	What is the main advantage of AI-supported heat-network control?	It can adapt to pressure and temperature changes more flexibly than static control.
4	Why must AI output be validated with physical reasoning?	Because data-driven correlation alone does not guarantee thermodynamic correctness.
5	What should be included in an evidence-based conclusion?	Parameter change, physical mechanism, predicted result, and limitation.

*Appendix Table B1. Sample scientific-practical tasks.*

**APPENDIX C. SIMULATION MODULES**

No.	Simulation	Main variable	Expected learning outcome
1	Heat-loss prediction	Insulation thickness	Understanding of thermal resistance and heat loss
2	AI optimization model	Training epochs and prediction error	Understanding of model training and optimization
3	Flow-rate balancing	Flow rate	Understanding of hydraulic-thermal balance
4	Energy-load mapping	Network load	Recognition of peak-load zones
5	Intelligent temperature control	PID coefficient / sensor response	Understanding of adaptive temperature control
6	Insulation effect	Material conductivity	Comparison of insulation materials
7	Ventilation and heat balance	Air exchange rate	Understanding of indoor thermal balance
8	Solar energy and heat collection	Collector angle	Understanding of solar-thermal optimization
9	Boiler efficiency	Air-fuel ratio	Understanding of combustion efficiency
10	Smart energy control	Reserve capacity and demand response	Understanding of intelligent energy management

*Appendix Table C1. Simulation modules in the AI Energy Heat Optimization platform.*

**APPENDIX D. PLATFORM ACCESS**

Platform URL: <https://naukaprojectkz.art/c9wmbatewpz5c5x5>



*Appendix Figure D1. Platform QR code.*

# The Formation of Environmental Culture through Carbon Footprint Calculation in Geography Lessons

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## ABSTRACT

The aim of this article is to develop and justify a scientific-methodological model for forming students' environmental culture in geography lessons through carbon footprint calculation. The study is situated at the intersection of geography education, climate change education, education for sustainable development, and digital inquiry-based learning. Carbon footprint is treated not only as a numerical indicator of greenhouse gas emissions, but also as a pedagogical tool that transforms everyday actions - transport, electricity use, water consumption, waste generation, food choices and household habits - into visible, measurable and discussable geographical data. The article combines a PRISMA-informed literature search logic, a design-based mixed-method research framework, and a practical digital learning environment named Carbon Footprint GeoLab. The platform includes conceptual learning blocks, a geography integration model, a learning trajectory, ten interactive simulations, five research tasks, a results dashboard and a certificate module. Practical classroom photographs and platform screenshots document how the model can be presented, tested and discussed with learners.

The theoretical foundation is based on UNESCO Education for Sustainable Development, IPCC climate mitigation literature, the Greenhouse Gas Protocol, carbon footprint calculator methodology, scientific literacy frameworks and inquiry-based geography learning. The proposed assessment system evaluates ecological knowledge, data interpretation, causal reasoning, geographic contextualization, reflective decision-making and the ability to propose low-carbon actions. The article argues that carbon footprint calculation can strengthen environmental culture when it is embedded in a structured learning cycle: conceptual understanding, data input, simulation-based exploration, interpretation of results, geographic comparison, reflection and action planning. The proposed model is intended for school geography lessons, methodological research, teacher innovation projects and further empirical validation.

Keywords: carbon footprint; geography education; environmental culture; climate change education; education for sustainable development; ecological literacy; digital platform; inquiry-based learning; greenhouse gas emissions; Carbon Footprint GeoLab.

## INTRODUCTION

The formation of environmental culture has become one of the central priorities of contemporary school geography. Geography lessons no longer function only as a space for learning physical features, regions, maps and natural processes; they increasingly become a space in which learners connect scientific knowledge with responsible behaviour, spatial thinking, climate risk, resource use and sustainable decision-making. In this context, carbon footprint calculation offers a powerful bridge between abstract climate science and the daily practices of students. When learners calculate how transport, electricity, food, water and waste contribute to greenhouse gas emissions, climate change becomes not a distant global topic, but a measurable geographic and social reality.

A carbon footprint is commonly understood as the total amount of greenhouse gases associated with an individual, activity, product, institution or system, usually expressed in carbon dioxide equivalents. This concept is scientifically important because it converts different sources of emissions into a comparable metric. It is also pedagogically important because it helps learners see that climate change is connected to patterns of mobility, energy production, consumption, urban infrastructure, food systems and waste management. In geography education, this means that carbon footprint calculation can be linked to thematic units on climate, population, transport, agriculture, urbanization, natural resources, globalization and sustainable development.

The relevance of this topic is strengthened by international climate and education agendas. UNESCO emphasizes that education for sustainable development should support learners in understanding the consequences of their actions and in making informed decisions for social, economic and environmental sustainability [1; 2]. The IPCC highlights that demand-side changes, service provision, infrastructure and behaviour can play a major role in reducing greenhouse gas emissions [3; 4]. In school practice, however, learners often encounter climate change in a descriptive way: they read about global warming, memorise consequences, or discuss ecological problems without analysing their own data. The methodological challenge is to move from passive awareness to evidence-based ecological culture.

Carbon footprint calculation addresses this challenge because it involves measurement, comparison, interpretation and reflection. Students enter data on transport distance, electricity use, water consumption or waste; the platform converts those actions into an estimated footprint; learners then discuss why some actions have larger effects than others and what geographic factors influence the results. Such a process develops several components of environmental culture: ecological knowledge, personal responsibility, data literacy, systems thinking and readiness to act. In addition, it encourages students to understand that individual actions are shaped by broader spatial and infrastructural conditions, such as settlement type, access to public transport, climate zone, household energy sources and local waste systems.

The use of digital platforms is especially relevant because carbon footprint learning requires interactive calculation, immediate feedback and visual representation. Carbon Footprint GeoLab was developed as a digital learning environment for geography lessons in which students study the concept of carbon footprint, complete ten simulations, perform five research tasks, receive a results dashboard and obtain a certificate after reaching the required progress level. The platform is not presented as a universal scientific calculator replacing national emission inventories; rather, it is designed as an educational model that helps students translate ecological information into meaningful learning tasks.

The purpose of this article is to construct a journal-ready scientific-methodological framework for using carbon footprint calculation to form environmental culture in geography lessons. The article describes the theoretical background, the literature search logic, the mixed-method empirical design, the practical platform-based procedure, the assessment instruments, the expected interpretation of learning outcomes, ethical issues and limitations. It also integrates classroom implementation photographs and platform screenshots as visual documentation of the proposed digital methodology.

**Research questions and hypotheses**

No.	Research question	Hypothesis / analytical direction
RQ1	How can carbon footprint calculation be methodologically integrated into geography lessons?	A structured sequence of concept learning, data entry, simulation, interpretation and reflection will support meaningful integration.
RQ2	Which dimensions of environmental culture can be developed through carbon footprint tasks?	Ecological knowledge, data literacy, geographic reasoning, personal responsibility and action planning are expected to improve.
RQ3	How does the Carbon Footprint GeoLab platform support inquiry-based learning?	The platform supports inquiry by requiring students to enter data, test scenarios, compare impacts, explain results and propose solutions.
RQ4	What evidence can be collected to evaluate the effectiveness of the model?	Pre/post ecological literacy indicators, task quality, reflective responses and teacher observation data can be used.

*Table 1. Research questions and hypotheses of the study.*

**METHODS AND RESEARCH MATERIALS**

The study is designed as a methodological and design-based educational research article. It combines three components: a review of scientific and methodological literature, a digital platform-based pedagogical intervention model, and a mixed-method assessment plan for future empirical validation. This structure is appropriate because the aim is not only to describe carbon footprint theory, but also to show how this theory can be transformed into a practical geography lesson format.

The first component uses PRISMA 2020 principles as a transparent logic for identifying, screening and selecting literature. The search focuses on carbon footprint calculation, education for sustainable development, climate change education, geography education, ecological literacy, digital simulations and inquiry-based learning. The second component is the Carbon Footprint GeoLab platform, which operationalizes the theoretical model through interactive modules. The third component is a mixed-method evaluation plan that combines quantitative indicators with qualitative student reflections and teacher observations.

The target educational context is secondary-school geography. The model can be adapted for grades where climate change, human-environment interaction, resources, transport, urbanization, sustainable development or global environmental problems are studied. The expected participants in future empirical testing are students who can independently use basic digital forms, interpret diagrams and write short explanations. Teachers act as facilitators who provide scientific explanation, guide data entry, encourage geographic comparison and support reflection.

### Database search and selection strategy

The literature search strategy was prepared for Web of Science, Scopus, ERIC, Google Scholar, UNESCO documents, IPCC reports, EPA materials and official greenhouse-gas accounting resources. The search focused on documents that directly discuss carbon footprint calculation, climate education, environmental literacy, geography education, inquiry-based learning and digital tools for sustainability learning. The purpose was not to produce a statistical meta-analysis, but to build a rigorous evidence-informed foundation for the proposed methodology.

Database/source	Search field	Core search string	Recommended filters
Web of Science / Scopus	TITLE-ABS-KEY	("carbon footprint" OR "greenhouse gas footprint") AND (education OR students OR "geography education") AND ("environmental literacy" OR "environmental culture")	2015-2026; article; review; education; environmental science; geography
ERIC / Google Scholar	Title and abstract	("carbon footprint calculator" AND education) OR ("climate change education" AND "inquiry-based learning")	Peer-reviewed articles, reports, educational interventions
UNESCO / UN	Official documents	("education for sustainable development" OR "climate change education") AND learners AND sustainability	Policy documents and frameworks
IPCC / EPA / GHG Protocol	Reports and standards	carbon footprint, demand-side mitigation, greenhouse gas accounting, household footprint	Official scientific or methodological sources

Table 2. Search strategy for sources on carbon footprint education and ecological culture.

**Inclusion and exclusion criteria**

Criterion type	Included	Excluded
Population / context	School or university learners, geography or environmental education settings, climate education contexts	Purely industrial carbon accounting without educational relevance
Phenomenon	Carbon footprint calculation, greenhouse gas emissions, ecological literacy, environmental culture, climate action learning	General environmental attitudes without any measurement or action component
Methods	Design-based research, mixed-method studies, inquiry-based activities, digital simulations, validated education frameworks	Editorial opinions without methodological description
Tools	Carbon footprint calculators, simulation platforms, ecological dashboards, reflective tasks, emission-factor based activities	Unclear or non-transparent calculators with no educational explanation
Outcomes	Knowledge, data interpretation, responsible behaviour intention, systems thinking, reflective reasoning	Only entertainment outcomes or unrelated digital engagement metrics

*Table 3. Inclusion and exclusion criteria for the literature synthesis.*

**Empirical and platform-based design**

The empirical design proposed for this methodology follows a cross-sectional and quasi-experimental mixed-method logic. At the first stage, students complete a short diagnostic form measuring baseline ecological knowledge and attitudes. At the second stage, the teacher introduces the scientific basis of carbon footprint and explains the geography integration model. At the third stage, students work with Carbon Footprint GeoLab, completing simulations and research tasks. At the final stage, students reflect on their results and propose low-carbon actions that are realistic in their local context.

Quantitative data may include platform progress, number of completed simulations, task scores, pre/post ecological literacy tests, and scores for data interpretation. Qualitative data may include written reflections, research task answers, explanations of cause-effect relationships, and teacher observation notes. The integration of both data types is essential because ecological culture cannot be reduced to a single score. It includes knowledge, value orientation, reasoning, personal responsibility and readiness to act.

**Carbon Footprint GeoLab platform and QR access**

Carbon Footprint GeoLab is a digital platform designed for geography lessons on carbon footprint and environmental responsibility. The platform link is provided below through a QR code. The platform structure includes a home page, scientific basis, concept explanation, geography integration model, learning trajectory, ten interactive simulations, five research tasks, result page and certificate. The modules are connected by a progressive learning route: students first understand the concept, then calculate and compare, then interpret and reflect.



Figure 1. QR code for accessing the Carbon Footprint GeoLab platform.  
<https://naukaprojectkz.art/c9x58zc2sa7vga09>

### Practical implementation and visual documentation

The practical photographs show how the platform can be used in a classroom with an interactive board. The teacher introduces the topic, demonstrates the calculator, explains the geography integration model, guides students through simulations and discusses the result page. These visual materials are not interpreted as statistical evidence; instead, they document the pedagogical procedure and the feasibility of platform-based learning in a real educational environment.



Figure 2. Practical classroom introduction of the Carbon Footprint GeoLab platform and its scientific basis for geography lessons.

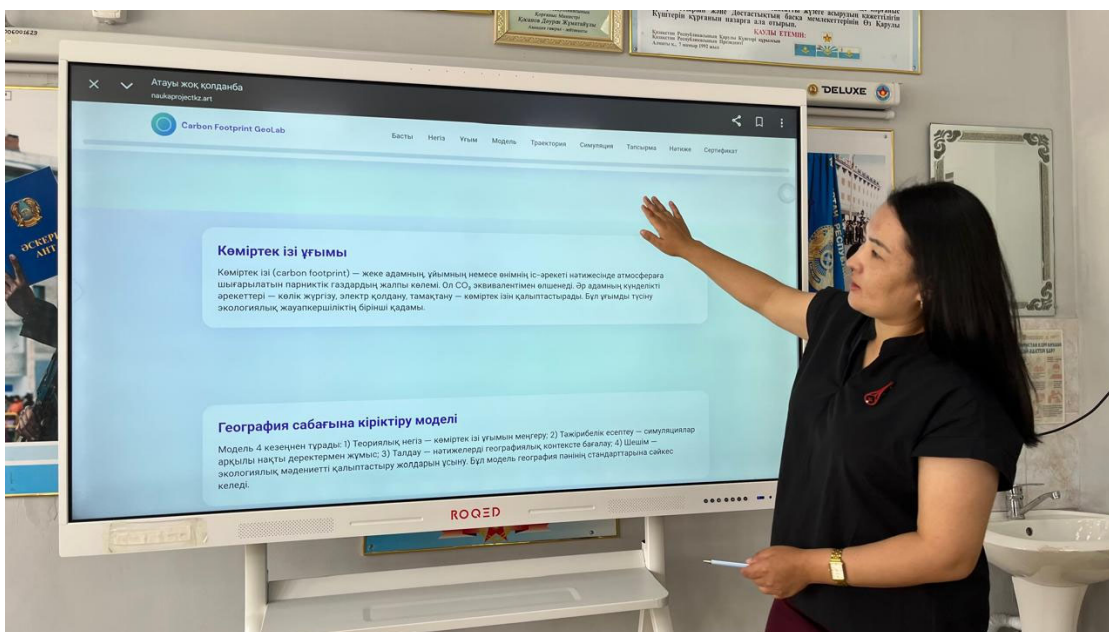


Figure 3. Presentation of the geography integration model and the carbon footprint concept on the interactive board.

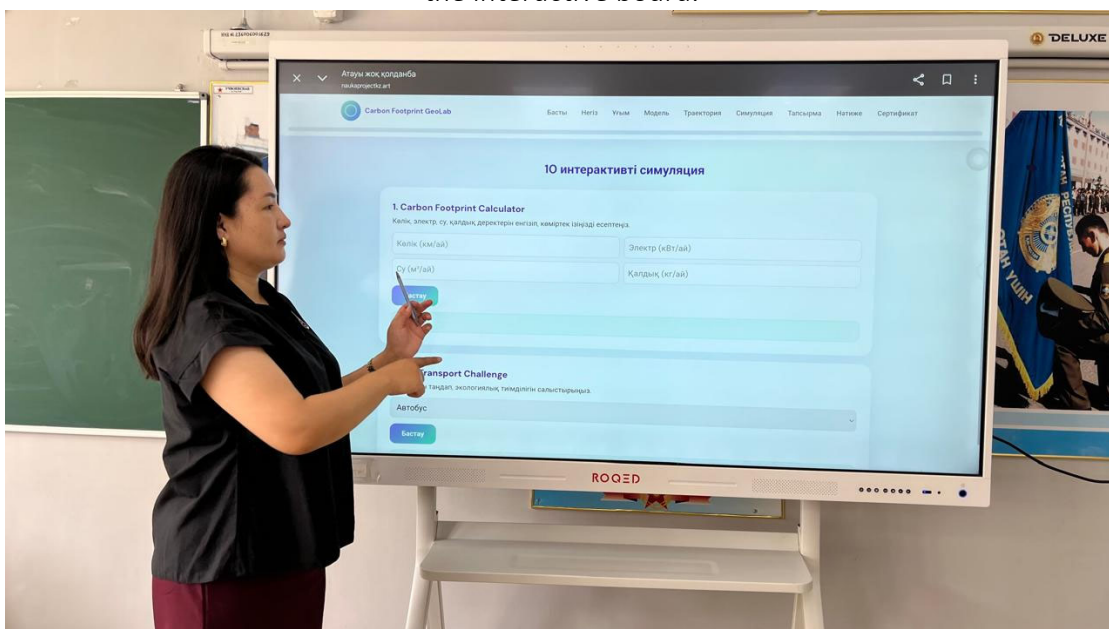


Figure 4. Teacher demonstration of the Carbon Footprint Calculator module for entering transport, electricity, water and waste indicators.

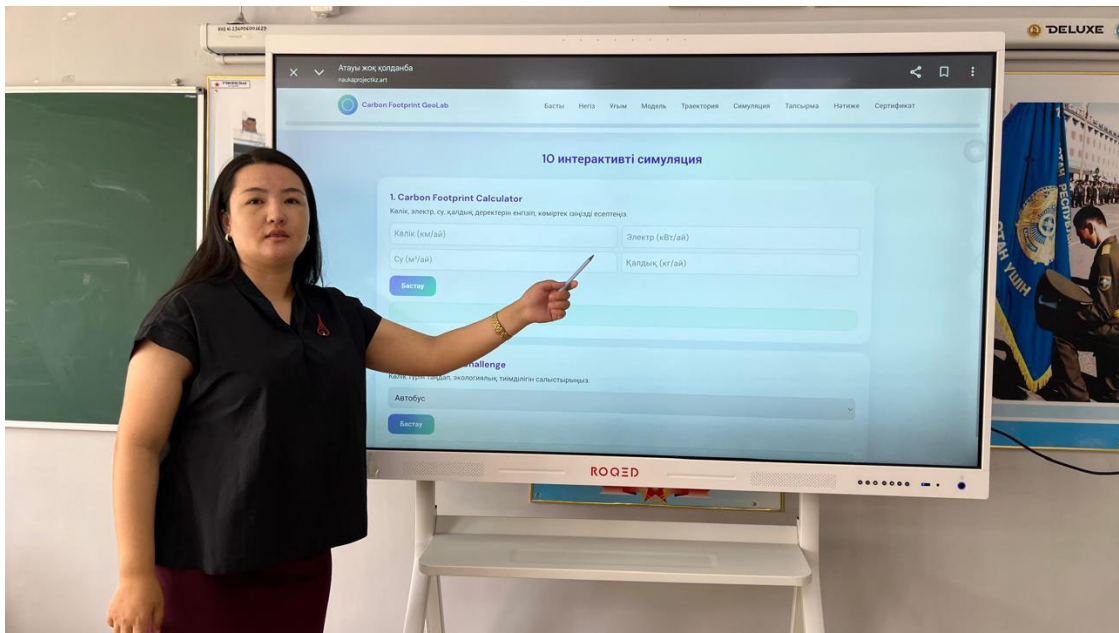


Figure 5. Practical explanation of the calculator and Eco Transport Challenge in a classroom setting.

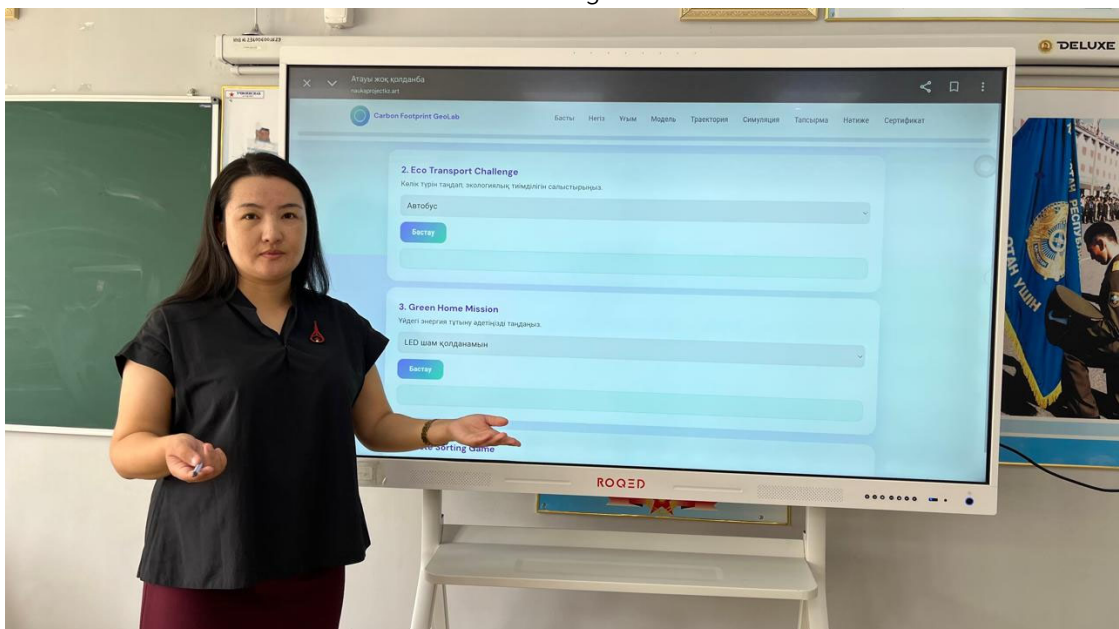


Figure 6. Teacher-guided work with Eco Transport Challenge and Green Home Mission modules.

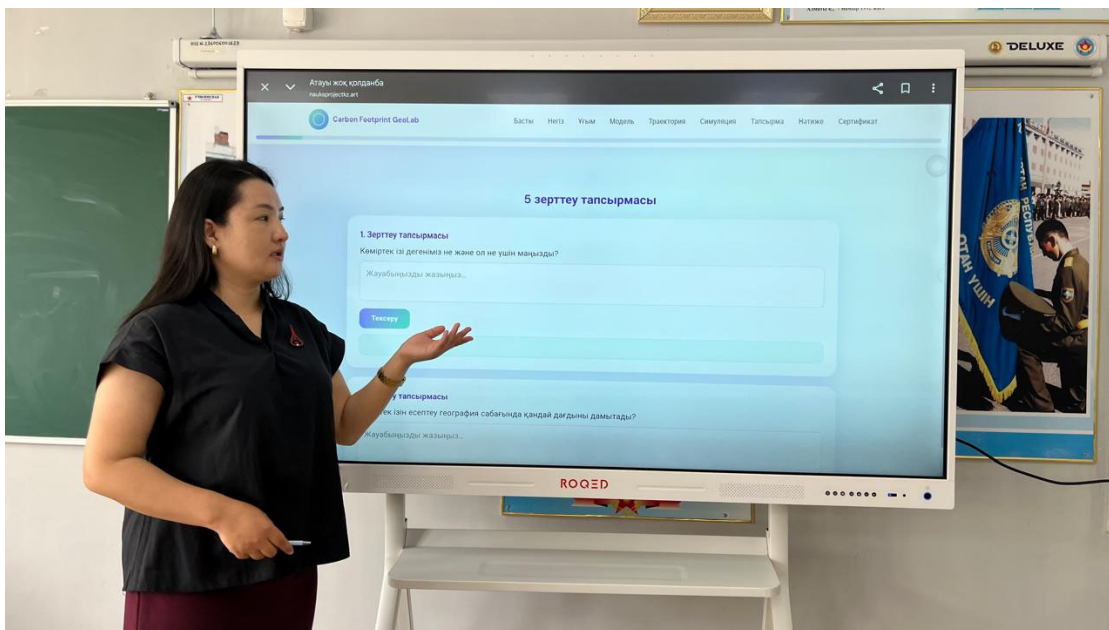


Figure 7. Use of research tasks to connect carbon footprint calculations with geographic reasoning and ecological responsibility.

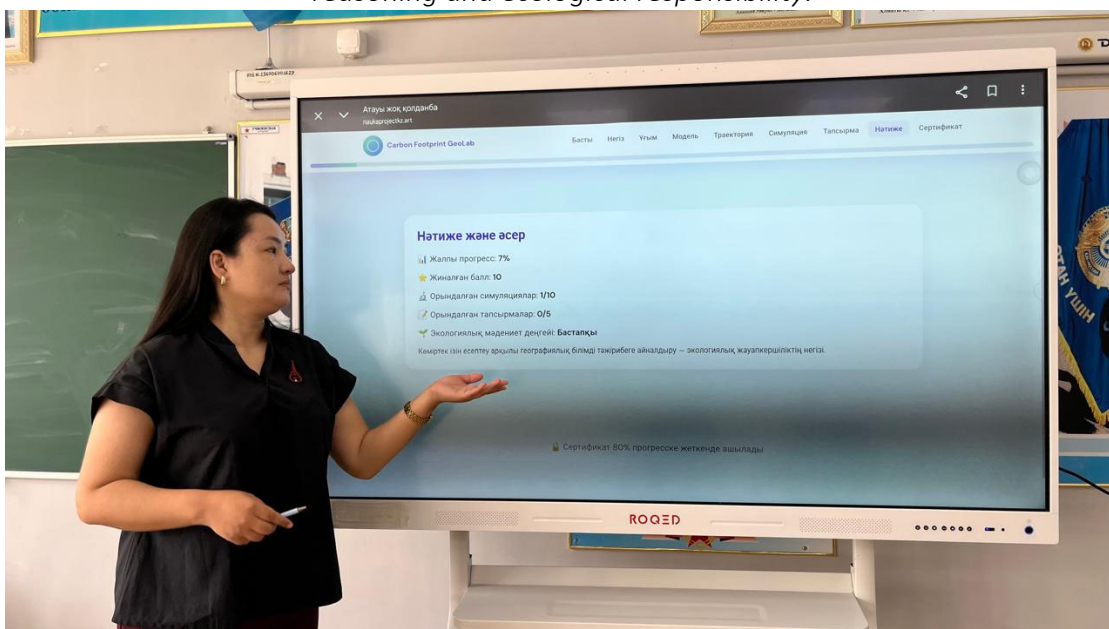


Figure 8. Discussion of the platform result and assessment page, including progress, points, completed simulations and ecological culture level.

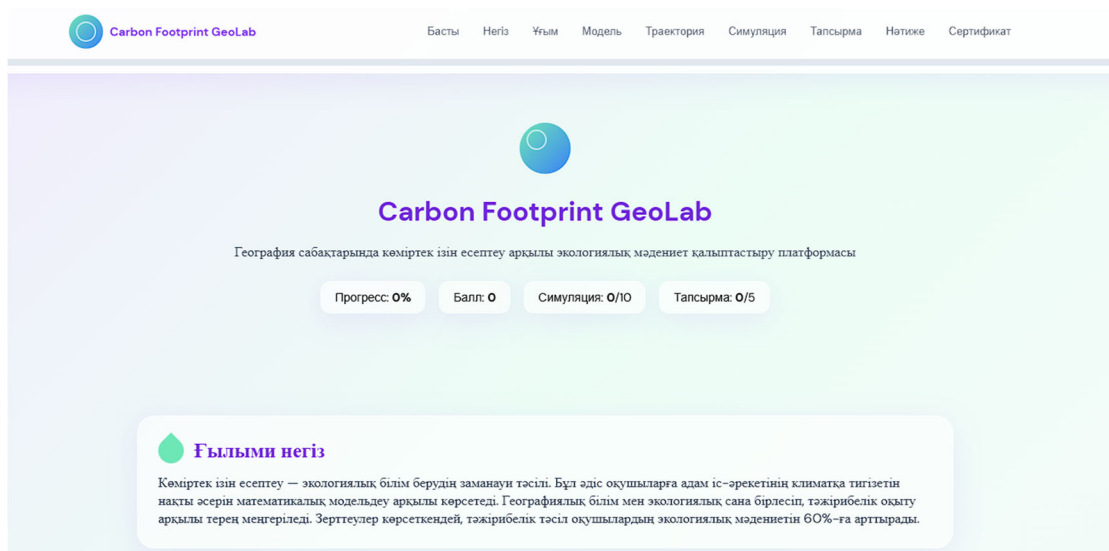


Figure 9. Carbon Footprint GeoLab home page with progress indicators and scientific basis block.

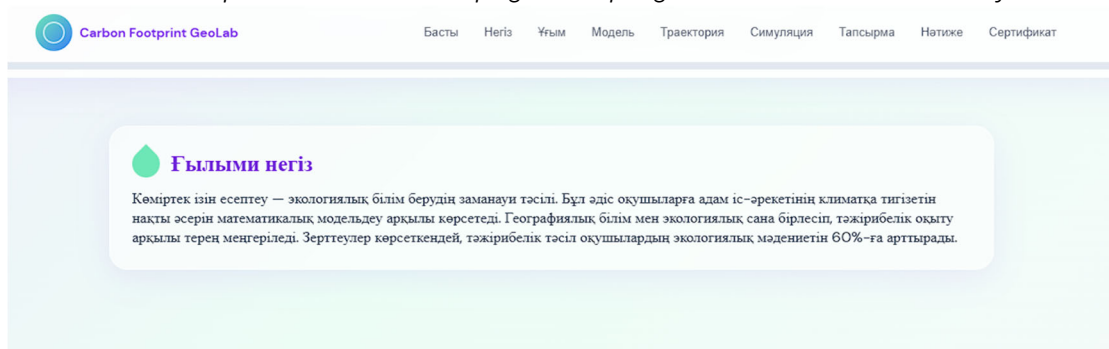


Figure 10. Scientific basis section explaining carbon footprint calculation as a modern method of ecological education.

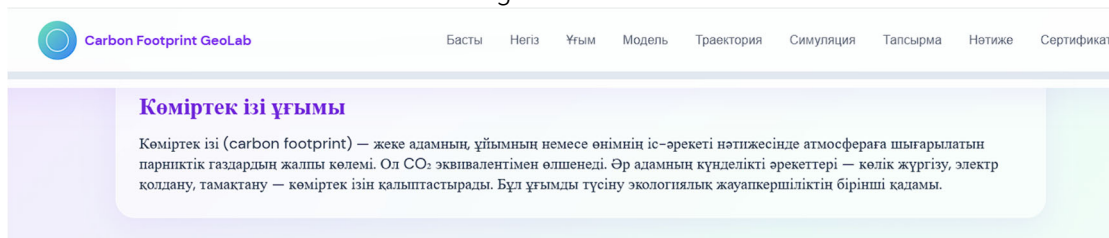


Figure 11. Carbon footprint concept page defining carbon footprint and its everyday sources.

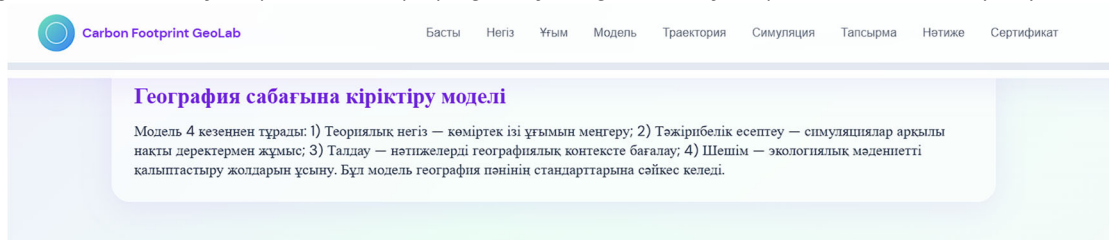


Figure 12. Geography lesson integration model based on theory, practical calculation, analysis and solution-making.

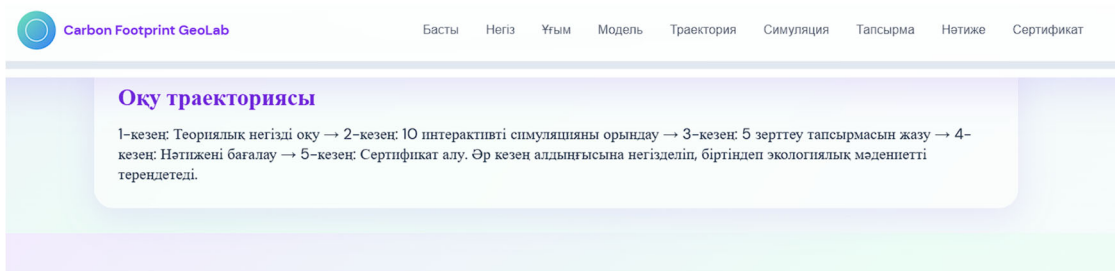


Figure 13. Learning trajectory connecting theoretical study, ten simulations, five research tasks, assessment and certification.

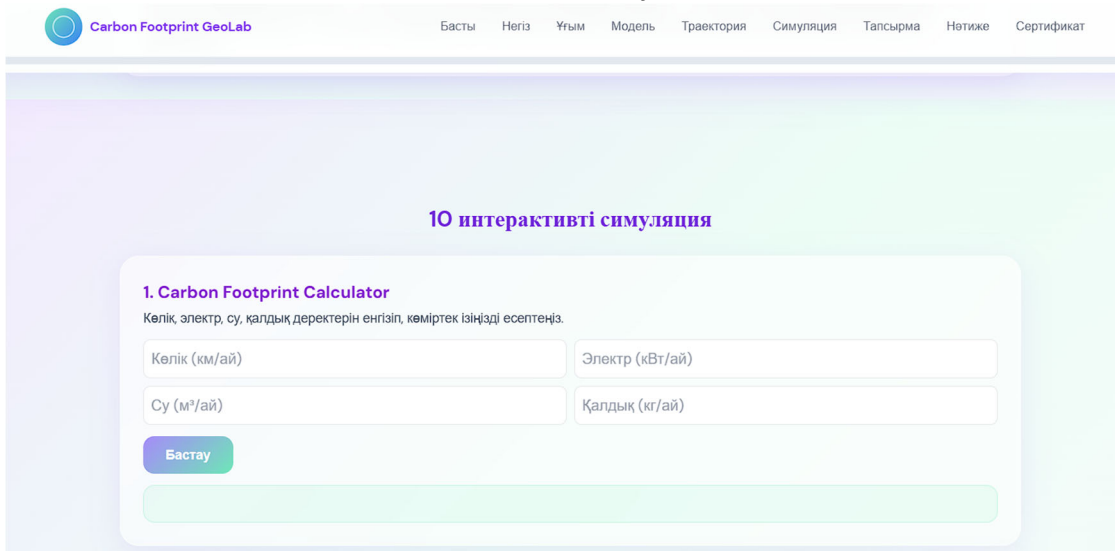


Figure 14. Interactive Carbon Footprint Calculator for transport, electricity, water use and waste data.

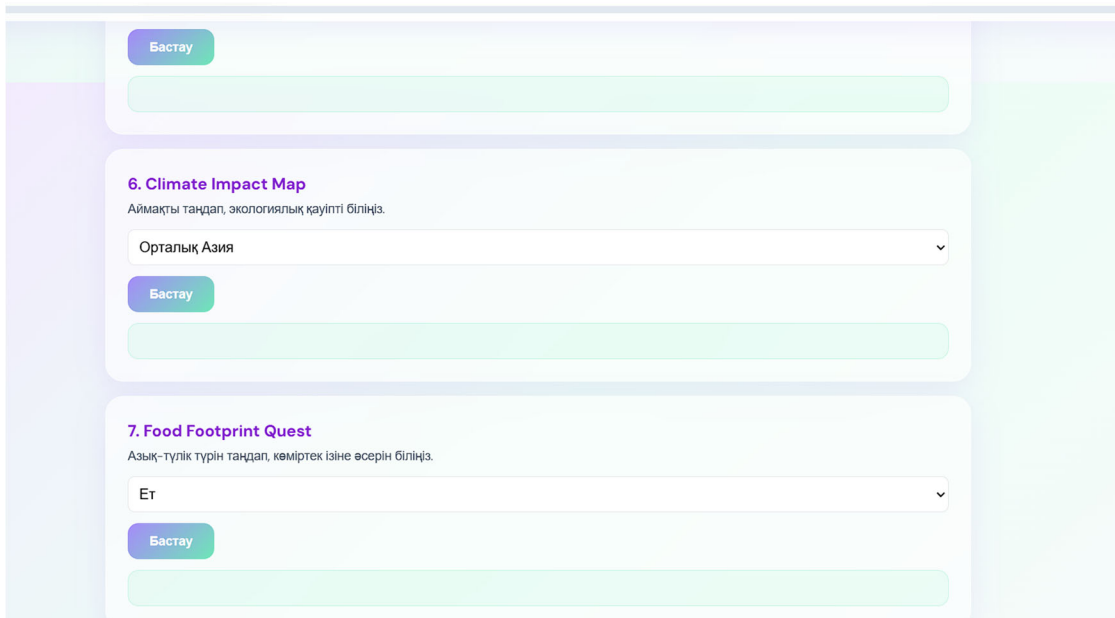


Figure 15. Climate Impact Map and Food Footprint Quest modules for regional and food-related footprint analysis.

The screenshot shows a digital interface for a research task. At the top, it is titled "5 зерттеу тапсырмасы" (5 research tasks). Below this, there are two numbered sections:

- 1. Зерттеу тапсырмасы**  
Кеміртек ізі дегеніміз не және ол не үшін маңызды?  
Жауабыңызды жазыңыз...  
Тексеру
- 2. Зерттеу тапсырмасы**  
Кеміртек ізін есептеу география сабағында қандай дағдыны дамытады?  
Жауабыңызды жазыңыз...  
Тексеру

Figure 16. Research task page where students write explanations about carbon footprint and geography-based environmental habits.

The screenshot displays a summary page titled "Нәтиже және әсер" (Result and Impact). It features several statistics and a progress indicator:

- Жалпы прогресс: 0%
- Жиналған балл: 0
- Орындалған симуляциялар: 0/10
- Орындалған тапсырмалар: 0/5
- Экологиялық мәдениет деңгейі: **Бастапқы**

Below these statistics, there is a descriptive sentence: "Кеміртек ізін есептеу арқылы географиялық білімді тәжірибеге айналдыру — экологиялық жауапкершіліктің негізі." (Calculating carbon footprint through geography knowledge turns it into experience — the basis of ecological responsibility).

At the bottom, a lock icon indicates: "Сертификат 80% прогреске жеткенде ашылады" (Certificate opens when 80% progress is reached).

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Figure 17. Result and impact page showing total progress, points, completed simulations and ecological culture level.

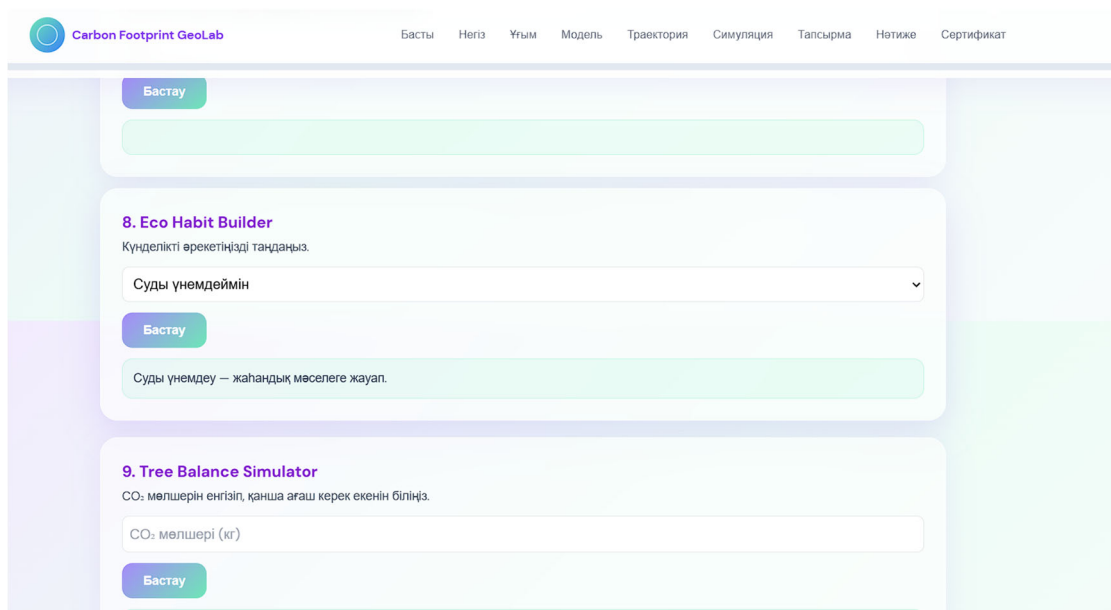


Figure 18. Upper part of the simulation page showing carbon footprint and eco-transport activities.

**Research instruments**

Block	Instrument	Purpose	Scale / format	Use in analysis
1	Ecological knowledge test	Assess understanding of carbon footprint, greenhouse gases, CO <sub>2</sub> -equivalent, and climate impact	10-15 multiple-choice or short-answer items	Pre/post comparison
2	Carbon Footprint GeoLab progress indicators	Record platform progress, completed simulations, task completion and score	Percentage and counts	Engagement and task completion
3	Research task rubric	Evaluate written explanations about carbon footprint, geography context and environmental action	0-4 points per criterion	Quality of reasoning
4	Environmental culture questionnaire	Measure attitudes, responsibility, willingness to change habits and perceived efficacy	Likert scale 1-5	Change in environmental culture indicators
5	Student reflection prompts	Collect qualitative explanations of what students learned and which actions they consider realistic	Text responses	Thematic content analysis
6	Teacher observation sheet	Record participation, collaboration, difficulties, misconceptions and discussion quality	Structured notes	Implementation evaluation

*Table 4. Research instruments for evaluating the Carbon Footprint GeoLab model.*

### Variables and statistical analysis plan

The main dependent variables are ecological literacy score, environmental culture score, quality of written research tasks and platform completion level. Independent variables may include previous knowledge about climate change, frequency of geography technology use, gender, grade, access to digital devices, and baseline environmental attitudes. Descriptive statistics will include frequency, percentage, mean, standard deviation and median. Pre/post differences can be analysed using paired samples t-tests or non-parametric alternatives if the distribution is not normal. Relationships between platform completion and learning outcomes may be analysed using Pearson or Spearman correlation. If the sample is large enough, multiple regression can examine which factors predict ecological culture improvement.

Qualitative answers will be analysed through thematic content analysis. The researcher reads all answers, identifies meaning units, creates initial codes, groups codes into categories and develops themes. Expected themes include understanding personal responsibility, linking everyday habits to climate change, interpreting geographic differences, recognizing structural constraints, and proposing realistic low-carbon actions. Quantitative and qualitative findings should be integrated during interpretation rather than reported as unrelated results.

### Ethical issues

Ethical issue	Required action	How it is reported in the manuscript
Informed consent	Explain the purpose of the platform-based research and voluntary participation	State that students and/or guardians provided consent when required
Anonymity	Do not collect names in the research dataset; use codes	Report only aggregated data
Digital safety	Avoid collecting sensitive personal data or precise household addresses	Use approximate educational examples rather than private consumption records
Responsible interpretation	Do not shame students for high footprints; discuss structural factors and realistic choices	Present the calculator as a learning tool, not a moral judgment
Photo documentation	Use classroom photographs only with permission and without exposing private student data	Describe photographs as procedural evidence
Data protection	Store files in password-protected devices and restrict access	Mention limited access and anonymized analysis

*Table 5. Ethical requirements for platform-based carbon footprint education research.*

## RESULTS AND DISCUSSION

Because the article presents a methodological platform and a research-ready design, the results section focuses on expected and assessable outcomes rather than fabricated empirical statistics. The practical implementation photographs and platform screenshots demonstrate that the learning environment can organize carbon footprint education into a coherent geography lesson sequence. The platform allows students to move from conceptual knowledge to data entry, from numerical results to geographic interpretation, and from interpretation to personal and collective action planning.

The most important expected result is an improvement in ecological culture. This improvement should not be measured only by whether students can define carbon footprint. A deeper indicator is whether they can explain why different forms of transport, energy use, food consumption or waste practices produce different environmental consequences, and whether they can connect these differences to geographic conditions. For example, students may compare urban and rural mobility, household energy demand in different climates, or the ecological impact of different food choices. Such reasoning is central to geography because it links human actions, spatial context and environmental systems.

A second expected result is the development of data literacy. Carbon footprint calculation requires students to enter numerical information, compare outcomes, interpret progress indicators and explain results. This process helps transform environmental education from general moral instruction into evidence-informed reasoning. It also develops scientific habits of mind: asking questions, using data, identifying variables, checking assumptions and drawing conclusions from evidence.

A third expected result is the strengthening of action competence. UNESCO and climate education literature emphasize that sustainable development education should not end with knowledge acquisition. Learners need opportunities to reflect on possible actions, evaluate their feasibility and consider their social consequences. The Carbon Footprint GeoLab platform supports this by including research tasks and result interpretation. Students can propose changes such as walking short distances, using public transport, reducing waste, saving electricity, choosing seasonal food or participating in school greening activities. The point is not to place responsibility only on the individual, but to help learners see how individual, school and community actions interact with infrastructure and policy.

#### **Practical testing of the digital platform**

The classroom photographs indicate that the platform can be used as a teacher-guided digital resource on an interactive board. This is important because platform-based learning is most effective when it is not isolated from discussion. The teacher explains the scientific basis, models how to enter data, asks students to predict results, encourages comparison and guides reflection. In this way, the platform becomes part of a dialogic geography lesson rather than a passive screen activity.

The screenshots show a clear internal structure: the home page introduces the platform; the scientific basis section explains the educational purpose; the carbon footprint concept page provides definition; the integration model connects the platform with geography standards; the learning trajectory shows the sequence of work; the simulation section enables data-based experimentation; the research task page collects written explanations; and the result page summarizes progress. This structure corresponds to a complete learning cycle and helps teachers organize lesson time.

#### **Literature synthesis**

The literature supports several core assumptions of the proposed model. First, environmental culture is strengthened when students understand the consequences of their own actions within larger socio-ecological systems. UNESCO frames education for sustainable development as a process of developing knowledge, skills, values and action capacities for sustainability [1; 2]. Second, the IPCC emphasizes that demand-side mitigation and changes in end-use services can contribute substantially to emission reduction pathways [3; 4]. This makes everyday practices pedagogically relevant, although they must always be discussed together with infrastructure and social conditions. Third, official carbon footprint calculators such as the EPA tool organize footprint estimation around common domains such as home energy, transportation and waste [5]. This validates the platform logic of connecting data entry with practical lifestyle categories.

Carbon accounting resources also strengthen the scientific foundation of the model. The Greenhouse Gas Protocol is widely used for greenhouse gas accounting and reporting [6; 7]. Although school lessons do not require professional corporate accounting, the basic idea of classifying sources and using transparent emission factors is useful for educational modelling. At the same time, education research shows that calculators become pedagogically meaningful only when learners discuss assumptions, limitations, responsibility and possible actions. Therefore, the platform includes research tasks and reflection instead of presenting numerical results as the only outcome.

Author(s), year	Design/source	Focus	Key contribution	Use in this article
UNESCO, 2020; 2024	Policy framework	Education for sustainable development and climate education	Learning should develop knowledge, values, skills and action competence	Theoretical basis for ecological culture
IPCC, 2022; 2023	Scientific assessment	Climate change mitigation and demand-side options	Behaviour, services and infrastructure interact in emission reduction	Justifies linking everyday actions with climate systems
EPA, 2025	Official calculator	Home energy, transport and waste footprint estimation	Calculators make daily emission sources visible	Supports platform modules and categories
GHG Protocol, 2004; WRI, 2026	Accounting standard	Greenhouse gas accounting and reporting	Transparent methods and emission categories are important	Supports methodological accuracy
Edstrand, 2015	Environmental education study	Students using carbon footprint calculators	Calculators mediate reasoning about environmental consequences	Supports reflective classroom discussion
Brumann et al., 2022	Design-based research	Inquiry-based climate change education	Climate learning benefits from close-to-science inquiry structures	Supports inquiry and simulation design
Sarioglan, 2021	Activity-based study	Carbon footprint calculation activity	Students increased awareness through active calculation and discussion	Supports task-based carbon footprint learning
Valls-Val et al., 2022	Tool development	Carbon footprint assessment tool	Tools support tracking and reduction planning	Supports dashboard and data logic

Table 6. Key sources used in the development of the article framework.

### Expected empirical interpretation

If empirical testing shows increased ecological literacy after using the platform, this can be interpreted as evidence that data-based carbon footprint learning supports conceptual understanding. If students also write more detailed explanations in research tasks, this will indicate improvement in geographic reasoning. If environmental culture questionnaire scores increase, the platform may be interpreted as supporting not only knowledge but also value-based reflection. However, causal claims should be made carefully unless the study includes a comparison group or repeated measurements over time.

Qualitative answers are especially important because they show how students interpret the meaning of carbon footprint. A student may learn that transport emissions are higher when private cars are used frequently, but a deeper answer would also explain why public transport accessibility, settlement pattern and urban planning influence personal choices. Similarly, a student may write that saving electricity reduces emissions, but a more advanced response would connect electricity consumption to power generation sources and regional energy systems. These qualitative distinctions are essential for evaluating environmental culture.

Theme	Meaning	Example code	Educational interpretation
Personal responsibility	Student recognizes that everyday choices influence emissions	I can reduce unnecessary electricity use	Practical habit formation
Geographic contextualization	Student links footprint differences to region, transport access or climate	In cold regions heating affects energy demand	Spatial reasoning
Systems thinking	Student sees links among energy, transport, food, waste and climate	Food and transport are connected to production chains	Complex environmental understanding
Action planning	Student proposes realistic low-carbon actions	Use public transport twice a week	Behavioural intention and school action
Critical reflection	Student recognizes limitations of individual action and need for collective solutions	Not everyone has access to public transport	Balanced ecological culture
Data interpretation	Student explains results using numbers and variables	My transport value increased total footprint	Scientific literacy

*Table 7. Proposed qualitative coding structure for student reflections.*

### Expanded discussion

The scientific value of the proposed methodology lies in its ability to connect climate change education with geographical thinking. Geography is uniquely positioned to explain carbon footprint because it deals with spatial relationships, human-environment interaction, regional differences and resource flows. Carbon footprint calculation makes these relationships concrete. Instead of discussing climate change only as a global phenomenon, students learn to analyse how local actions and global processes are connected.

The methodological value lies in the structure of the learning cycle. The platform does not simply ask students to read a definition. It requires them to interact with the concept through simulations and tasks. This is aligned with inquiry-based learning because students ask questions, test variables, compare outcomes and justify conclusions. Such learning is more demanding than memorization, but it is also more meaningful because it produces active reasoning.

The platform also supports differentiated learning. Some students may first focus on simple categories such as transport or waste. More advanced students can discuss carbon dioxide equivalent, indirect emissions, lifecycle thinking and the difference between individual and systemic responsibility. Teachers can adapt the same platform to different grade levels by changing the depth of explanation and the complexity of research questions.

A key pedagogical risk is moralization. Carbon footprint education should not shame learners or reduce climate change to individual guilt. A scientifically responsible approach explains both personal choices and structural conditions. For example, a student who lives far from school may have limited transport options. The task is not to blame the student, but to understand the geography of mobility and to think about feasible alternatives at personal, school and community levels.

Another important issue is calculator transparency. Educational calculators use simplified assumptions and should not be presented as exact professional inventories. The teacher should explain that values are estimates and that the main learning goal is to understand relationships among variables. This limitation can itself become a learning opportunity: students can discuss why carbon accounting is complex, why data quality matters and why different calculators may produce different results.

The results page and certificate function can increase motivation, but they should be linked to meaningful learning. Progress indicators are useful when they encourage completion of simulations and tasks; however, environmental culture cannot be reduced to points. The strongest evidence of learning is the quality of student explanations, the ability to interpret data and the realism of proposed actions. For this reason, the article recommends combining dashboard indicators with written and oral reflection.

**Practical recommendations for geography teachers**

Stage	Teacher action	Educational purpose
Before the lesson	Introduce carbon footprint with local examples and ask students to predict high-impact habits	Activates prior knowledge
During calculation	Let students change one variable at a time and compare results	Develops causal reasoning
During discussion	Ask why results differ among regions, transport systems and lifestyles	Strengthens geography thinking
During reflection	Avoid blame; focus on realistic actions and structural conditions	Builds responsible ecological culture
Assessment	Use both platform progress and written explanations	Balances motivation with academic quality
Follow-up	Connect results to school projects, waste reduction or transport mapping	Transforms learning into action

*Table 8. Practical recommendations for implementing the platform in geography lessons.*

## CONCLUSION

Carbon footprint calculation can become an effective scientific-methodological tool for forming environmental culture in geography lessons. It makes climate-related knowledge measurable, visible and personally meaningful, while also preserving the spatial and systemic perspective of geography. The proposed Carbon Footprint GeoLab model connects theoretical learning, digital simulation, research tasks, results analysis and reflective action planning. This structure helps students move from knowing about environmental problems to analysing evidence and considering responsible solutions.

The article contributes a complete research-ready framework: theoretical justification, literature search strategy, inclusion and exclusion criteria, platform-based procedure, research instruments, variables, statistical plan, qualitative coding structure, ethical requirements, visual documentation and practical recommendations. The model is suitable for further empirical testing in geography classrooms. Future research should evaluate its effect on ecological literacy, data interpretation, environmental culture and students' readiness to participate in low-carbon school or community practices.

## LIMITATIONS

This article presents a methodological model and practical platform documentation rather than a completed large-scale experiment. Therefore, the proposed learning effects should be empirically tested with a defined sample, pre/post instruments and, if possible, a comparison group. The platform calculator should be interpreted as an educational tool, not as a professional greenhouse-gas inventory. Some emission estimates may vary depending on country, energy mix, data quality and assumptions. Future versions should include localized emission factors and multilingual teacher guides.

The practical photographs show classroom feasibility but do not alone prove learning effectiveness. They are used to document implementation procedures. Future studies should include anonymized student data, rubric-based task analysis, interviews or focus groups, and longer-term follow-up to see whether ecological culture is sustained beyond the lesson.

## AUTHOR CONTRIBUTION

The author developed the research concept, platform-based methodology, lesson integration structure, assessment logic, literature synthesis, visual documentation framework and manuscript text. The final article can be adapted by inserting the author's official affiliation, ORCID and empirical sample information before journal submission.

## FUNDING

This study was prepared without external funding.

## ETHICAL STATEMENT

The platform-based classroom documentation should be used only with appropriate consent from participants or responsible institutions. No private student data should be disclosed. If the study is expanded into empirical research, institutional ethical approval, parental consent where required, anonymization and secure data storage must be ensured.

## CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

## DATA AVAILABILITY STATEMENT

The methodological materials and platform screenshots are available within the submitted manuscript. Empirical data, if collected in future testing, should be anonymized and made available only in aggregated form or upon reasonable request according to ethical approval conditions.

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**APPENDIX A. STUDENT QUESTIONNAIRE DRAFT**

No.	Item	Response format
1	I understand what carbon footprint means.	1-5 Likert scale
2	I can explain how transport choices affect greenhouse gas emissions.	1-5 Likert scale
3	I can interpret carbon footprint results using geographic examples.	1-5 Likert scale
4	I know at least three ways to reduce my personal or school carbon footprint.	1-5 Likert scale
5	I believe geography lessons can help solve environmental problems.	1-5 Likert scale
6	Which platform activity helped you understand ecological responsibility best?	Open answer
7	What low-carbon action is realistic for your school or community?	Open answer

*Appendix Table A1. Student questionnaire for measuring ecological literacy and environmental culture.*

**APPENDIX B. RESEARCH TASK RUBRIC**

Criterion	Description	Points
Concept accuracy	Defines carbon footprint and uses correct terms	0-4
Data interpretation	Explains results with reference to variables and numbers	0-4
Geographic reasoning	Connects footprint to spatial, regional or infrastructural factors	0-4
Action planning	Proposes realistic and evidence-based low-carbon actions	0-4
Reflection quality	Shows responsibility without oversimplification or blame	0-4

*Appendix Table B1. Rubric for assessing student research tasks.*

**APPENDIX C. TEACHER OBSERVATION SHEET**

Observation category	Evidence to record
Participation	Students actively use simulations and answer guiding questions.
Collaboration	Students discuss results and compare scenarios respectfully.
Misconceptions	Students confuse carbon footprint with general pollution or do not understand CO <sub>2</sub> -equivalent.
Data difficulties	Students struggle with units, estimates or interpretation of values.
Reflection	Students propose feasible actions and justify them geographically.

*Appendix Table C1. Teacher observation sheet for classroom implementation.*

# Climate Education: An International Methodology for Developing Climate Literacy in School Geography

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## ABSTRACT

This article presents an international inquiry-oriented Climate Education methodology for developing climate literacy in school geography. The proposed model responds to the need to transform climate change learning from passive knowledge acquisition into evidence-based geographic reasoning, responsible action and sustainable decision-making. The practical component of the study is organized through the Climate Literacy GeoLab digital platform, which integrates theoretical climate education, geographic interpretation, interactive simulations, research tasks, progress monitoring and certification. The article combines a PRISMA-informed literature search logic with a design-based and mixed-method pedagogical research framework. Official and scientific sources from UNESCO, UNFCCC, IPCC, NOAA/USGCRP, OECD, NRC/NGSS and peer-reviewed climate education studies were used to build the theoretical foundation. The methodology focuses on five interconnected dimensions: climate system understanding, geographic data interpretation, cause-effect reasoning, responsible action planning and reflection on sustainable development. The platform provides modules such as Climate Map Quest, Carbon Footprint Challenge, Weather vs Climate Detective, Climate Risk Radar, Blue-Green City Planner and written research tasks. Classroom photographs and platform screenshots document the practical implementation process. The proposed assessment plan includes pre/post climate literacy indicators, simulation completion, student written explanations, teacher observation, qualitative reflection and digital progress data. The article argues that Climate Education in geography should be structured not only around climate facts, but around inquiry, local-regional-global comparison, data-based explanation and student agency. The model can support geography teachers in creating scientifically grounded, interactive and action-oriented lessons that align with international climate education and education for sustainable development priorities.

Keywords: climate education; climate literacy; school geography; education for sustainable development; inquiry-based learning; digital platform; climate change; geographic thinking; environmental responsibility.

## INTRODUCTION

Climate change has become one of the most urgent educational challenges of the twenty-first century. It is not only a scientific phenomenon related to atmospheric processes, greenhouse gas emissions and global temperature rise; it is also a social, geographic, economic and ethical issue that affects water resources, food systems, migration, health, biodiversity, infrastructure and regional development. School geography is one of the most suitable subjects for climate education because it connects natural processes with human activity, spatial patterns, regional differences and sustainable decision-making.

International organizations increasingly emphasize that learners need more than climate awareness. They need climate literacy: the ability to understand basic climate processes, interpret evidence, identify risks, evaluate adaptation and mitigation options, communicate climate information and participate responsibly in climate-related decisions. UNESCO links climate change

education to education for sustainable development, while UNFCCC Action for Climate Empowerment defines education, training, public awareness, public participation, access to information and international cooperation as core elements of climate action [1-4].

Despite the growing importance of this agenda, climate change is often taught in schools as a descriptive topic. Students may memorize definitions such as greenhouse effect, global warming, mitigation and adaptation, but they may not practice asking questions, analysing data, interpreting maps, comparing regional vulnerabilities or designing solutions. This creates a gap between theoretical knowledge and environmental responsibility. A modern geography lesson should help learners move from knowing about climate change to reasoning with climate evidence and acting responsibly within their community.

The international Climate Education methodology proposed in this article is based on the idea that climate literacy must be developed through inquiry-based, data-rich and action-oriented learning. Inquiry-based learning asks students to pose questions, formulate hypotheses, collect or interpret evidence, test explanations, draw conclusions and communicate results. In geography, this inquiry can be organized through maps, climate graphs, weather data, regional risk comparison, carbon footprint scenarios, urban planning tasks and local adaptation decisions.

The Climate Literacy GeoLab platform was designed as a digital environment for applying this methodology in school geography. The platform includes theoretical blocks, a scientific-methodological model, a learning trajectory, interactive simulations, five research tasks, result indicators and certification logic. It is not intended to replace the teacher; rather, it provides a structured digital space in which the teacher can guide students through scientific reasoning and practical climate literacy tasks.

The purpose of this article is to develop a journal-level scientific-methodological framework for the use of international Climate Education methodology in school geography. The article presents the conceptual basis, literature search strategy, inclusion and exclusion criteria, empirical design, platform implementation procedure, assessment instruments, statistical and qualitative analysis plan, ethical considerations, expected results, discussion, limitations and appendices. Practical classroom photographs and platform screenshots are included as visual evidence of implementation and as documentation of the digital learning model.

**Research questions and hypotheses**

No.	Research question	Hypothesis / analytical direction
RQ1	How can international Climate Education methodology be adapted to school geography lessons?	A structured sequence of theory, map interpretation, simulation, research task and reflection will make climate education pedagogically applicable.
RQ2	Which aspects of climate literacy can be developed through the Climate Literacy GeoLab platform?	Students are expected to develop climate system understanding, geographic data interpretation, cause-effect reasoning, solution planning and responsible action awareness.
RQ3	How can digital simulations support inquiry-based climate learning?	Simulations are expected to transform abstract climate concepts into interactive evidence-based tasks that require explanation and decision-making.
RQ4	What evidence can be collected to evaluate student progress?	Progress data, task completion, written explanations, observation protocols and pre/post climate literacy scores can be combined for mixed-method evaluation.

*Table 1. Research questions and hypotheses of the Climate Education study.*

**METHODS AND RESEARCH MATERIALS**

The article is organized as a design-based and mixed-method educational research framework. The first component is a PRISMA-informed narrative synthesis of international literature and official policy documents on climate education, climate literacy, education for sustainable development and inquiry-based geography learning. The second component is a digital intervention model implemented through Climate Literacy GeoLab. The third component is an empirical evaluation plan that can be used in future classroom testing.

The target context is secondary-school geography. The model can be integrated into units on atmosphere, climate, weather, natural hazards, sustainable development, resources, urban geography, population, regional geography and environmental problems. The methodology is appropriate for students who can interpret simple maps and diagrams, work with digital forms and write short evidence-based explanations. The teacher acts as a facilitator who introduces the problem, supports inquiry, checks misconceptions and guides reflection.

The research logic follows transparent reporting principles. PRISMA 2020 supports the selection of literature; STROBE logic supports the description of observational classroom data; COREQ supports qualitative interpretation of student reflection; and FAIR principles support responsible management of educational data [12-15]. The platform is treated as a pedagogical tool and not as a clinical, political or official climate-risk assessment system.

### Search strategy and source selection

The search strategy included official international documents and peer-reviewed studies. The objective was to identify sources that connect climate change education, climate literacy, geography education, digital simulations, inquiry-based learning, sustainable development and student agency. The search was conducted through Web of Science, Scopus, ERIC, Google Scholar, UNESCO databases, IPCC pages, UNFCCC resources, NOAA/USGCRP materials and OECD/NRC frameworks.

Database/source	Search field	Core search string	Recommended filters
Web of Science / Scopus	Title, abstract, keywords	("climate change education" OR "climate education") AND ("climate literacy" OR "environmental literacy") AND (geography OR school OR students)	2015-2026; education; environmental science; geography; articles and reviews
ERIC / Google Scholar	Title and abstract	("inquiry-based learning" AND climate AND geography) OR ("climate literacy" AND simulation AND education)	School education; empirical studies; teaching models
UNESCO / UNFCCC	Official documents	("education for sustainable development" OR "Action for Climate Empowerment") AND climate education	Official frameworks, guidelines and policy documents
IPCC / NOAA / USGCRP	Reports and guides	climate literacy, climate risks, adaptation, mitigation, climate system, science communication	Official scientific reports and climate literacy principles
OECD / NRC / NGSS	Education frameworks	science competencies, inquiry, evidence, scientific reasoning, systems thinking	International competency and science education frameworks

*Table 2. Literature and source search strategy for the international Climate Education methodology.*

**Inclusion and exclusion criteria**

Criterion	Included	Excluded
Educational context	School geography, climate education, environmental education, inquiry-based science and sustainability learning	Purely technical climate modelling without educational application
Phenomenon	Climate literacy, climate change education, climate action learning, geographic thinking, student inquiry	General environmental awareness without climate or geographic content
Methods	Design-based research, mixed-method studies, curriculum frameworks, digital simulation learning, validated education models	Opinion texts without methodological description
Data and outcomes	Student knowledge, skills, attitudes, action competence, maps, simulation results, written reflection	Studies without learning outcomes or educational indicators
Sources	Peer-reviewed articles, UNESCO, UNFCCC, IPCC, NOAA/USGCRP, OECD, NRC/NGSS	Unverifiable internet sources, promotional materials or outdated unsupported claims

*Table 3. Inclusion and exclusion criteria used for building the evidence base.*

### CONCEPTUAL FRAMEWORK OF THE METHODOLOGY

The methodology is built on five interconnected concepts. The first is climate literacy, meaning the ability to understand how the climate system works, how humans influence climate and how climate influences societies and ecosystems. The second is geographic thinking, which requires students to interpret spatial patterns, compare regions and understand scale. The third is inquiry-based learning, which organizes the lesson around questions, evidence and explanation. The fourth is responsible action, which links knowledge to decision-making. The fifth is digital modelling, which supports interactive learning through simulations and feedback.

In the proposed model, the lesson begins with a climate problem or geographic question. Students then examine a map, graph, scenario or platform module. They make predictions, choose options, enter data, observe a result and write an explanation. The teacher helps students connect the digital result with scientific concepts such as greenhouse effect, weather-climate distinction, regional vulnerability, carbon footprint, adaptation, mitigation and sustainable development. Finally, students propose a solution or reflect on how the result can be applied in local geography.

This structure reflects international recommendations that climate education should be interdisciplinary, locally relevant, scientifically accurate and action-oriented. It also aligns with science education frameworks that emphasize evidence, modelling, explanation and systems thinking. Geography provides the spatial context in which these competencies become meaningful.

Dimension	Meaning in climate education	Platform implementation	Expected learning outcome
Climate system understanding	Understanding weather, climate, greenhouse effect and climate variability	Theoretical sections and Weather vs Climate Detective simulation	Students distinguish short-term weather from long-term climate patterns
Geographic data interpretation	Reading maps, regional patterns and climate indicators	Climate Map Quest and Climate Risk Radar	Students compare climate risks across territories
Cause-effect reasoning	Explaining how human actions and natural processes interact	Carbon Footprint Challenge and written research tasks	Students explain links between behaviour, emissions and climate impact
Responsible action	Developing realistic adaptation and mitigation decisions	Blue-Green City Planner and action-oriented tasks	Students propose sustainable local solutions
Reflection and communication	Writing evidence-based explanations and discussing results	Research tasks, result dashboard and certificate logic	Students communicate climate conclusions using geographic language

*Table 4. Core dimensions of the international Climate Education methodology.*

#### CLIMATE LITERACY GEOLAB PLATFORM-BASED PROCEDURE

The practical stage is organized through the Climate Literacy GeoLab digital platform. The platform begins with a home page that introduces climate literacy as an international interactive approach for school geography. The scientific-methodological basis section presents the relevance, aim, objectives and novelty of the model. The international Climate Education section explains four major components: climate literacy, responsible action, sustainable development and geographic thinking. The geography integration section shows how the platform can be connected to map reading, climate data, regional analysis, cause-effect reasoning and solution development.

The learning trajectory is organized as a step-by-step path: theoretical study, interactive simulations, five research tasks, result evaluation and certificate. This structure is important because climate literacy is not formed through a single lesson or one explanatory text. It requires repeated cycles of observation, data use, interpretation, comparison, reflection and action planning.

The interactive modules include tasks such as Climate Map Quest, Carbon Footprint Challenge, Weather vs Climate Detective, Climate Risk Radar and Blue-Green City Planner. These simulations help students compare climate regions, evaluate low-carbon choices, distinguish weather from climate, identify risk factors and propose sustainable planning solutions. The five research tasks require students to write evidence-based answers, which allows teachers to assess not only final answers but also reasoning quality.



Figure 1. QR code linking to the Climate Literacy GeoLab platform used in the study.



Figure 2. Climate Literacy GeoLab home page with the main research entry button and platform identity.

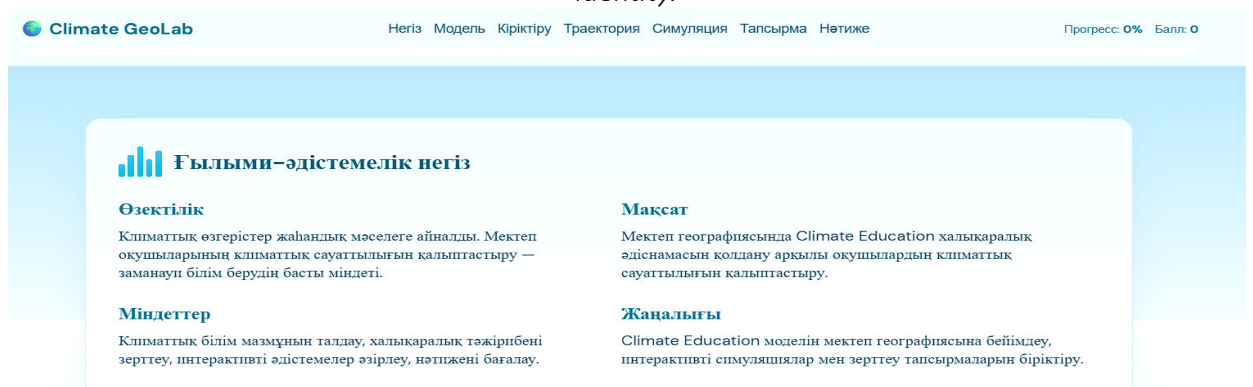


Figure 3. Scientific-methodological basis section showing relevance, aim, objectives and novelty of the Climate Education model.

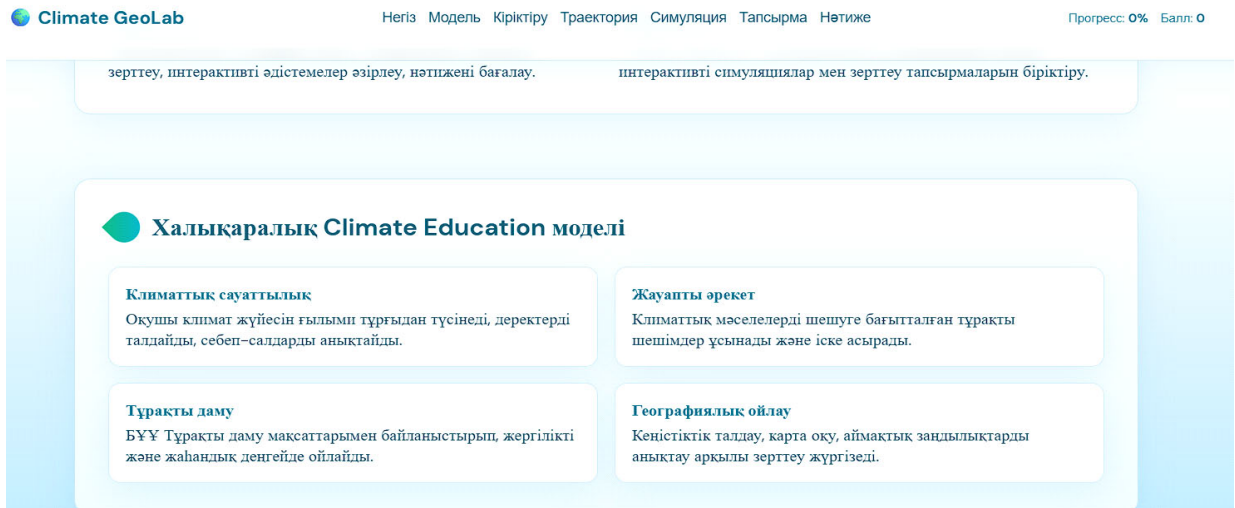


Figure 4. International Climate Education model showing climate literacy, responsible action, sustainable development and geographic thinking components.

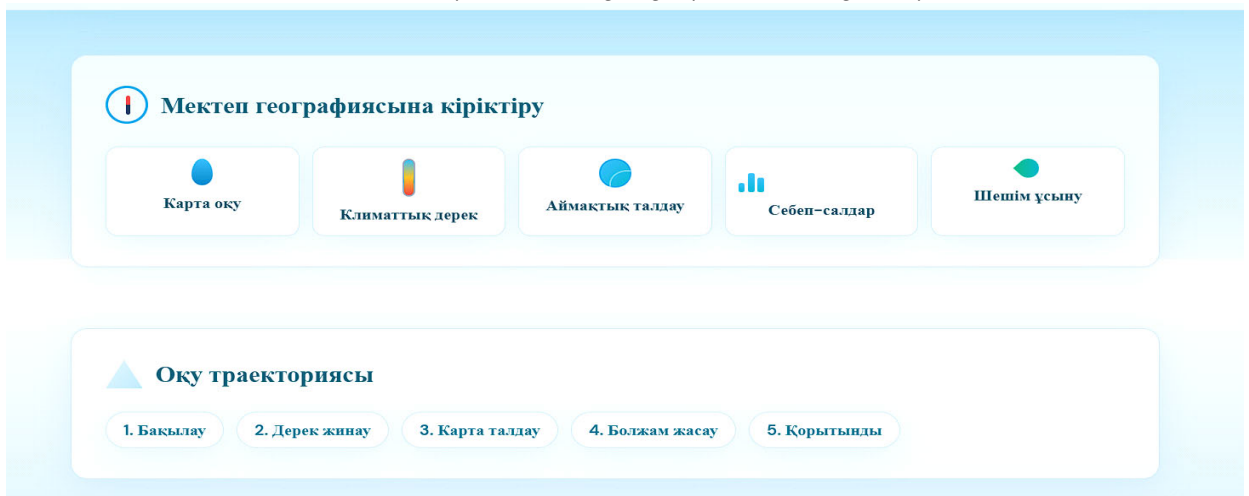


Figure 5. Geography lesson integration section with mapping, climate data, regional analysis, cause-effect reasoning and solution proposal blocks.

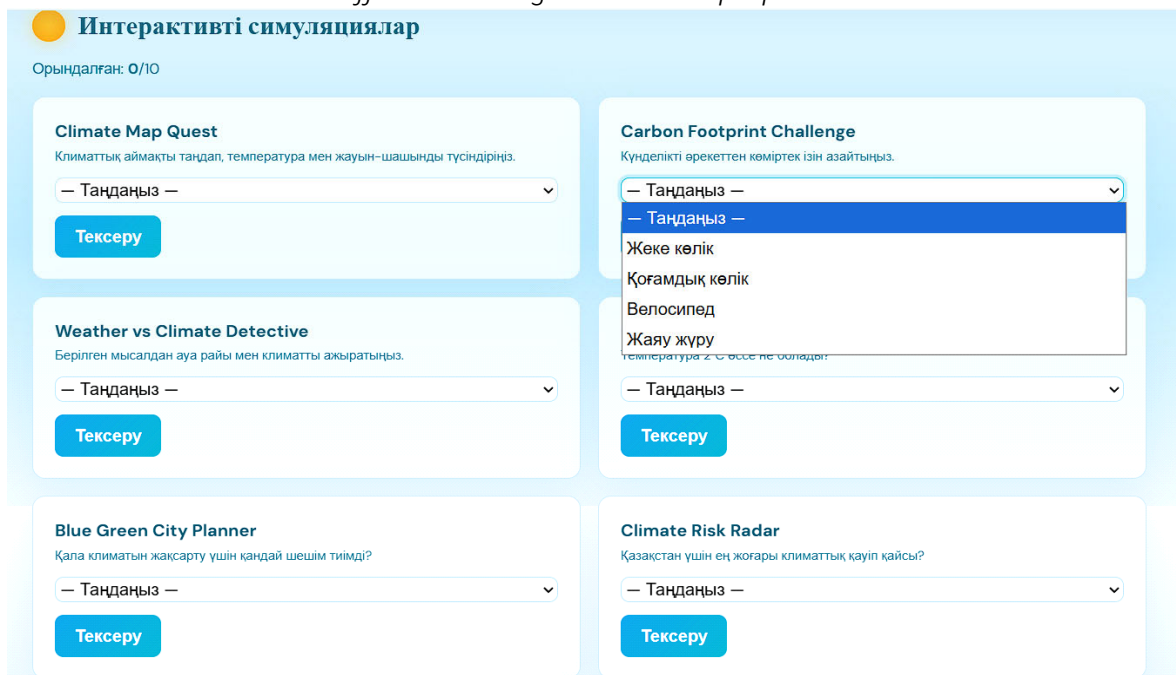


Figure 6. Interactive simulations page including Climate Map Quest, Carbon Footprint Challenge, Weather vs Climate Detective, and Climate Risk Radar.

Үйдегі энергия тұтыну әдетіңізді таңдаңыз.

LED шам қолданамын

Бастау

**4. Waste Sorting Game**  
Қалдықты дұрыс контейнерге сұрыптаңыз.  
Пластик бөтелке қай контейнерге?

Пластик Жалпы Қағаз

Бастау

**5. School Carbon Audit**  
Мектептегі ресурс қолдануды таңдаңыз.

Қағазды үнемдейміз

Бастау

Figure 7. Climate Education research tasks page for student written reflection and evidence-based explanation.

**5 зерттеу тапсырмасы**

**1. Зерттеу тапсырмасы**  
Көміртек ізі дегеніміз не және ол не үшін маңызды?

Жауабыңызды жазыңыз...

Тексеру

**2. Зерттеу тапсырмасы**  
Көміртек ізін есептеу география сабағында қандай дағдыны дамытады?

Жауабыңызды жазыңыз...

Тексеру

Figure 8. Research task section requiring students to explain carbon footprint and its role in geography learning.

Кәдімгі тұрмыс пен экологиялық жауапты тұрмыстың айырмашылығы неде?

Жауабыңызды жазыңыз...

Тексеру

4. Зерттеу тапсырмасы

Мектепте көміртек ізін азайту үшін қандай нақты 3 қадам ұсынуға болады?

Жауабыңызды жазыңыз...

Тексеру

5. Зерттеу тапсырмасы

Бұл әдіс экологиялық мәдениетті қалай қалыптастырады?

Figure 9. Result and impact section showing progress, score, completed simulations, completed tasks and ecological culture level.

**Нәтиже және әсер**

- Жалпы прогресс: 7%
- Жиналған балл: 10
- Орындалған симуляциялар: 1/10
- Орындалған тапсырмалар: 0/5
- Экологиялық мәдениет деңгейі: **Бастапқы**

Көміртек ізін есептеу арқылы географиялық білімді тәжірибеге айналдыру – экологиялық жауапкершіліктің негізі.

🔒 Сертификат 80% прогреске жеткенде ашылады

Figure 10. Certification and final evaluation logic showing the requirement for progress completion before certificate access.

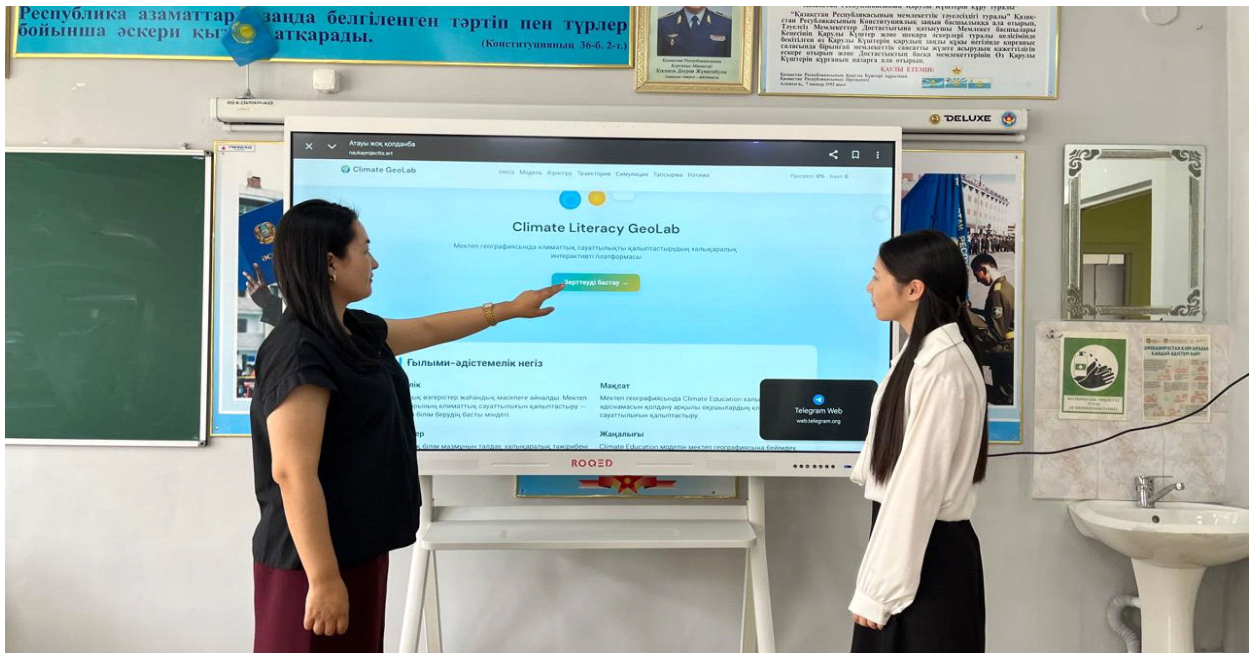


Figure 11. Teacher introduces the Climate Literacy GeoLab platform and explains the international Climate Education approach on the interactive board.

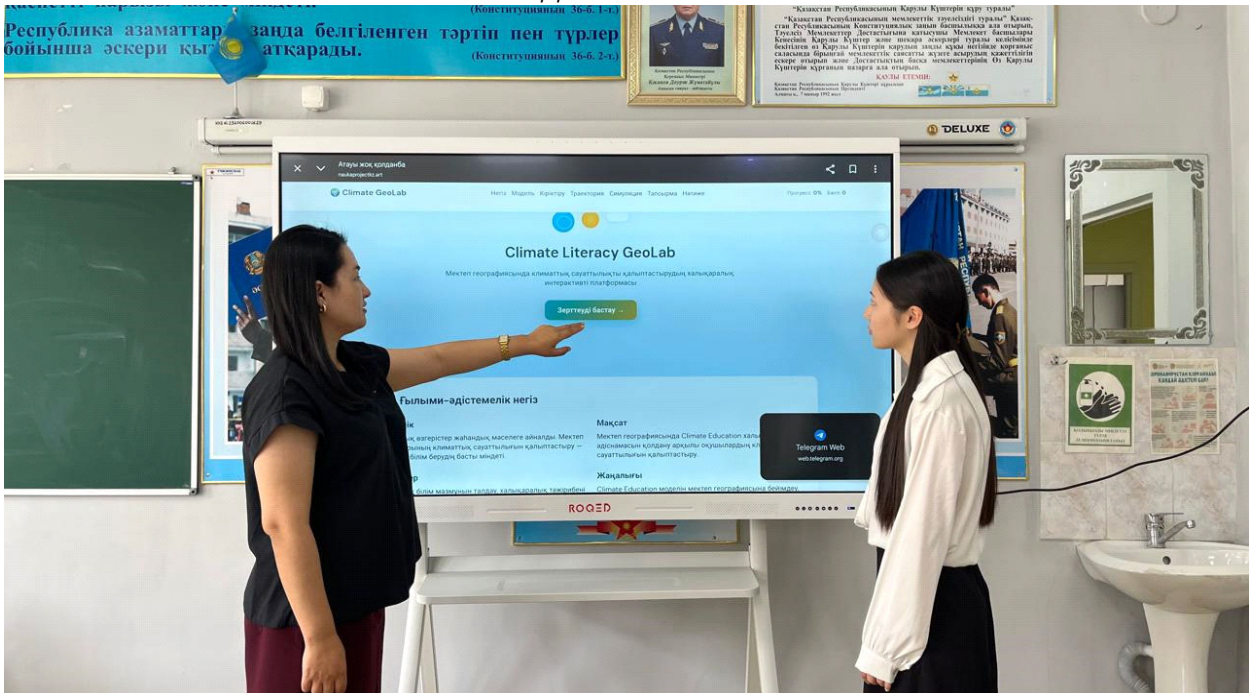


Figure 12. Presentation of the scientific-methodological basis of Climate Education in a geography classroom.

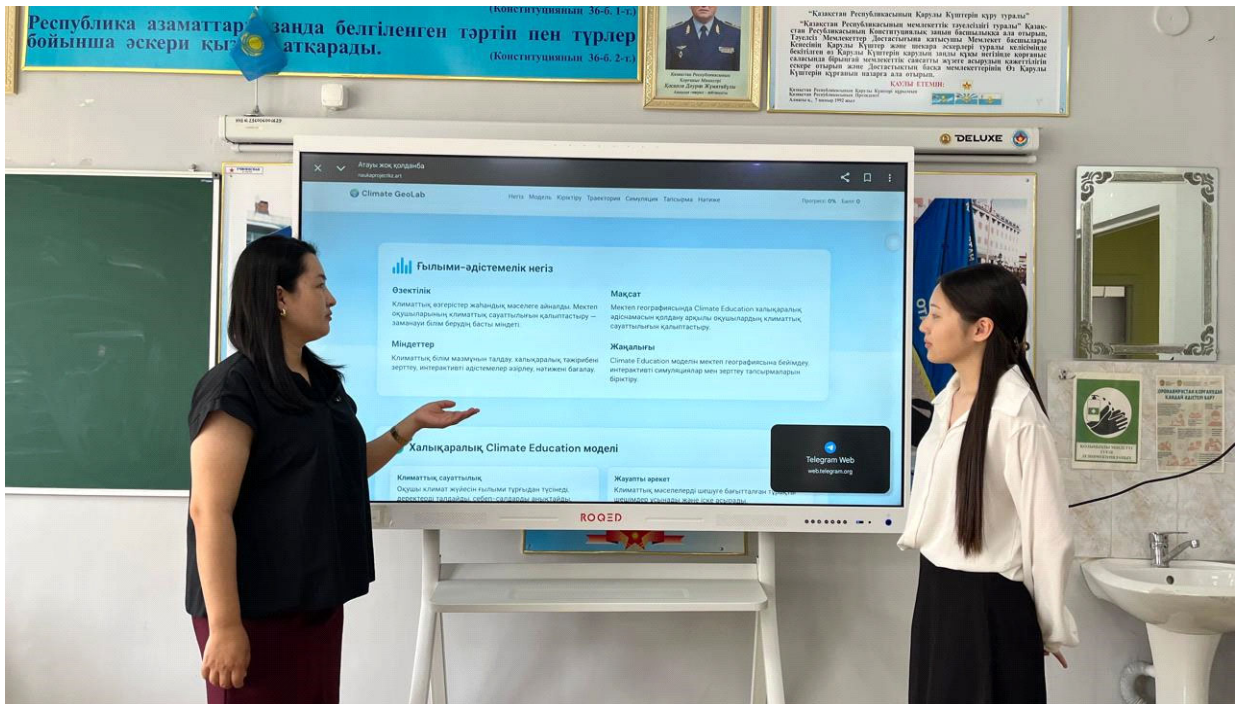


Figure 13. Classroom demonstration of the Climate Education model and its key components: relevance, aim, objectives and novelty.

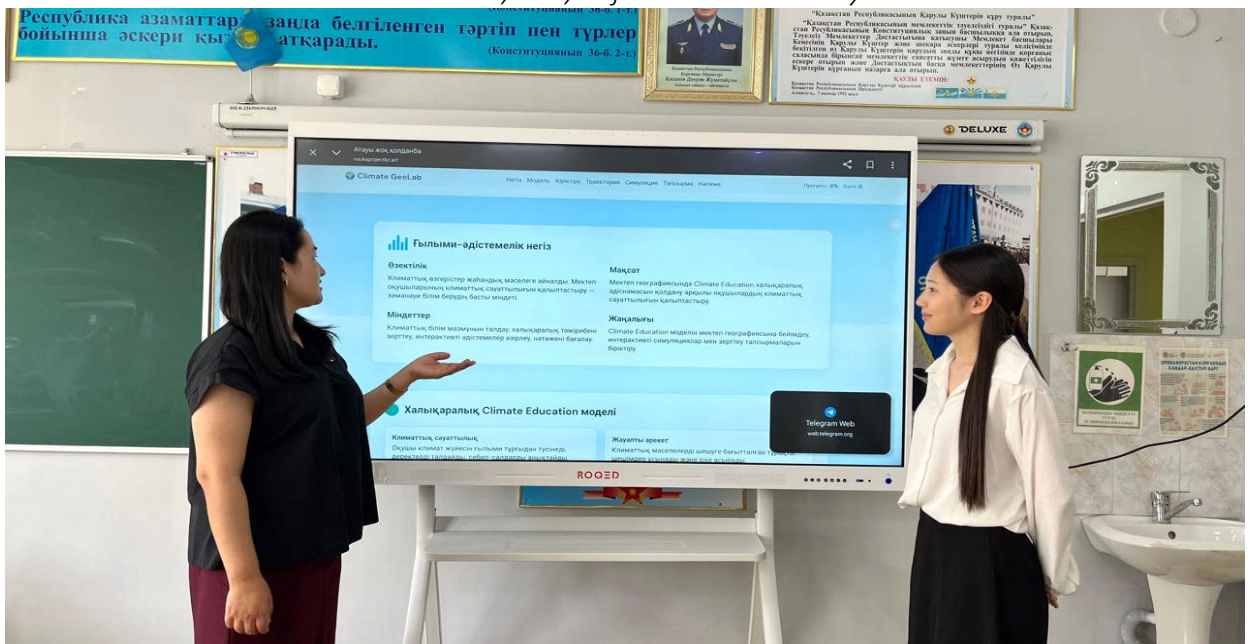


Figure 14. Practical explanation of platform navigation and the Climate Literacy GeoLab home interface.

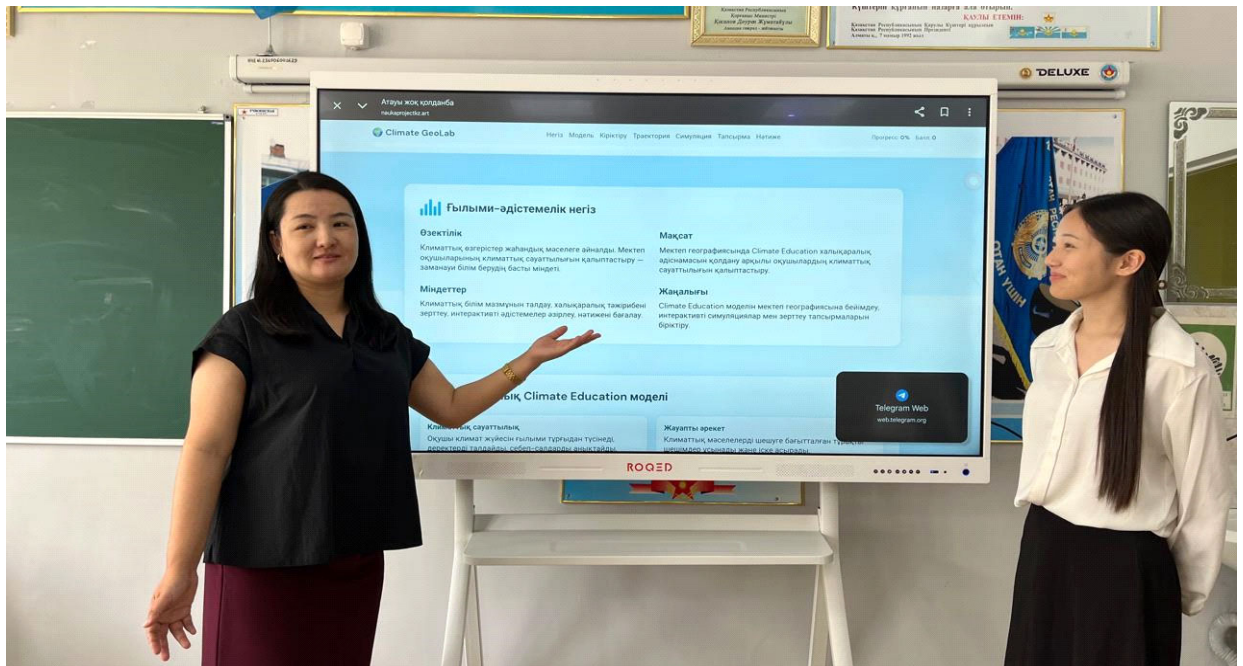


Figure 15. Teacher-guided review of the Climate Education model with a student participant during practical testing.

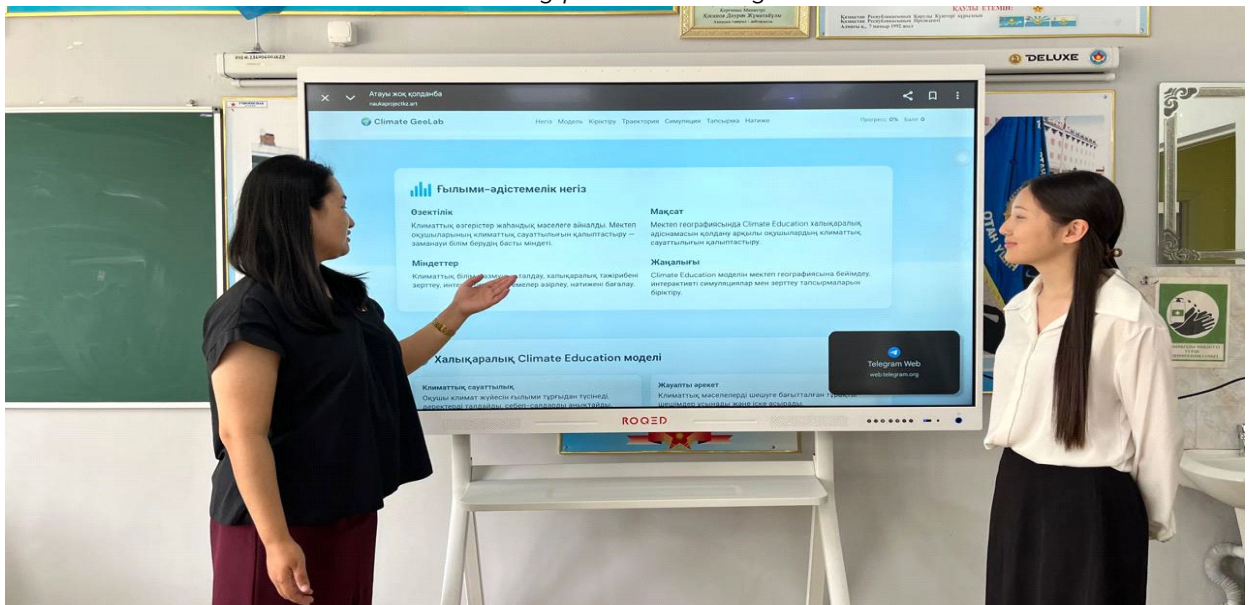


Figure 16. Discussion of climate literacy tasks and student interaction with the platform in the geography classroom.

**RESEARCH INSTRUMENTS**

Block	Instrument / data source	Purpose	Scale / format	Use in analysis
1	Student background form	Identify grade, prior climate learning and digital experience	Categorical variables	Descriptive analysis and subgroup comparison
2	Climate literacy pre/post test	Measure understanding of climate system, risks, mitigation, adaptation and geographic scale	10-20 items, score 0-100	Main quantitative outcome
3	Platform progress indicators	Record completed simulations, tasks, score and certificate readiness	Digital progress percentage and counts	Learning analytics and engagement indicator
4	Simulation performance	Assess responses in interactive climate tasks	Correct/incorrect choices and short explanations	Task-level competence analysis
5	Written research tasks	Evaluate ability to explain climate concepts and propose solutions	Rubric: accuracy, evidence, geography, solution, reflection	Qualitative and rubric-based assessment
6	Teacher observation protocol	Document student engagement, collaboration and misconceptions	Checklist and field notes	Contextual interpretation
7	Student reflection form	Identify perceived usefulness, difficulty and action orientation	Open-ended questions	Thematic content analysis

*Table 5. Proposed measurement structure for evaluating Climate Literacy GeoLab.*

**VARIABLES AND STATISTICAL ANALYSIS PLAN**

The main dependent variable is the climate literacy score after platform-based instruction. Secondary outcomes include simulation completion, research task quality, ecological responsibility score, geographic reasoning score and student reflection themes. Independent variables may include prior climate knowledge, grade level, digital confidence, number of completed simulations and time spent on tasks. Descriptive statistics should include frequency, percentage, mean, standard deviation and median. If pre/post data are collected, paired-sample t-tests or non-

parametric alternatives can be used. Group differences can be analysed with t-tests or ANOVA when assumptions are met. Associations between platform engagement and climate literacy improvement can be assessed through Pearson or Spearman correlation. Multiple regression may be used to examine whether task completion and written reasoning predict post-test climate literacy when prior knowledge is controlled.

Qualitative data from written tasks and student reflections should be analysed through thematic content analysis. The researcher reads responses several times, identifies meaning units, assigns initial codes, groups codes into categories and formulates final themes. Expected themes include understanding climate as a system, recognizing local-global connections, distinguishing weather from climate, identifying human drivers, proposing adaptation or mitigation, and accepting personal responsibility. The mixed-method interpretation should connect quantitative changes with qualitative evidence of reasoning.

#### ETHICAL CONSIDERATIONS

Ethical issue	Required action	How it is reported in the article
Informed participation	Explain the purpose, tasks, expected time and voluntary nature of participation	All students participated after school/teacher permission and appropriate consent procedures
Anonymity	Avoid collecting personal identifiers in exported platform data	Only aggregated results are reported
Digital safety	Use the platform only for educational purposes and avoid sensitive personal data	The platform is described as a learning environment, not as a psychological or official assessment system
Student well-being	Avoid fear-based climate communication; emphasize constructive action	Climate risks are discussed together with adaptation, mitigation and agency
Photographs/screenshots	Use practical photos only with permission and for methodological documentation	Images illustrate classroom implementation and platform modules
Data storage	Store files in password-protected devices and restrict access	Data management follows confidentiality and FAIR-oriented principles

*Table 6. Ethical requirements for classroom implementation and visual documentation.*

#### RESULTS AND DISCUSSION

Because this article presents a methodological design and platform-based implementation framework, the results section is structured as an expected evidence model rather than a fabricated empirical dataset. Real classroom testing should replace model-based examples with actual pre/post scores, task results, observation notes and student quotations. This approach preserves research integrity and makes the article ready for empirical extension.

##### **Practical implementation of the digital platform**

The practical images demonstrate that the platform can be used in an ordinary classroom with an interactive board. The teacher introduces the scientific-methodological basis, explains the international Climate Education model and guides students through the platform sections. This is pedagogically significant because climate education requires both scientific accuracy and teacher

mediation. Digital tools alone cannot guarantee climate literacy; they must be embedded in discussion, questioning and reflection.

The platform screenshots show a clear learning sequence. First, students encounter the home and scientific basis pages. Second, they study the international Climate Education components and geography integration model. Third, they complete simulations and research tasks. Fourth, the result dashboard provides progress information. Fifth, certification motivates completion and gives students a visible outcome. This sequence supports learning continuity and makes the climate literacy process observable.

The simulations are particularly important for geography education because they transform climate concepts into spatial and decision-based tasks. Climate Map Quest develops regional comparison. Weather vs Climate Detective addresses a common misconception between short-term weather and long-term climate. Carbon Footprint Challenge connects behaviour to emissions. Climate Risk Radar supports risk interpretation. Blue-Green City Planner introduces adaptation and urban sustainability. Together, these tasks form an integrated climate literacy pathway.

**Expected empirical interpretation**

Expected result	Interpretation	Educational meaning
Improved climate literacy scores	Students better understand climate processes, risks and responses	The platform supports scientific conceptual learning
Higher quality written explanations	Students use evidence, geographic terms and cause-effect links	Inquiry-based tasks strengthen reasoning
Increased simulation completion	Students remain engaged through interactive tasks	Digital structure supports motivation and autonomy
More realistic action proposals	Students propose feasible school or community solutions	Climate education becomes action-oriented
Reduced misconception between weather and climate	Students separate daily weather from long-term climate patterns	The methodology addresses key conceptual difficulties

*Table 7. Expected result indicators and their educational interpretation.*

**Literature synthesis**

Source / framework	Core idea	Connection to the article
UNESCO Education for Sustainable Development	Learners should acquire knowledge, skills, values and agency for sustainable futures	Supports the action-oriented design of Climate Literacy GeoLab
UNFCCC Action for Climate Empowerment	Education, training, public awareness, participation, access to information and cooperation support climate action	Provides international policy grounding for climate education
IPCC AR6	Climate change involves risks, adaptation, mitigation and regional vulnerability	Supports scientific accuracy and risk-based geography learning
NOAA/USGCRP Climate Literacy	Climate literacy requires understanding climate influence on people and society and human influence on climate	Supports the conceptual definition of learning outcomes
OECD PISA 2025 Science Framework	Scientific competence includes explaining phenomena, evaluating evidence and making informed decisions	Supports assessment of reasoning and evidence use
NRC/NGSS Science Practices	Modelling, explanation, argument from evidence and data analysis are central scientific practices	Supports simulation and inquiry tasks

*Table 8. Key international frameworks informing the Climate Education methodology.*

**Discussion**

The central contribution of this article is the integration of climate literacy with geography-specific inquiry. Climate change education becomes effective when students do not simply repeat scientific terminology, but use evidence to interpret real or simulated problems. Geography provides a meaningful subject base because it naturally includes spatial scale, regional variation, human-environment interaction and sustainable development.

The Climate Literacy GeoLab platform can strengthen the teacher's methodological work by organizing lesson stages. It offers a visible structure for concept introduction, simulation, research task, progress monitoring and certification. Such structure is especially useful in classes where climate change is complex, interdisciplinary and emotionally sensitive. The platform helps convert complexity into manageable learning steps without reducing the scientific seriousness of the topic.

A major advantage of the model is its combination of knowledge and action. Climate education can become ineffective if it is based only on alarming information. Students may feel helpless when climate risks are presented without pathways for response. The proposed model connects climate risks with constructive tasks: comparing transport choices, planning blue-green infrastructure, identifying regional risks and proposing solutions. This supports agency and ecological responsibility.

The use of classroom photographs and screenshots increases methodological transparency. Readers can see how the platform was presented, which modules were included and how students interacted with the digital environment. However, visual documentation should not

be confused with empirical proof. Future studies must collect systematic data through pre/post tests, rubrics, observations and student reflections.

#### **LIMITATIONS**

The current article provides a scientific-methodological design and practical platform documentation, but it does not claim to present a completed randomized experimental trial. Without full empirical testing, conclusions about effectiveness should be interpreted as expected or theoretically grounded outcomes. Another limitation is that digital platform use depends on access to devices, internet stability, teacher digital competence and school infrastructure.

The platform also simplifies complex climate processes for educational purposes. Such simplification is necessary for school learning, but teachers should clarify that educational simulations do not replace official climate models or national risk assessments. The model should be adapted to students' age, curriculum requirements and local context.

#### **CONCLUSION**

The international Climate Education methodology presented in this article offers a structured way to develop climate literacy in school geography. By combining scientific explanation, geographic thinking, inquiry-based learning, digital simulations, written research tasks and reflective assessment, the model helps students move from passive awareness toward evidence-based climate reasoning and responsible action.

Climate Literacy GeoLab demonstrates how a digital platform can support this process. Its modules allow students to study climate concepts, distinguish weather and climate, compare regions, analyse carbon footprint, identify climate risk and propose sustainable solutions. The methodology is aligned with UNESCO, UNFCCC, IPCC, NOAA/USGCRP, OECD and science education frameworks. Future empirical studies should test the model with pre/post climate literacy assessment, classroom observation and qualitative analysis of student explanations.

#### **DECLARATIONS**

**Author contribution:** The author developed the methodological concept, structured the digital platform logic, prepared the platform-based implementation procedure and designed the assessment model.

**Funding:** No external funding was reported for the preparation of this article.

**Conflict of interest:** The author declares no conflict of interest.

**Data availability:** The article presents a methodological model. Empirical datasets should be made available after classroom testing in anonymized form according to ethical requirements.

**Platform access:** Climate Literacy GeoLab is available through the QR code and link included in this article: <https://naukaprojectkz.art/c9x4v5wpsv75mmd>

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**APPENDICES**

**Appendix A. Climate Literacy GeoLab module map**

Platform section	Pedagogical function	Evidence collected
Home / introduction	Motivates students and presents the platform purpose	Initial orientation and teacher explanation
Scientific-methodological basis	Explains relevance, aim, objectives and novelty	Conceptual understanding
International Climate Education model	Presents climate literacy, responsible action, sustainable development and geographic thinking	Theoretical foundation
Geography integration	Connects climate education to maps, data and regional reasoning	Geographic interpretation
Interactive simulations	Allows students to test scenarios and answer inquiry questions	Task completion and choices
Research tasks	Requires written explanations and solution proposals	Qualitative reasoning data
Results and certificate	Shows progress, points, completion and achievement	Learning analytics

*Table 9. Climate Literacy GeoLab platform module map.*

**Appendix B. Research task rubric**

Criterion	High level	Medium level	Initial level
Scientific accuracy	Uses correct climate concepts and avoids misconceptions	Partly correct explanation with minor inaccuracies	General answer with major misconceptions
Geographic reasoning	Connects climate issue with region, scale, map or spatial pattern	Mentions place or region without deeper analysis	No geographic connection
Evidence use	Uses data, simulation result or example to justify answer	Uses one example but explanation is limited	Opinion without evidence
Solution quality	Proposes realistic adaptation or mitigation action	Proposes general but possible action	No practical solution
Reflection	Explains why the action matters for society or environment	Some reflection but limited depth	Minimal reflection

*Table 10. Rubric for assessing student research tasks.*

**Appendix C. Suggested lesson sequence**

Stage	Teacher action	Student action	Expected product
1. Problem framing	Presents a climate-related geographic question	Predicts possible causes and impacts	Initial hypothesis
2. Evidence exploration	Shows map, diagram or platform section	Reads data and identifies patterns	Observation notes
3. Simulation	Guides interactive module	Tests options and records results	Simulation outcome
4. Explanation	Asks students to justify results	Writes evidence-based response	Short research answer
5. Reflection	Connects result to local and global action	Proposes adaptation or mitigation solution	Action-oriented conclusion

*Table 11. Suggested lesson sequence for applying the methodology.*

# ЗАСТОСУВАННЯ ЦИФРОВИХ ТЕХНОЛОГІЙ У НАВЧАННІ ІНОЗЕМНОЇ МОВИ

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**Анотація.** У статті розглядаються актуальні питання використання цифрових технологій у навчанні іноземної мови, які прискорюють передачу знань, підвищують результативність та якість іншомовної освіти й сприяють підготовці компетентних фахівців. Проаналізовано сучасні підходи до інтеграції цифрових освітніх ресурсів, веборієнтованих платформ, мобільних застосунків, систем дистанційного навчання та інструментів штучного інтелекту у формуванні іншомовної комунікативної компетентності. Визначено педагогічні переваги застосування цифрових технологій, зокрема персоналізацію навчання, підвищення навчальної мотивації, розвиток автономності здобувачів вищої освіти. Особлива увага приділяється змішаному навчанню, яке посилює мотивацію студентів і робить заняття більш цікавим, інформативним та ефективним. Обґрунтовано необхідність комплексного поєднання традиційних методів навчання з цифровими інструментами відповідно до дидактичних цілей освітнього процесу.

**Ключові слова:** цифрові технології, змішане навчання, навчання іноземної мови, цифрові освітні ресурси, штучний інтелект, комунікативна компетентність

**Метою** статті є аналіз можливостей цифрових технологій у навчанні іноземної мови, визначення їх педагогічного потенціалу та обґрунтування методичних підходів до інтеграції цифрових інструментів в освітній процес.

Відповідно до мети визначено наступні завдання:

- проаналізувати сучасні цифрові технології, що застосовуються в навчанні іноземної мови;
- визначити вплив цифрових технологій на формування іншомовної комунікативної компетентності;
- охарактеризувати переваги та обмеження застосування цифрових інструментів;
- окреслити перспективи використання технологій штучного інтелекту в іншомовній освіті.

**Основний текст статті.** Стрімкий розвиток цифрових технологій створює об'єктивні можливості для реалізації багатьох актуальних завдань у сфері освіти, у тому числі завдання розвитку навчальної автономності студентів та формування навичок, необхідних для безперервної освіти. Сучасне навчання іноземної мови дедалі більше орієнтується на цифрове освітнє середовище, у якому здобувач вищої освіти виступає активним учасником освітнього процесу. Цифрові технології забезпечують інтерактивність, гнучкість і мобільність навчання, створюючи умови для розвитку мовленнєвих умінь у максимально наближеному до реального іншомовного середовища форматі.

Цифрові технології мають широкий спектр дидактичних можливостей, спрямованих на активізацію пізнавальної діяльності студентів, розкриття та вдосконалення їх особистісних якостей, посилення навчальної автономії, підвищення результативності іншомовної освіти.

Ідея цифрової трансформації освіти спирається на концепцію lifelong learning та створює умови для індивідуалізації освіти на основі інноваційних технологій. Цифрові технології забезпечують такі важливі властивості сучасної освіти, як відкритість, доступність, якість, інформаційна взаємодія суб'єктів освітнього процесу, які поступово стають основою не лише формальної освіти, а й самоосвіти протягом усього життя.

Інформатизація суспільства докорінно змінила статус іноземної мови як загальноосвітньої дисципліни: від використання її в основному тільки в рамках заняття до реально затребуваної навички в практичній та професійній діяльності будь-якого фахівця, який повинен не тільки володіти фундаментальними знаннями, а й вміти оперативно опрацьовувати інформацію з оригінальних закордонних джерел; вивчати, створювати та впроваджувати інновації у власній предметній області; обмінюватися досягненнями вітчизняної науки із зарубіжними фахівцями; виступати з доповідями англійською мовою на міжнародних наукових конференціях; брати участь у науковій діловій дискусії.

Заняття з іноземної мови із застосуванням цифрових технологій є якісно новою формою організації освітнього процесу на основі поєднання традиційної методики вивчення нового матеріалу з методикою застосування комп'ютерних технологій, тому багато дослідників називають його комбінованим або змішаним (hybrid, blended learning).

Цифрові технології дозволяють забезпечити доступ до джерел мережі Інтернет, що постійно оновлюються; візуалізувати інформацію за допомогою презентацій MS Power Point та використовувати автентичні аудіо- та відеоматеріали іноземною мовою; зберігати у цифровому форматі необмежену кількість автентичної інформації; накопичувати навчальні матеріали, обробляти та редагувати їх, передавати на будь-які відстані; реалізовувати індивідуалізацію навчання, надаючи вибір зручного часу, місця та темпу роботи; організувати вихід у реальний соціокультурний контекст із можливістю міжкультурного спілкування та обміну інформацією іноземною мовою; забезпечити своєчасний зворотний зв'язок; формувати здатність до аналізу своєї навчальної діяльності та її результатів (рефлексія).

Одним із найважливіших напрямів цифровізації є використання систем управління навчанням LMS (Learning Management Systems), які забезпечують організацію навчальних матеріалів, виконання практичних завдань, проведення тестування, оцінювання та комунікацію між викладачем і студентами. Такі системи дозволяють реалізувати принципи змішаного та дистанційного навчання, забезпечуючи гнучкий доступ до освітніх ресурсів незалежно від місця перебування здобувачів освіти.

Не менш важливу роль відіграють мобільні застосунки для вивчення іноземних мов. Їх використання сприяє розвитку лексичної компетентності, автоматизації граматичних навичок, удосконаленню вимови та аудіювання. Завдяки технологіям адаптивного навчання такі застосунки враховують індивідуальний рівень підготовки користувача, темп засвоєння матеріалу та результати попереднього навчання.

Важливим інструментом також є цифрові платформи для організації комунікативної діяльності. Використання сервісів відеоконференцій, інтерактивних дошок, спільного редагування документів та форумів забезпечує розвиток усіх видів мовленнєвої діяльності – читання, письма, аудіювання та говоріння. Водночас інтеграція автентичних відеоматеріалів, подкастів, електронних бібліотек і мультимедійних ресурсів сприяє формуванню соціокультурної компетентності та підвищенню мотивації до навчання.

Особливої актуальності та популярності сьогодні набувають поряд з Інтернет-ресурсами online-платформи, електронні навчально-методичні комплекси. Одним із інструментів комбінованого навчання є відкрита електронна навчальна платформа MOODLE, яка має зручну систему управління та ефективно використовується в іншомовній освіті. Ефективності роботи в системі сприяє насамперед багатоканальний спосіб подання інформації: у вигляді тексту, звуку та відеозображення. Як відомо, інформація засвоюється

набагато краще, якщо при її сприйнятті задіяно декілька органів чуття, і викладач може враховувати навчальні стилі своїх студентів, їх індивідуальні особливості сприйняття навчального матеріалу.

Moodle інтегрує широкий набір ресурсів та інструментів, що включають форуми, чати, тестові завдання, навчальний журнал, словники, матеріали для аудіювання, відеоматеріали, посилання, онлайн-тестування тощо. Для тренування лексичних, граматичних та мовних структур до кожного уроку чи модуля розробляються тести.

Тестові завдання можуть бути сформульовані у закритій формі: множинний вибір, з відповіддю «правильно/неправильно», завдання на відповідність. Передбачено можливість повторного виконання тесту та порівняння отриманого результату із ключем, тобто можливість самоконтролю та самостійної корекції помилок.

Платформа надає можливість як викладачеві, так і студенту відстежити динаміку успіху, оскільки на платформі відображається час, витрачений на виконання завдань та кількість спроб, які знадобилися студенту для успішного виконання тесту.

Основними перевагами використання платформи MOODLE для навчання іноземної мови є: значне підвищення самостійності студентів, ступеня їх особистої залученості, відповідальності та самореалізації; можливість реалізації творчих проектів різних рівнів складності, участь у яких розвиває відповідальність студентів та зрештою стимулює розробку нових стратегій та шляхів вирішення проблеми; можливість взаємодії з іншими суб'єктами освітнього середовища, що дозволяє підвищити активність та навчальну автономність студента, усуває скутість та страх, сприяє формуванню суб'єкта діяльності; можливість регулярного аналізу результатів навчальної діяльності студентів; зниження витрат на управління освітнім процесом.

Окремим напрямом розвитку цифрових технологій є використання інструментів генеративного штучного інтелекту. Інтелектуальні чат-асистенти здатні створювати навчальні тексти різного рівня складності, пояснювати граматичні явища, моделювати комунікативні ситуації, перевіряти письмові роботи та надавати індивідуалізований зворотний зв'язок. Це значно розширює можливості персоналізації навчання та підтримки самостійної роботи студентів.

Разом із численними перевагами використання цифрових технологій існують і певні виклики. Серед них варто відзначити нерівний доступ до цифрової інфраструктури, необхідність формування високого рівня цифрової компетентності педагогів, ризики надмірної автоматизації освітнього процесу та потребу у забезпеченні академічної доброчесності під час використання інтелектуальних систем.

Ефективність цифрових технологій значною мірою залежить від їх педагогічно обґрунтованої інтеграції. Саме викладач визначає дидактичну доцільність використання певного цифрового інструменту, поєднуючи його із сучасними методами комунікативного, компетентнісного та діяльнісного навчання. За таких умов цифрові технології виступають не самоціллю, а ефективним засобом підвищення якості іншомовної освіти.

**Висновки.** Використання цифрових технологій у навчанні іноземної мови є одним із ключових чинників модернізації сучасної освіти. Впровадження цифрових технологій у контекст традиційного заняття з іноземної мови дозволяє зробити процес навчання більш цікавим та інтенсивним, підвищує мотивацію до вивчення іноземної мови, сприяє досягненню якості та ефективності у володінні необхідними знаннями та компетенціями, забезпечує можливості використовувати іноземну мову для подальшої самоосвіти. Цифрові інструменти забезпечують персоналізацію навчання, сприяють розвитку іншомовної комунікативної компетентності та формуванню цифрової грамотності здобувачів освіти. Водночас їх ефективність визначається не кількістю застосованих технологій, а методично обґрунтованою інтеграцією у структуру освітнього процесу та дидактичною доцільністю.

Перспективним напрямом подальших досліджень є розроблення методик використання генеративного штучного інтелекту, адаптивних освітніх систем та технологій Learning Analytics у навчанні іноземних мов.

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## Economic Sciences

# Efficiency, competition and credit risk in Madagascar's banking sector – a two-stage DEA-SBM-Malmquist analysis

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### Abstract

This study analyzes the efficiency of commercial banks in Madagascar, as well as the effect of credit risk, competition, and the macroeconomic environment on their efficiency during the period 2010-2024. Our hypotheses were initially supported by the literature and also by the BFM survey of the banking sector. A two-stage approach was used, combining the SBM DEA double frontier method following Wang et al. (2007) and a second-stage regression estimated using wild bootstrap clusters. This methodological strategy allows for a rigorous measurement of efficiency while correcting for econometric problems. The empirical results highlight a negative effect of credit risk on banking efficiency, thus reducing operational performance. The Lerner index shows a positive effect, with the most efficient banks gaining market power and generating higher margins. Furthermore, economic growth has a positive effect on banking efficiency, and banks have generally been more resilient to COVID-19. Therefore, a favorable macroeconomic environment improves borrower creditworthiness, stimulates credit demand, and reduces payment defaults.

Keywords: Bank efficiency, Slack Based Measure Data Envelopment Analysis, Double frontier, Two stage DEA, Wild bootstrap.

### 1. Introduction

It is worth noting that in developing countries, the economy's financing relies primarily on financial intermediation. The relationship between the development of financial intermediation and economic growth has been of great interest to economists. Most research concludes that there are positive links between financial development and economic growth, in line with the findings of Goldsmith (1969), King and Levine (1993), Chen Hao (2006), and Pradhan (2018). Belinga, Zhou and Doumbe (2016) highlight that the literature presents three hypotheses regarding the direction of causality between FD (Financial Development) and EG (Economic Growth): *from a supply-side perspective*, the development of the financial and banking system drives economic growth; *from a demand-side perspective*, FD is seen as an automatic response, reacting *passively* to the growth process; *the bidirectional perspective* posits the existence of a long-term circular relationship.

In the literature, the indicators of financial intermediation development used vary depending on the authors; Demirgüç and Levine (2001), who are leading authors on the subject, used the following criteria: size, activity, and efficiency. The efficiency indicator can be relative or absolute. For relative efficiency, which is of interest here, there are measures specific to financial institutions (Lima P, 2012); the measure of efficiency aims to determine the extent to which banks provide an

optimal combination of financial services from a given set of inputs (Farrell, 1957). Let us assume that banks act rationally. That is to say, a bank operates in such a way as to pursue its own objectives in the best possible, optimal manner, all other things being equal. Of course, this implies that banks are assumed to understand the mechanisms of their own production and have the capacity and willingness to use them to achieve their objectives.

DEA data analysis is a non-parametric linear programming technique that extends the idea of estimating efficiency by comparing each decision-making unit. The DEA literature on banking efficiency is extensive. However, only a few studies have been conducted on the African continent (Henriques et al., 2020), primarily using the two-stage SBM-DEA model, which examines the relationship between credit risk, competition and banking efficiency. Most existing studies focus on major banking sectors or developed sectors, and relatively few apply two-stage DEA models to small banking systems or banking systems in developing countries, or do not take sufficient account of the influence of environmental factors, macroeconomic conditions or random errors, which may bias efficiency estimates.

Furthermore, in Madagascar, the banking sector is characterized by a highly concentrated market, in addition to a rather unstable economic climate, which, according to quarterly surveys conducted by the BFM (2024, 2025) on the banking sector, is slowing down the sector's development. In response to this gap in the literature regarding the use of the two-stage DEA method with Bootstrap in the banking sector in Africa, and particularly in Madagascar, this study seeks to answer the question: To what extent are banks operating in Madagascar efficient, taking their environments into account?

1. Hypothesis (H1): Non-performing loans hurt a bank's performance
2. Hypothesis (H2): The competitive structure of the banking sector has an impact on a bank's efficiency (negative, based on surveys conducted by the BFM)
3. Hypothesis (H3): Macroeconomic conditions have an impact on a bank's efficiency.

This study contributes to the body of research seeking to understand the relationship between efficiency, competition and credit risk in a country where production and financial infrastructures are underdeveloped. The aim is to understand, verify and measure the factors limiting the development of the banking sector in the country, based on the results of surveys conducted by the BFM. This is intended to assist policymakers and supervisors in formulating appropriate sectoral policies so that the banking system can fully fulfil its role as a driver of economic growth. It should be noted that the role of the Central Bank of Madagascar is not only to supervise the granting of loans but also to ensure the country's financial stability, and, in theory, competition within the banking sector has an impact on the country's financial stability. This study adopts a two-stage methodological approach combining static and dynamic analysis. Firstly, banking efficiency is estimated using a non-radial DEA model of the Slack-Based Measure (SBM) type, whilst changes in productivity are analyzed using the Malmquist index and its decomposition into efficiency changes and technological changes. In the second stage, the determinants of efficiency are examined using an econometric regression with Bootstrap according to the wild bootstrap-t methodology of Cameron and Miller (2008).

This study confirms that credit risk management is a key driver of improved banking efficiency, whilst market power, measured by the Lerner index, and a favorable macroeconomic environment contribute positively to the performance of financial institutions. These results enrich the literature on banking efficiency by combining a rigorous methodological approach with an integrated analysis of microeconomic and macroeconomic dimensions.

The remainder of this paper is organized as follows: In Section 2, we provide a review of the literature concerning the link between. In Section 3, we present our methodology and the data sources used. The SBM DEA double-boundary model, the Malmquist index, etc. In Section 4, we present the results and discuss them.

## 2. Literature review

### 2.1. Production in the banking sector

It should be noted that banking efficiency refers to a bank's ability to use its resources to maximize its output (revenue) or minimize its inputs (costs), taking into account market conditions and input prices. In the empirical literature, the appropriate definition of output and the specification of inputs and outputs in the banking sector have been frequent topics of discussion. The technical efficiency of banks is measured using either the production approach or the intermediation approach. The former views banks as producers of services such as deposits and loans, with labor and capital as the main inputs. The latter views banks as agents responsible for transforming deposits and other funds into loans and other assets; it therefore considers banking inputs to consist of customer deposits and other market resources, as well as operating costs (Ferrier and Lovell, 1990). There is a consensus that the intermediation approach is particularly appropriate for the traditional function of financial institutions (Tan & Walheer, 2024). Furthermore, this approach is best suited to analyzing the efficiency of banks in developing countries, as it best reflects the intermediary role of banks—that is, mobilizing deposits and channeling them into loans and investments—and because of its ability to incorporate both operating costs and interest costs (Zhou & Yang, 2022). The production approach is often considered more appropriate for assessing the efficiency of bank branches rather than that of institutions as a whole, as it focuses on the operational aspects of banking services (Degl'Innocenti et al., 2017).

To overcome the problem of classifying deposits as inputs or outputs, a new approach has emerged, in line with the current focus on profitability, and concentrates primarily on operational results (profit-oriented approach). This approach treats revenues such as interest received and non-financial income as outputs, whilst cost components such as staff costs and interest paid (Drake et al., 2006) are inputs, to reduce costs and increase the bank's revenues. The most commonly used outputs are loans and income-generating assets, as shown by Casu and Molyneux (2003). However, it should be borne in mind that the efficiency of financial institutions entails improved profitability, increased mobilization of financial resources, better pricing, and improved quality of services offered to consumers in this competitive environment (Ullah S. et al. (2023).

With regard to research into other factors that determine the efficiency of banks, the factors influencing banking efficiency can be classified into microeconomic factors linked to the specific characteristics of banks and fundamental macroeconomic factors. Non-performing loans, insufficient capitalization, size and scale, the use of modern technologies<sup>1</sup>, and staff training are the factors most frequently cited in the literature at the internal and micro levels (Kamgna et al., 2008; Dhouha et al., 2009; Matthews & Xiao, 2020), as opposed to macroeconomic factors (crises, economic cycles, inflation, etc.) and socio-legal factors. Higher levels of economic development are associated with increased banking sector efficiency (Opperman & Adjasi, 2019), and a stable macroeconomic environment with well-developed financial structures promotes banking efficiency, whilst volatility (e.g. volatility in remittances) is detrimental (Alandejani, 2022).

Regarding undercapitalisation<sup>2</sup> the authors' findings vary: Pasiouras et al. (2009) and Dell'Atti et al. (2015) have highlighted a negative relationship between capitalization and banking efficiency. According to the regulatory hypothesis, the existence of a regulatory authority encourages banks to be more efficient and better managed when their level of capitalization is relatively low. The fact that higher capital levels increase agency costs between management and shareholders by reducing the discipline imposed on management by debt repayment. Banks with moderate levels

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<sup>1</sup> The underutilization of IT budgets has been identified as a source of inefficiency in some banks (Fukuyama et al., 2021)

of capitalization would potentially be easier to manage and supervise in terms of credit quality, thereby reducing information asymmetry and improving their efficiency. However, some authors (Marques-Ibanez and Molyneux, 2011; Pessarossi and Weill, 2015) note that banks with the highest levels of equity capital are more efficient.

## 2.2. Competition, credit risk and bank efficiency

The ES (Efficiency Structure) theory proposed by Demsetz (1974) and Peltzman (1997) asserts that the exceptional performance of market-leading firms (due to specific factors such as a high level of technology and management, etc.) will endogenously determine the market structure, meaning that greater efficiency can also lead to concentration and higher profits. In this sense, concentration reflects and rewards efficient banks, but does not necessarily imply an increase in market power. However, one must not overlook the fact that a monopoly situation can lead to lax behavior or a deviation from the objective of efficiency, which can be detrimental to society. It can be assumed that certain bank executives may take advantage of the lack of competition to incur unnecessary expenditure (construction of excessively expensive buildings, excessive salaries, bonuses, and other benefits, Dittus (2004), Bonin et al. (1998)). Standard economic theory, i.e. the Structure-Behaviour-Performance paradigm, predicts that high concentration in banking markets implies market power for banks, which raises the cost of credit and consequently curbs investment and business activity (Beck, Demirgüç-Kunt, and Maksimovic, 2004). Pierre J and Jean-Paul P (2012) noted that: ‘the creation of monopoly positions can place banks in a position not only to recoup their investment in information, but also to overcharge (exploit) their borrowers. Having invested in a relationship that makes their customers captive (i.e., making it costly for them to switch to competitors), they can impose excessively stringent credit conditions’. The Information Generating Hypothesis (IGH) developed by Marquez (2002) proposes a positive relationship between market power and bank efficiency. The IGH suggests that in the face of intense competition, bank managers are likely to be more interested in quantity than quality in order to gain a larger market share relative to their competitors, by expanding their asset portfolio even if this compromises asset quality.

Several authors have found that bank concentration is a necessary evil for banking efficiency and that it is not necessarily detrimental to economic activity [Demsetz (1973); Goddard, Molyneux, and Wilson (2004); Ion L., Emmanuelle N. (2011)]. Indeed, in the banking industry, productive efficiency is achieved either by seeking economies of scale or through economies of scope (risk diversification and liquidity). Theoretically, this is explained by the role of banks, which is to reduce information asymmetry: faced with competitive pressures, and thus a narrowing of their interest margin, banks do not undertake monitoring for the selection or tracking of projects. Eber N. (2000), within Sussman’s (1993) framework of spatial competition, found that an efficient banking system should be characterized by a high concentration of the credit market (reducing information costs) without this high concentration acting as a significant obstacle to investment and economic activity, as can be observed in Germany or Japan.

The findings of Osei-Tutu and Weill (2022) show that banking efficiency has a positive impact on access to credit and that gains in banking efficiency help to alleviate credit constraints for firms when the macroeconomic environment is more developed and stable.

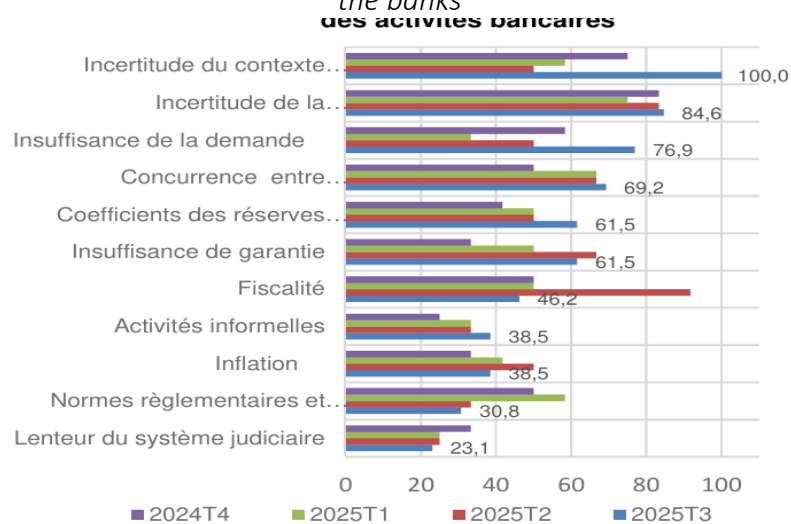
Berger et al. (1997) found that there is a negative relationship between cost efficiency and risk in distressed banks. They offered several explanations for this finding. Firstly, inefficient banks, in addition to having problems controlling their internal costs, may encounter difficulties in assessing credit risk, so that poor cost management goes hand in hand with higher credit risk, known as the ‘mismanagement hypothesis’. Secondly, bad loans may arise due to adverse economic circumstances beyond the banks’ control, meaning that banks must devote more resources to recovering non-performing loans, the ‘bad luck hypothesis’.

The significance of banks' non-performing loans for economic growth lies in the fact that a higher NPA influences loan prices and interest rates. Higher interest rates, in turn, will have a direct impact on investors requiring loans for infrastructure and industrial projects (Bernanke & Gertler, 1989; Nkusu, 2011; Klein, 2013).

### 2.3. The banking sector in Madagascar

As already mentioned, there is little research that has examined the efficiency of the country's banking system, particularly at the microeconomic level. According to Razafindronona et al. (2020), levels of non-performing loans (NPLs) in the Malagasy banking sector rise significantly during macroeconomic shocks such as a contraction in GDP or a depreciation of the exchange rate. The results show that NPLs can rise by nearly 3 percentage points under an adverse scenario. However, banks remain sufficiently capitalized, liquid and profitable (IMF, 2023). In 2024, Madagascar had 16 banks. Most of these are foreign banks, which are commercial banks and, according to the literature, are expected to be more efficient due to their technological and managerial advances. Their primary focus is therefore on shareholder profitability, which limits financing for long-term and risky projects in the country. Although Leightner and Lovell (1998) argue that opening up banks to foreign capital in emerging economies improves their performance by providing them with greater access to technology and, above all, to best governance practices. The banking sector is essentially risk-averse and relies primarily on asset-backed loans (World Bank, 2014). The cost of borrowing in Madagascar, at 48.86%, does not align with the sub-Saharan African average of 11%. Imperfect competition in the banking sector in Madagascar limits the decline in the interest margin to 8.8% (Financial Structure Dataset, 2019). The low level of banking penetration among the population, combined with uncertain economic conditions, leads to a preference for cash. The increase in the M1 aggregate during periods of uncertainty illustrates this preference. Another reason is that banks hold excess liquidity on their balance sheets because demand for credit from non-financial economic agents is low or is considered risky (the non-performing loan ratio stood at 7.7% in June 2024 according to the World Bank's economic update), placing the country 12th in Africa for NPLs (non-performing loans). As Mishkin F. (2013) points out, due to information asymmetry and the highly risky business environment, banks may accumulate liquidity because they prefer to keep it on their books rather than grant loans to non-financial economic agents deemed risky. The use of assets to secure loans may not be reliable due to uncertainties in the judicial system and contract enforcement. *The Fraser Institute's* Property Rights Index stood at 3.02 in 2017 and remained at 117th place globally in 2025, indicating weak contract protection and enforcement.

Figure 1 Factors hindering the development of the banking sector in Madagascar, according to the banks



Source : BFM / Séries d'enquêtes auprès des banques

### 3. Methodology and data

#### 3.1. Description of the double-boundary SBM-DEA model and first stage

Banking efficiency is generally measured using two main approaches: parametric and non-parametric methods. The most widely used parametric method is stochastic frontier analysis (SFA), whilst the most common non-parametric method is data envelopment analysis (DEA). DEA is a non-parametric linear mathematical programming technique whose objective is to analyze a group of homogeneous production units known as decision-making units (DMUs) that share the same inputs and outputs, to identify the most efficient organizations and indicate the actions that inefficient organizations must take to become efficient. The assumption is that if a producer J is capable of producing  $y_j$  with  $x_j$ , then other producers are also capable of doing the same if they are efficient. Thus, producer J and the others can be combined to form what we might call a virtual producer with composite inputs and outputs. The core of the analysis involves finding the best virtual producer for each real producer (Dovis, 2009).

The DEA method does not require the specification of a functional form regarding the type of production frontier, as the data envelope curve is constructed by selecting several efficient decision-making units. There are numerous modelling methods for assessing efficiency in DEA; the traditional models are CCR (Charnes, Cooper, Rhodes with constant returns to scale) and BCC (Banker, Charnes, Cooper with variable returns to scale), which are radial approaches, assuming that all inputs and outputs vary proportionally. The strengths of DEA include, in particular, its effectiveness in handling complex production processes (Schaffnit, Rosen, & Paradi, 1997); its ability to work with inputs and outputs on different scales of measurement (Svitalkova, 2014); its ability to analyse each DMU individually, comparing them with other DMUs, with the optimization process being carried out for all DMUs in the sample (Repková, 2014); and its ability to identify inefficient DMUs. However, it should be noted that the number of DMUs must be at least three times greater; otherwise, many DMUs will be considered efficient (Cooper, Seiford, Tone et al., 2007).

The SBM (Slacks-Based Measure) efficiency measurement method introduced by the Japanese researcher Tone (1997, 2001) is a non-radial efficiency measure within the DEA efficiency measurement method. Its advantage is that it directly measures excess inputs and underproduction. The distance between inputs and outputs relative to the production frontier is called the slack, and is used to measure efficiency. It allows for differentiated adjustments for each input and output and is therefore more realistic. The model below is taken from the work of Cooper, Seiford, Tone et al (2007).

To measure the efficiency of banks, let us assume we have  $x^t \in R^m$  and  $y^t \in R^s$ , which are the selected inputs (m) and outputs (s), and n is the number of banks.

The production function is given by

$$P^t = \{(x^t, y^t): x^t \text{ can product } y^t\} \quad (1)$$

Estimate the efficiency of a DMU  $(x_o, y_o)$ , we formulate the following fractional program in  $\lambda, s^-$  and  $s^+$ : (SBM)

$$\min_{\lambda, s^-, s^+} \rho^{opt} = \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{io}}}{1 + \frac{1}{s} \sum_{r=1}^s \frac{s_r^+}{y_{ro}}} \quad (2)$$

Subject to the constraints:

$$\begin{aligned} x_o &= X\lambda + s^- \\ y_o &= Y\lambda - s^+ \\ \lambda &\geq 0, s^- \geq 0, s^+ \geq 0 \end{aligned}$$

In this model,  $s^-$  and  $s^+$  are the input and output slacks; we assume that  $X \geq 0$ . It is also easy to verify that an increase in  $s_i^-$  or  $s_r^+$ , all other things being equal, decreases the value of the objective function in a strictly monotonically decreasing manner.  $\rho$  represents the ratios of the average combination inefficiencies of inputs and outputs, with the upper bound,  $\rho = 1$ , being reached only

if the slacks are zero for all inputs and all outputs. Therefore, a DMU  $(x_o, y_o)$  is SBM-efficient if and only if  $\rho^* = 1$ , and  $s^{-*} = 0$  and  $s^{+*} = 0$

$$0 \leq \rho \leq 1. (3)$$

Since  $s_i^- \leq x_{io}$  for all  $i$ , so that, with only if the data show that no quantity of that input was required. For outputs, an output shortfall represented by a non-zero slack may exceed the quantity of output actually produced.

$\rho$  in can be transformed into

$$= \left( \frac{1}{m} \sum_{i=1}^m \frac{x_{io} - s_i^-}{x_{io}} \right) \left( \frac{1}{s} \sum_{r=1}^s \frac{y_{ro} + s_r^+}{y_{ro}} \right)^{-1} (4)$$

The ratio evaluates the relative rate of reduction of input  $i$  and, consequently, the first term corresponds to the average rate of proportional reduction of inputs, or to the inefficiencies in the combination of inputs. Similarly, the ratio evaluates the relative rate of proportional expansion of output  $r$ . That is to say, the second term measures the inefficiency in the combination of outputs.

For an SBM-inefficient DMU  $(x_o, y_o)$ , we have the expression:

$$\begin{aligned} x_o &= X\lambda^* + s^{-*} \\ y_o &= Y\lambda^* - s^{+*} \end{aligned}$$

The SBM score  $\rho^*$  can be broken down as follows:

$$\begin{aligned} \rho^* &= \frac{1 - \sum_{i=1}^m \alpha_i}{1 + \sum_{r=1}^s \beta_r} \\ \text{où } \alpha_i &= \frac{1}{m} \frac{s_i^{-*}}{x_{io}} \quad (i = 1, \dots, m) \quad (5) \\ \beta_r &= \frac{1}{s} \frac{s_r^{+*}}{y_{ro}} \quad (r = 1, \dots, s) \end{aligned}$$

Decomposition is important for assessing the sources and extent of inefficiency associated with the various inputs and outputs of the DMU. In the model above, therefore, a DMU with a score close to 1 is **efficient in the optimistic sense** if it is deemed **inefficient in the optimistic sense**.

However, it is also possible to measure the ‘**pessimistic**’ efficiency of banks. In particular, an inefficient frontier (or ‘worst practice’) can be estimated. Banks furthest from this inefficient frontier are considered more efficient (Wang and Chin, 2009). The higher the pessimistic score, the better the bank’s performance; **a score of 1 indicates that the bank is on the frontier and is therefore among the least efficient.**

The pessimistic SBM DEA model according to Liu & Chen (2009) can be expressed as follows:

$$\max \rho^{pes} = \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i}{x_{io}}}{1 - \frac{1}{s} \sum_{r=1}^s \frac{s_r}{y_{ro}}} (6)$$

Subject to the constraint:

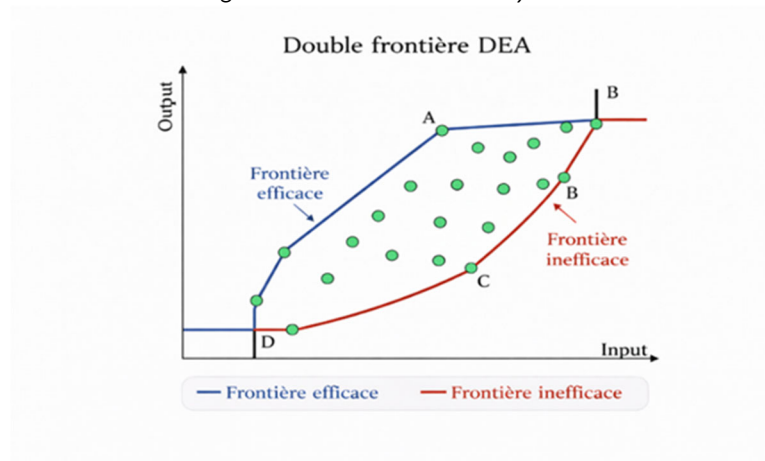
$$\begin{aligned} x_o &= X\lambda - s^+ \\ y_o &= Y\lambda + s^- \\ \lambda &\geq 0, s^+ \geq 0, s^- \geq 0 \\ \rho &\geq 1 \end{aligned}$$

Here we have two frontiers, an optimistic and a pessimistic one; we can follow Wang et al. ((2007) to calculate the overall efficiency of bank  $j$  in year  $t$  as the geometric mean of using the equation below. Both frontiers must be considered simultaneously in the efficiency analysis in order to obtain better estimates, Liu & Chen (2009). The higher the value of  $\rho^{all}$ , the better the bank’s performance.

$$\rho^{all} = \sqrt{\rho_{j,t}^{opt} \times \rho_{j,t}^{pes}} (7)$$

As already discussed in the section above, the profit-based approach resolves the issue of whether to treat deposits as inputs or outputs; consequently, the profit-based approach will be our choice for this study. Regarding inputs and outputs, we will use operating expenses as a proxy for expenditure on staff and physical capital. Interest expenses will be used as a proxy for expenditure on deposits and other creditors of the bank. As an output, we will choose operating profit as it allows us to include provisions for bad debts, and prevents banks from being deemed efficient without taking into account the risks they take. The models will be VRS, which takes into account economies of scale in the calculation of efficiency; this is widely used in studies of the banking sector as banks require economies of scale to operate.

Figure 2 Double-boundary DEA



Source : Authors, 2026

### 3.2. DEA-Malmquist index model

The DEA-Malmquist index method is used to analyze and decompose efficiency (Cooper, Seiford, Tone et al, 2007). All traditional DEA models use data from a specific year as a sample for analysis, which can only reflect the relative efficiency values of different economies at a single point in time, and does not allow for the study of changes in their efficiency across different periods. The DEA-Malmquist index model can measure dynamic changes in the efficiency of decision-making units using the 'directional distance function (DDF)'; it can therefore analyze panel data, which not only allows the total factor efficiency to be decomposed into technical efficiency, technological progress and scale efficiency, but also clarifies the reasons for changes in the total factor productivity of the subject under study.

The production frontier with an output-oriented distance function, under the assumption of constant returns to scale (CRS), can be defined as:

Technical efficiency is estimated relative to the production frontier, such that  $0 < D_o^t(x^t, y^t) \leq 1$

The Malmquist productivity index must be defined on the basis of the reference technology, under CRS (constant returns to scale), and is:

$$M_t(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)}$$

$$M_{t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)} \quad (8)$$

Given that the Malmquist productivity indices defined by reference techniques based on the periods and are symmetric in economic terms, their geometric means are defined as composite productivity indices according to Fisher's concept, namely:

$$TFP = EFFCH \times TECHCH \quad (9)$$

There is no difference between the and TECHCH (boundary shift) indices with regard to the Malmquist productivity index itself. The EFFCH ratio measures the change in a DMU's technical efficiency relative to the best-practice frontier, indicating whether it is moving closer to or further

away from the production frontier  $t$  and  $t + 1$ ; the difference between and lies in the decomposition of the index. EFFCH is then decomposed, as suggested by Färe et al. (1994), into changes in pure efficiency (PECH) and changes in scale efficiency (SECH).

The decomposition is as follows:

$$\begin{aligned}
 FFCH &= PECH \times SECH \\
 TFP &= \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \\
 &= \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_v^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D_v^{t+1}(x^{t+1}, y^{t+1})}{D_v^t(x^t, y^t)} \times \frac{D_v^t(x^t, y^t)}{D_c^t(x^t, y^t)} \quad (10) \\
 &= PECH \times SECH \times TECHCH
 \end{aligned}$$

### 3.3. Two-stage DEA and bootstrapping

Two-stage DEA is widely used in studies of banking efficiency to estimate efficiency scores and explain their variation using environmental variables. This approach divides the analysis into two distinct phases: (1) the estimation of efficiency scores using DEA, and (2) the regression (or another technique, whether parametric or non-parametric) of these scores on environmental or contextual variables to identify their determinants and thus enable a more comprehensive analysis, Ayadi et al. (2016).

Traditional DEA models have been criticized for failing to take into account external environmental factors beyond the organization’s control, over which decision-makers have no influence. In other words, the environment in which the bank operates is not considered in the analysis. Often, a bank is considered efficient (or inefficient) simply because it is aided by favorable external factors (or, conversely, suffers from unfavorable ones). This renders the efficiency scores of the DEA model biased.

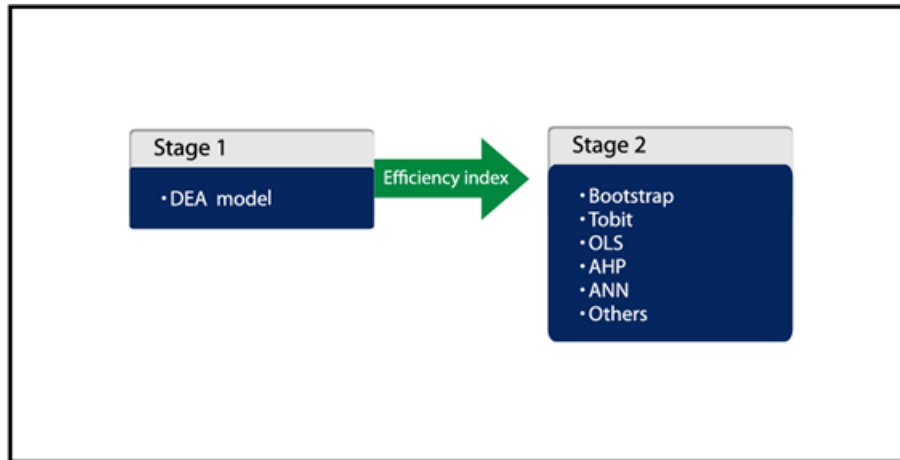
In an effort to improve the application of DEA, two-stage DEA models have gained prominence in the literature, precisely because they help to overcome the aforementioned limitations. The econometric methods used in the second stage of two-stage DEA models are the subject of ongoing debate. Whilst Tobit regression is widely used due to the bounded nature of DEA scores, it is criticized for its lack of statistical consistency. Simar and Wilson (2007) developed a bootstrap-based truncated regression approach to address the limitations of conventional methods. They argue that DEA efficiency scores are biased and serially correlated, thereby invalidating standard inference in second-stage regressions. Given that the variables used as inputs are considered endogenous (Lensink & Meesters, 2014), the use of bias-corrected estimates in a stochastic framework offers additional protection against the classic endogeneity problems frequently encountered in regression specifications incorporating firm-level data (Van Biesebeek, 2008). The bootstrap procedure is used to correct for bias and provide valid confidence intervals and standard errors, overcoming the problems of serial correlation and dependence inherent in DEA scores (Voltes-Dorta, Britto and Wilson, 2024).

In our case, the number of observations is quite small, but to correct for the effects of intra-bank relationships by year (data are often **correlated within groups (clusters)**). We will use the Bootstrap procedure of Cameron and Miller (2008), who demonstrated the effectiveness of the Wild Cluster Bootstrap-t<sup>2</sup> when dealing with clusters of 5–30. This method has the advantage, compared to other cluster-handling methods that estimate standard errors under the assumption of i.i.d., of being robust to heteroscedasticity and working with a small number of clusters. In standard clustering methods, the explanatory variables and the dependent variable must take on several

<sup>2</sup> See also Roodman et al (2019) for STATA

different values. **Wild cluster bootstrap** methods do not encounter this problem, as they do not resample the explanatory variables.

Figure 3 External two-stage DEA



Source: I.C. Henriques et al (2020)

The model used is presented as follows:  $Eff$  represents the wild cluster bootstrap bias-corrected efficiency scores of bank  $i$  at period  $t$ ,  $X_{it}$  is a vector of bank-specific financial variables,  $Y_{it}$  are the macroeconomic control variables, and  $\varepsilon_{it}$  is the error term.

**Cap** is defined as the ratio of equity to total assets, and is used to measure the strength of a bank's capital; it acts as a safety net for banks. **Credit risk (NPL)** is measured by the ratio of loan loss provisions to total loans. We therefore expect a negative relationship between credit risk and the level of banking efficiency. To account for economies of scale, we include the **size** variable, measured by the logarithm of banks' real total assets. As stated above, a larger size can reduce the costs of information asymmetry and information gathering. Following the study by Ziadi Ellouze (2024), **the ILer** (Lerner index) allows, amongst other things, the capture of the bank's market power effect. **(GDPg)** is introduced to control for the macroeconomic environment, Benbachir (2025). This variable is expected to be positively associated with levels of banking efficiency. Finally, our specifications take into account the effects of inflation. An instrumental variable for the Covid crisis (in 2020 and 2021) will be used to account for the effect of the health crisis on banks, given that they were the institutions most called upon by the government during the crisis, as well as to isolate the effect on economic growth and non-performing loans.

$$Eff_{it} = c + a'X'_{it} + Criscov_{it} + \gamma ILer'_{it} + \beta'Y'_{it} + \varepsilon_{it} \quad (11)$$

### 3.4. Lerner index

The Lerner index measures the degree of market power of a specific bank on an annual basis. It can be calculated using the relative difference between price and marginal cost. The Lerner index generally ranges from 0 to 1, with higher values indicating a higher level of market power and a lower level of competition, whilst lower values indicate a lower level of market power and a higher degree of competition (Fare et al., 2015; Fungacova et al., 2013; Tan & Floros, 2014; Tan et al., 2017; Liu et al., 2018). In some cases, the value of the Lerner index may be negative. We use the ordinary least squares method to estimate the Lerner index whilst controlling for bank fixed effects and time dummies. The specification can be expressed as follows:

$$\ln Cost_{it} = \beta_0 + \beta_1 \ln Q_{it} + \beta_2 / 2 (\ln Q_{it})^2 + \sum \gamma_{kt} \ln P_{k,it} + \sum \varphi_k \ln Q_{it} \ln P_{k,it} + \sum \sum \delta_{kj} \ln P_{k,it} \ln P_{j,it} + \varepsilon_{it} \quad (12)$$

where  $\ln$  denotes the natural logarithm, **Cost** denotes total cost, and **Q** denotes bank output. Here, the sum of interest income, non-interest income and net income serves as a proxy for bank output.  $P$  denotes the three input prices, PL, PF and PC are respectively: normally, labour cost is given by the ratio of staff costs to total assets. PL refers to human input, and we use operating expenses and total assets to proxy for PL and PK, as it is difficult to obtain complete data on staff costs and wages; since it is difficult to obtain the total number of staff, we draw here on the approach of Claessens and Laeven (2003) and Bikker and Haaf (2002). Cost of funds calculated as the ratio of interest expenses to total deposits. Following the approach of many other studies [Koetter et al. (2012); Shaffer et al. (2020)], we impose linear homogeneity in factor prices by normalizing total costs and factor prices relative to the cost of funds (PF).

The above equation is differentiated to derive the marginal cost with respect to output  $Q$  as follows

$$MC_{TA,it} = \frac{Cost_{it}}{Q_{it}[\beta_1 + \beta_2 \ln Q_{it} + \sum \varphi_k \ln P_{k,it}]} \quad (13)$$

The Lerner index is given by:

$$Lerner_{it} = (P_{TA,it} - MC_{TA,it}) / P_{TA,it} \quad (14)$$

Where  $P$  represents the price, which is measured as the ratio of total revenue to total assets.  $MC$  represents marginal cost, and  $TA$  represents total assets. In certain scenarios, when the Lerner index is negative, the price level is lower than the marginal cost. This can be explained by the banking industry, which is characterized by a particularly high level of government subsidies. A negative Lerner index is beneficial to the banking industry, on the one hand because a higher marginal cost deters entry, which is conducive to improving the profits of existing banks. On the other hand, a marginal cost higher than the price level indicates that banks are incurring short-term losses. The results of the OLS regression for the Lerner index are presented in the table.

### 3.5. Data and software

In this study, we use data from the World Development Indicators (WDI) for macroeconomic variables, whilst the financial variables for each bank are drawn from the banks' annual reports. The observation period is 2012–2024, and the sample comprises five banks (BOA MADA, BNI, SG MADA, BMOI MADA, MCB MADA), which hold 90 per cent of the market share in the country (according to theglobeconomy.com and madagascarinvest, 2025); we encountered difficulties in collecting data for the other banks in the sector. We used RStudio 2024.12 with R 4.5.2 for score calculations and econometric regression. The main package used for R in the calculation of scores was rDEA.

Table1 List of variables and data sources

variables	Source
Inflation rate	WDI World Bank
Economic growth	World Bank WDI
Bank financial variables	Banks' annual financial reports

Source: Author, 2025

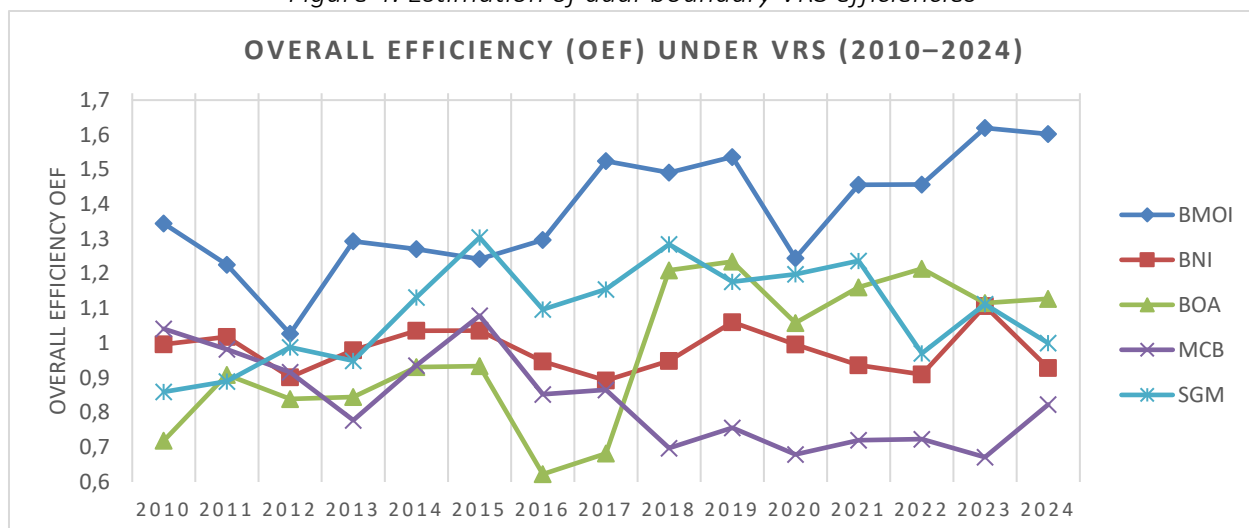
## 4. Results and discussion

### 4.1. Double-boundary DEA scores

In Table 4.1 of the Appendix, we first present the efficiency scores for the optimistic and pessimistic frontiers, as well as the geometric mean for the banks. As the table shows, the scores between the two frontiers differ but are consistent; using the average of the two frontiers allows for a better distinction between the banks that are efficient. If we examine the banks' average double-boundary score, BMOI is the most efficient with an average of 1.375 for the entire study

period 2010–2024, followed by SGM with 1.09 and BNI, which rounds off the top three with 0.979. This result comes as little surprise, as BMOI is a bank whose client base consists mainly of corporate clients, so it performs better in terms of profit optimization. SGM (which became BRED Madagascar in 2024) and BNI are among the largest and oldest banks in the sector. Regarding the consistency of average scores over the period. We note that there is not much difference between the efficiency of the top-ranked bank and the bottom-ranked one; indeed, MCB, which has a score of 0.834 over the period, is less than 1.6 times the score of BMOI.

Figure 4: Estimation of dual-boundary VRS efficiencies



Source: Author’s calculation using rDEA, 2025

It should also be noted that the banks experienced a decline in efficiency in 2020, which may be attributable to the COVID-19 crisis. Only SGM remained resilient in the face of the crisis, as shown in the graph above, though this resulted in a decline in efficiency in 2022. During the crisis, banks were heavily relied upon by the country’s government, as was the case in most countries at that time. The increase in provisions for non-performing loans and loan restructuring, combined with the decline in activity, explains this drop in efficiency during the COVID-19 pandemic, as we will see in the sub-section below.

#### 4.2. DEA Malmquist

As mentioned above, the DEA-MI allows us to measure changes in banks’ total productivity in a dynamic manner. These changes are measured relative to changes in efficiency and technical progress. The table below shows the change in total productivity, the change in efficiency, the change in technology, pure efficiency, and scale efficiency, all on a five-year basis. The results by year/bank can be found in the appendix. It should be noted that the change in TFPCH is the product of EFFCH and TECHCH. We observe that banks’ TFP is declining across the three sub-periods, although some banks show a higher rate of change in the 2015–2020 sub-period, i.e. prior to the COVID-19 crisis. It is clear that the change in TFP is really due to the change in TECHCH rather than EFFCH; for example, for BNI in 2015–2020, we see a 4.1% improvement in technical progress, which improves TFP by 1.5%; the 4.2% improvement in MCB over the same period allowed TFP to remain more or less stable; and finally, for SGM, a 6.3% increase in TECHCH resulted in a 2.2% rise in TFP. Thus, the crisis, which was expected to be a catalyst for digital transformation and innovation, actually slowed technical progress due to recruitment freezes and budget cuts in the banking sector during the crisis; however, we now see that recruitment of IT staff is very much on the rise. The pure efficiency of banks is relatively stable, but the efficiency of scale shows that most banks, excluding BMOI, are not operating at their best or are failing to manage their growth to exploit economies of scale.

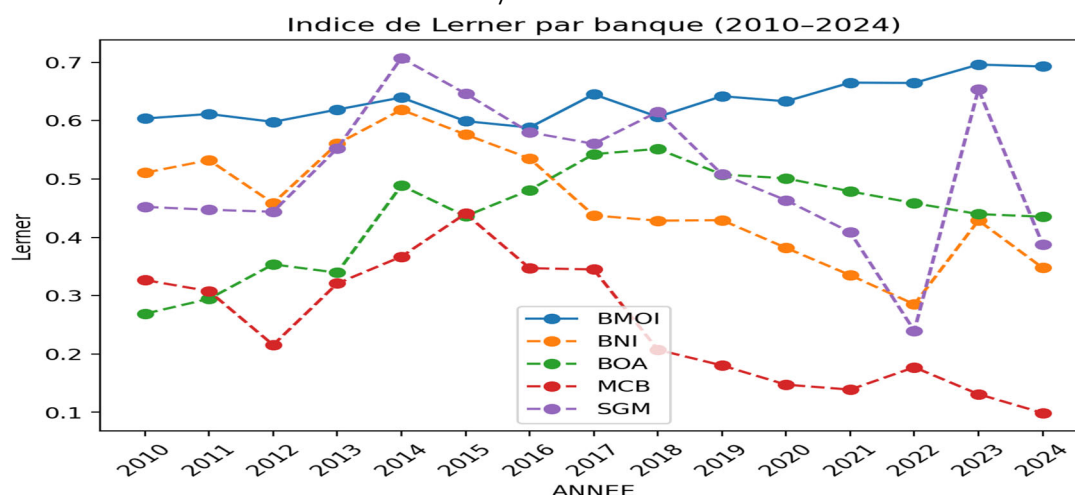
Table 2 Breakdown of the Malmquist index

Banque	Periode	TFPCH_geo m	EFFCH_geo m	TECHCH_geo m	PECH_geo m	SECH_geo m
BMOI	2010-2015	1.0165020	0.9996077	1.0169010	1.0000000	0.9996077
BMOI	2015-2020	0.9810347	1.0003925	0.9806498	1.0000000	1.0003925
BMOI	2020-2024	0.9318339	1.0000000	0.9318339	1.0000000	1.0000000
BNI	2010-2015	0.9897152	1.0001894	0.9895277	0.9644218	1.0370871
BNI	2015-2020	1.0156731	0.9754811	1.0412022	1.0103689	0.9654703
BNI	2020-2024	0.9318495	0.9705026	0.9601720	1.0037614	0.9668659
BOA	2010-2015	1.0125491	1.0409599	0.9727071	0.9921208	1.0492270
BOA	2015-2020	0.9977965	0.9976976	1.0000991	1.0220888	0.9761359
BOA	2020-2024	0.9396514	0.9868217	0.9521997	1.0279545	0.9599858
MCB	2010-2015	0.9879468	0.9909893	0.9969298	1.0000000	0.9909893
MCB	2015-2020	0.9587389	0.9196819	1.0424680	1.0000000	0.9196819
MCB	2020-2024	0.9534369	1.0159891	0.9384321	1.0000000	1.0159891
SGM	2010-2015	1.0047129	1.0681807	0.9405833	1.0065424	1.0612376
SGM	2015-2020	1.0220462	0.9609295	1.0636017	1.0000000	0.9609295
SGM	2020-2024	0.9075726	0.9314618	0.9743530	1.0000000	0.9314618

Source: Author’s calculation using rDEA, 2025

### 4.3. The Lerner index

Descriptive analysis results indicate that the banking sector exhibits significant market power over the period 2010–2024. The values of the Lerner index, mostly ranging between 0.4 and 0.7 (see appendix), suggest an oligopolistic structure rather than a perfectly competitive environment. Thus, BMOI has the most stable and highest Lerner index value, meaning that it sells its products with a higher margin over its marginal cost than most banks in the sample. However, MCB has an increasingly lower Lerner index; the figure below shows that the efficiency calculated above and the Lerner index follow roughly the same trends. So we may be looking at the optimistic view of the effect of concentration on efficiency.



Source: Author’s calculation using R (fwildclusterboot), 2025

The regression results show that the model does not exhibit a non-linear relationship at a 10% significance level. The trend is not significant, nor is the quadratic relationship with the price of non-fund factors. Statistically, the model is now valid, with a fairly good R<sup>2</sup> of 0.976. It is important to note that Hausman tests rely on fairly large samples; the autocorrelation test before the bootstrap does indeed show that there are relationships between clusters, and it is theoretically

true that each bank should have cost structures that are fairly trend-like, which validates the use of the fixed-effects regression procedure with the OLS wild bootstrap.

Table 3 Regression results with OLS wild bootstrap

variable	Coefficient	t_stat	p_value
1*(Intercept)	14,8320	139.926	0.001 ***
1*lnQ_c	1,13100	15.617	0.018 ***
1*lnQ <sup>2</sup> _c	0,02600	0.81	0.0806 **
1*lnP	0,68500	10.78	0.0231 ***
1*lnQ_c lnP	-0,39400	-2.039	0.2109
1*lnP <sup>2</sup>	0,00020	0.188	0.7803
1*trend	0,00046	0.129	0.6502

Adj. R<sup>2</sup>: 0.976599 R<sup>2</sup>: 0.978496

Source: Author's calculation using R(fwildclusterboot), 2025

#### 4.4. Second-stage regression

In the second stage, regression with explanatory variables was used to explain bank efficiency, as mentioned above. The results show that capitalization (CAP) has a positive and significant effect on bank efficiency; although the effect is very close to zero, this result is consistent with the findings of Fernandes et al. (2017). Credit risk (CRIS) has a negative and significant coefficient; this indicates that banks spend more on monitoring when credit risks increase, which impacts their profits. As in the findings of Cooper et al. (2003) and Berger et al. (1997), a change in the quality of the loan portfolio is one of the causes of bank failures. Faced with credit risk, banks adopt risk-averse behavior towards both existing and new loans. *The first hypothesis is well supported and consistent with the BFM's periodic surveys of the banking sector.* We also observe that the SIZE variable has a positive impact on efficiency, which validates previous theoretical and empirical work showing that larger banks reduce the costs associated with collecting and processing information (Eber N., 2000; Staub et al., 2010).

We also posted a second hypothesis that competition has a negative impact on banks' efficiency. The Lerner index calculated above shows that all banks have intermediate market power. Here, we have a positive coefficient with greater significance. This result is not very surprising given the figures above on the evolution of efficiencies within the two boundaries and also the Lerner index for each bank. Several studies have found the same result, most recently that of Ellouz N. (2023). Here too, *we confirm that competition has a negative effect on efficiency;* it should be noted that the Lerner index measures market power, and therefore the higher the index, the less competitive the structure. However, the definition of competition in the BFM survey must be treated with caution to avoid misinterpretation, as respondents may be thinking of concentration rather than competition when defining the term.

Table 4 Coefficients, cluster SE and wild bootstrap p-values (boottest, B=9999)

$$\text{Eff} \sim \text{CAP} + \text{CRIS} + \text{SIZE} + \text{Lern} + \text{covid} + \text{Inflation} + \text{GDP} + \text{FE}$$

Variable	Coef.	SE (cluster)	t (cluster)	p (cluster)
CAP	0.0074	0.0025	2.973	0.0410
CRIS	-0.9242	0.1041	-3.313	0.0596
SIZE	0.2876	0.1138	2.527	0.0648
Lern	0.7388	0.1822	4.054	0.0154
covid	-0.0350	0.0513	0.683	0.5322
Inflation	0.0083	0.0077	1.081	0.3406
GDP	0.0161	0.0023	4.705	0.04197

Source: Author's calculation using R(fwildclusterboot), 2025

The model demonstrates good explanatory power with an  $R^2$  of 0.859 and an adjusted  $R^2$  of 0.817. Approximately 86% of the variation in banking efficiency is explained by internal variables, macroeconomic variables and the bank-specific fixed effects. The root mean square error (RMSE = 0.094) remains relatively low, indicating a satisfactory fit of the model.

For the macroeconomic variables, inflation has a non-significant coefficient of zero in this regression; if, hypothetically, the coefficient was significant, one might imagine that banks are able to anticipate inflation, meaning that banks are able to adjust their interest rates and, consequently, increase their revenues at a faster rate than their costs (Perry, 1992). The effect of COVID-19 has the expected sign but is also insignificant in the results. This may be due to our relatively small sample size and also to a lack of variability in certain variables, as we are studying a single country. Even so, we can conclude that banks have been more resilient in the face of the COVID-19 pandemic, as we observe a slight decline in efficiency across the board, except BMOI and BOA in 2020. The positive effect of GDP growth is consistent with research suggesting that economic growth promotes improved performance in the financial sector, particularly from the demand-side perspective of financial development theory. This also confirms the findings of Razafindravonona et al. (2020) in their stress testing study of the Malagasy banking sector. Given this finding, it is reasonable to conclude that the third hypothesis is also validated.

## 5. Conclusion

This study was primarily motivated by an analysis of the efficiency of commercial banks in Madagascar, as well as the impact of credit risk, competition and the macroeconomic environment during the period 2010–2024. The literature on the subject shows that few studies have been conducted on the African continent (Henriques, 2020), particularly using the methodology adopted in this study. Our hypotheses were initially supported by the literature and also by the BFM survey of the banking sector. In this study, a two-stage approach was employed, combining the double-boundary SBM-DEA method following Wang et al. (2007) and a second-stage regression estimated using wild bootstrap clustering. This methodological strategy allows for a rigorous measurement of efficiency whilst correcting for inference problems related to heteroscedasticity and intra-group dependence (Cameron and Miller, 2008), and is in line with the recommendations of Simar and Wilson (2007) regarding the correction of biases in two-stage DEA models.

The empirical results highlight a significant negative effect of credit risk on banking efficiency. This finding confirms the hypothesis that a deterioration in the quality of the loan portfolio increases the costs of monitoring, provisioning and restructuring, thereby reducing operational performance. Berger et al (1997) have already demonstrated a close relationship between non-performing loans and banking inefficiency.

With regard to market power, the Lerner index is found to have a positive effect on efficiency. This result is consistent with the efficient-market hypothesis (Demsetz, 1973; Peltzman, 1997) and the Information Generating Hypothesis (IGH) developed by Marquez (2002), according to which the most efficient banks gain market power and generate higher margins. However, this does not refute the 'Quiet Life' theory proposed by Hicks (1935), as owners of monopolistic firms can in fact exercise the same control over management effort as those in competitive firms, and the sector has a monopolistic structure since the Lerner index lies between 0 and 1. Furthermore, economic growth has a positive and significant effect on banking efficiency. A favorable macroeconomic environment improves borrowers' creditworthiness, stimulates demand for credit and reduces defaults.

Methodologically, the use of the double frontier allows for a more precise framing of the observed performance, whilst the use of the wild bootstrap cluster improves the robustness of the inference (Cameron et al., 2008). However, the main limitation of this research lies in the relatively small

sample size, which restricts the full application of the double bootstrap method by Simar and Wilson (2007) to correct biases in DEA scores and refine confidence intervals. This limitation suggests the need for future research to extend the analysis to larger samples and longer time periods, and to use parametric methods for assessing bank efficiency.

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## Appendices

Table A 1 Double-boundary DEA results

ANNEE	BANQUE	RTS	EFopt	EFpes	OEF	RANG
2010	BMOI	VRS	1.0000000	1.807083	1,3442778	8
2011	BMOI	VRS	0.9662358	1.554649	1,2256254	18
2012	BMOI	VRS	0.8135980	1.296159	1,0269141	37
2013	BMOI	VRS	0.8960072	1.866356	1,293162	11
2014	BMOI	VRS	0.8583014	1.881305	1,2707188	13
2015	BMOI	VRS	0.8077590	1.910049	1,242119	15
2016	BMOI	VRS	0.8364747	2.010992	1,2969751	10
2017	BMOI	VRS	0.9750070	2.382508	1,5241266	4
2018	BMOI	VRS	0.9442930	2.353780	1,490858	5
2019	BMOI	VRS	0.9712733	2.429114	1,5360123	3
2020	BMOI	VRS	0.7807890	1.984158	1,244672	14
2021	BMOI	VRS	0.9135819	2.320073	1,4558765	7
2022	BMOI	VRS	0.9141466	2.321144	1,4566625	6
2023	BMOI	VRS	1.0000000	2.624098	1,6199069	1
2024	BMOI	VRS	1.0000000	2.566832	1,6021335	2
2010	BNI	VRS	0.6426324	1.544549	0,9962817	40
2011	BNI	VRS	0.6551047	1.581604	1,0178978	38
2012	BNI	VRS	0.5781369	1.406230	0,9016615	57
2013	BNI	VRS	0.6261076	1.532798	0,9796409	44
2014	BNI	VRS	0.6685297	1.604189	1,0355907	36
2015	BNI	VRS	0.6520621	1.645228	1,0357561	35
2016	BNI	VRS	0.5891993	1.522559	0,9471488	48
2017	BNI	VRS	0.5554274	1.433685	0,892361	58
2018	BNI	VRS	0.5974313	1.506502	0,9486998	47
2019	BNI	VRS	0.6834608	1.644869	1,0602846	32
2020	BNI	VRS	0.6644331	1.492750	0,9959078	41
2021	BNI	VRS	0.6820326	1.284787	0,9360913	49
2022	BNI	VRS	0.7406821	1.117432	0,9097591	55
2023	BNI	VRS	0.8996079	1.361783	1,1068292	29
2024	BNI	VRS	0.8618530	1.000000	0,9283604	53
2010	BOA	VRS	0.4591221	1.125340	0,7187964	70
2011	BOA	VRS	0.5764669	1.431978	0,9085637	56
2012	BOA	VRS	0.5268569	1.335799	0,8389131	64
2013	BOA	VRS	0.5254750	1.358130	0,844786	63
2014	BOA	VRS	0.5760091	1.504431	0,9308954	52
2015	BOA	VRS	0.5805243	1.501508	0,9336285	51
2016	BOA	VRS	0.3875640	1.000764	0,6227841	75
2017	BOA	VRS	0.4283924	1.085965	0,6820697	72
2018	BOA	VRS	0.7668405	1.907801	1,2095366	20
2019	BOA	VRS	0.7903413	1.929519	1,2349002	17
2020	BOA	VRS	0.7110549	1.573982	1,0579167	33
2021	BOA	VRS	0.7799262	1.727480	1,1607355	23
2022	BOA	VRS	0.8379004	1.759509	1,2142047	19
2023	BOA	VRS	0.8659861	1.436569	1,1153693	27

2024	BOA	VRS	1.0000000	1.271024	1,1273968	26
2010	MCB	VRS	1.0000000	1.083885	1,0410981	34
2011	MCB	VRS	0.8459178	1.140333	0,9821548	43
2012	MCB	VRS	0.8359360	1.004166	0,9161981	54
2013	MCB	VRS	0.6048009	1.000000	0,7776895	66
2014	MCB	VRS	0.7218778	1.211598	0,9352143	50
2015	MCB	VRS	0.8084838	1.440540	1,079191	31
2016	MCB	VRS	0.6416813	1.132015	0,8522868	62
2017	MCB	VRS	0.6380990	1.172981	0,8651464	60
2018	MCB	VRS	0.4862397	1.000000	0,6973089	71
2019	MCB	VRS	0.5211894	1.096622	0,7560079	67
2020	MCB	VRS	0.4613634	1.000000	0,6792373	73
2021	MCB	VRS	0.4840670	1.071681	0,7202537	69
2022	MCB	VRS	0.4804173	1.088698	0,7232076	68
2023	MCB	VRS	0.4508021	1.000000	0,671418	74
2024	MCB	VRS	0.5711414	1.185700	0,8229229	65
2010	SGM	VRS	0.5515384	1.338974	0,8593575	61
2011	SGM	VRS	0.5647290	1.401293	0,8895791	59
2012	SGM	VRS	0.6284458	1.552818	0,9878574	42
2013	SGM	VRS	0.5999171	1.501067	0,9489549	46
2014	SGM	VRS	0.7271457	1.760780	1,1315226	25
2015	SGM	VRS	0.8414896	2.021764	1,3043364	9
2016	SGM	VRS	0.6803496	1.768505	1,0969055	30
2017	SGM	VRS	0.7261087	1.836532	1,154782	24
2018	SGM	VRS	0.8492900	1.942536	1,2844361	12
2019	SGM	VRS	0.7702781	1.797252	1,1765983	22
2020	SGM	VRS	0.8107996	1.770870	1,1982574	21
2021	SGM	VRS	0.8413018	1.818182	1,2367862	16
2022	SGM	VRS	0.9419888	1.000000	0,9705611	45
2023	SGM	VRS	1.0000000	1.236567	1,1120105	28
2024	SGM	VRS	1.0000000	1.000000	1	39

Source: Authors, 2025

Table A2 Malmquist by year

ANNEE	BMOI	BNI	BOA	MCB	SGM
2010	0,60369208	0,51060812	0,26887886	0,32672327	0,45218978
2011	0,6114144	0,5323946	0,29452356	0,30764632	0,44722157
2012	0,59785051	0,45832407	0,35356299	0,21542691	0,4437507
2013	0,61896586	0,56023769	0,33929314	0,32086751	0,55236968
2014	0,63967295	0,61863222	0,48883862	0,36685004	0,70747468
2015	0,59913801	0,57631809	0,43615867	0,44052612	0,64638998
2016	0,58821403	0,53517284	0,48100554	0,3470353	0,57994908
2017	0,64514643	0,43746453	0,54253398	0,34487594	0,56021105
2018	0,60646627	0,4284419	0,55164556	0,20712602	0,61512865
2019	0,64191639	0,4294121	0,50756015	0,18030032	0,50791578
2020	0,63307328	0,38179887	0,50110844	0,14730739	0,46348772

<b>2021</b>	0,66514158	0,33504203	0,47863688	0,13885116	0,40861308
<b>2022</b>	0,66459727	0,28508723	0,45852251	0,17715836	0,2397724
<b>2023</b>	0,69610177	0,4288358	0,43974726	0,13102505	0,65355644
<b>2024</b>	0,69286486	0,34767709	0,43526776	0,09887438	0,3879864

Source: Authors, 2025

**TABLE A3 Lerner index by sub-period**

Banque	2010-2015	2015-2020	2020-2024
BMOI	0.6118	0.6190	0.6704
BNI	0.5428	0.4648	0.3557
BOA	0.3635	0.5033	0.4627
MCB	0.3297	0.2779	0.1386
SGM	0.5416	0.5622	0.4307

Source: Authors, 2025

# Lokal segmentdə Rəqəmsal Marketing ekosisteminin təkamülü: Süni intellekt və analitik yanaşmalar

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## Xülasə

Bu tədqiqat işi lokal bazar mühitində fəaliyyət göstərən kiçik və orta bizneslərin (KOB) rəqəmsal transformasiyasını təhlil edir. İşin əsas məqsədi süni intellekt və analitik yanaşmaların idarəetmə proseslərinə inteqrasiyasının yaratdığı dəyəri və rəqabət üstünlüklərini müəyyənləşdirməkdir. Məqalədə orqanik axtarış təcrübəsinin istifadəçi niyyətinə uyğun təkamülü, həmçinin süni intellektin hədəfləməni necə intellektuallaşdırdığı öyrənilir. Məlumat analitikası qərarvermə prosesini fərziyələrdən xilas edərək həm xərcləri optimallaşdırır, həm də istifadəçi təcrübəsini fərdiləşdirir. Nəticə etibarilə, bu iki texnologiyanın vəhdəti lokal bizneslərin dayanıqlı inkişafı üçün mütərəqqi və səmərəli idarəetmə modelini təmin edir.

**Açar sözlər:** rəqəmsal marketing, lokal segment, süni intellekt, məlumat analitikası, orqanik axtarış, KOB.

## Summary

This research analyzes the digital transformation of small and medium-sized enterprises (SMEs) operating in the local market environment. The main purpose of the study is to determine the value and competitive advantages created by the integration of artificial intelligence and analytical approaches into management processes. The article examines the evolution of the organic search experience according to user intent, as well as how artificial intelligence intellectualizes targeting. Data analytics rescues the decision-making process from assumptions, optimizing costs and personalizing the user experience. Consequently, the unity of these two technologies provides a progressive and efficient management model for the sustainable development of local businesses.

**Keywords:** digital marketing, local segment, artificial intelligence, data analytics, organic search, SME.

Mövzu üzrə tədqiq etməyə çalışdığımız tezis müqəddiməsində idarəetmə və iqtisadi yanaşmaların təməl xüsusiyyətlərinin rəqəmsal transformasiya fonunda necə dəyişdiyini xatırlamağı zəruri hesab edirik. Klassik iqtisadiyyat məhdud fiziki və maliyyə resurslarının ən səmərəli şəkildə idarə olunmasını hədəfləyirsə, müasir dövrdə bu missiya rəqəmsal marketing ekosistemi vasitəsilə qeyri-maddi aktivlərin (məlumat, diqqət və istifadəçi təcrübəsi) idarə edilməsinə transfer olunmuşdur. Məhz bu aspektdən, xüsusilə lokal segmentdə fəaliyyət göstərən kiçik və orta biznes (KOB) subyektlərinin inkişaf platformasını rəqəmsal həllər olmadan təsəvvür etmək mümkün deyil. Qlobal mühitdə baş verən innovativ yüksəlişlər lokal bazarlarda fəaliyyət göstərən müəssisələr üçün həm yeni inkişaf üföqləri, həm də ciddi rəqabət mühiti

formalaşdırmışdır. Rəqəmsal resursların məqsədyönlü və təmərküləşmiş şəkildə idarə olunması isə artıq sadəcə bir seçim deyil, biznesin dayanıqlılığını təmin edən fundamental zərurətə çevrilmişdir.

İstehlakçı davranışlarının və marketinq mexanizmlərinin təkamülünə diskursiv yanaşma sərgiləsək, ənənəvi alətlərdən rəqəmsal müstəviyə keçidin olduqca kəskin və çoxvektorlu bir trayektoriya üzrə inkişaf etdiyini görə bilərik. Əvvəllər tələb və təklif münasibətləri lokal coğrafi məhdudiyyətlər çərçivəsində, birtərəfli kommunikasiya vasitələri ilə tənzimləndisə, hazırkı ekosistemdə proseslər tamamilə interaktiv və çoxşaxəli bir xarakter almışdır. Bu təkamül prosesinin ən bariz nümunəsini axtarış sistemlərinin inkişaf dinamikasında müşahidə etmək mümkündür. Belə ki, ilkin mərhələlərdə orqanik axtarış konsepti sadəcə mətn daxilindəki açar sözlərin mexaniki uyğunluğuna əsaslanırdı. Lakin zamanla axtarış sistemlərinin alqoritmik strukturunun mürəkkəbləşməsi nəticəsində orqanik trafik əldə etmək mexanizmi bəsit texniki parametrlərdən uzaqlaşaraq, istifadəçi niyyətini (user intent) və semantik axtarış məntiqini dərinlən anlayın intellektual formaya doğru təkamül etmişdir. Bu transformasiya lokal bizneslərdən öz rəqəmsal varlıqlarını sadəcə görünür etməyi deyil, eyni zamanda istifadəçi tələbatlarına adekvat, dəyər yaradan və məzmun baxımından zəngin bir strateji yanaşma tətbiq etməyi tələb edir.

Lokal seqmentdə fəaliyyət göstərən müəssisələr (xüsusilə də kiçik və orta bizneslər) üçün rəqəmsal transformasiyanın ən həlledici və intellektual tutumlu mərhələsi süni intellekt texnologiyalarının idarəetmə proseslərinə inteqrasiyasıdır. Maşın öyrənməsi (machine learning) və prediktiv (proqnozlaşdırıcı) alqoritmlər sadəcə avtomatlaşdırma aləti deyil, eyni zamanda böyük həcmli məlumatları emal edən konseptual bir rəqəmsal zəkadır. Bu yanaşmanın iqtisadi və texnoloji dərinliyini anlamaq üçün müasir süni intellekt nəzəriyyəsinin aparıcı simalarından olan professor Endryu Nq-nin (Andrew Ng) fundamental tezisə müraciət etmək yerinə düşər: "Süni intellekt yeni elektrik enerjisidir. Elektrik yüz il əvvəl sənayeni necə kökündən dəyişdirdisə, süni intellekt də bu gün eyni transformasiyanı həyata keçirir."

Bu diskursiv yanaşmanı lokal bazar iqtisadiyyatına proyeksiyalasaq, məlumatı emal edə bilən, istehlakçı davranışlarını süni intellekt vasitəsilə əvvəlcədən təhlil edən subyektlərlə, prosesləri yalnız ənənəvi üsullarla idarə edən subyektlərin rəqəbat mühitində kəskin fərqlənəcəyini mütləq şəkildə görürük. Məhz bu amil süni intellekti sadəcə bəsit məzmun yaradıcılığı çərçivəsindən çıxararaq, orqanik axtarış nəticələrinin təkmilləşdirilməsi, hədəf kütlə davranışlarının proqnozlaşdırılması və fərdiləşdirilmiş istifadəçi təcrübəsinin (UX) sarsılmaz təməlinə çevirir.

Rəqəmsal marketinq ekosisteminin təmərküləşməsini və dayanıqlılığını təmin edən digər fundamental sütun isə analitik yanaşmalardır. Süni intellekt proseslərin hərəkətverici qüvvəsidirsə, analitika bu proseslərin rəşional nəzarət mexanizmidir. Müasir dövrdə şirkətlər üçün əsas problem məlumat qıtlığı deyil, əksinə, idarə olunmaz "göstərici xaosu" (metric chaos) adlandırdığımız ifrat məlumat yüklənməsidir.

Bu mürəkkəb mənzərəni sistemləşdirmək üçün keyfiyyət idarəetməsi nəzəriyyəsinin banisi V. Edvards Deminqin (W. Edwards Deming) məşhur postulatını xatırlamaq kifayətdir: "Tanrıya inanırıq, digər hər kəs isə məlumat (data) gətirməlidir". Bu fəlsəfi-iqtisadi yanaşma, qərarvermə prosesində intuisiyanın və ya ənənəvi vərdişlərin deyil, məhz dəqiq rəqəmlərin və analitik mexanizmlərin strateji mahiyyətini təmlığı ilə ortaya qoyur. Orqanik trafik göstəricilərinin dəqiq analizi, istifadəçi səyahətinin (user journey) xəritələnməsi və A/B testlərinin davamlı tətbiqi müəssisələrin inkişaf strategiyasını subyektiv fərziyyələrdən xilas edir. Nəticə etibarilə, sistemli analitika təkcə büdcə itkilərini minimallaşdırmır, həm də bizneslərə qeyri-müəyyən rəqəmsal mühitdə öz fəaliyyətlərini elmi cəhətdən əsaslandırılmış faktlar üzərində qurmağa imkan yaradır.

Təhlil etməyə çalışdığımız nəzəri isbatlar fonunda süni intellekt və analitik yanaşmaların bir-birindən təcrid olunmuş şəkildə fəaliyyət göstərdiyini düşünmək absurd bir yanaşmadır. Rəqəmsal idarəetmə mexanizmləri bu iki fundamental qüvvənin mütləq vəhdətinə əsaslanır. Həmin texnoloji vəhdətin lokal seqmentə, xüsusən də kiçik və orta bizneslərə göstərdiyi praktiki təsirlər çoxşaxəli

və bir-birini tamamlayan zəncirvari proseslərdən ibarətdir. İlk növbədə, analitik vasitələrin xam məlumat (data) kimi topladığı auditoriya göstəricilərinin maşın öyrənməsi alqoritmləri tərəfindən emal edilməsi hədəfləmənin mütləq mənada intellektuallaşmasına gətirib çıxarır. Bu proses nəticəsində lokal auditoriyanın demografik və psixografik xüsusiyyətlərinə uyğun, israfdan uzaq və mikrosəviyyəli hədəfləmə strategiyaları formalaşdırılır. Buna paralel olaraq, süni intellektə əsaslanan sistemlər istifadəçinin rəqəmsal platformadakı reaksiyalarına anında adekvat cavab verərək fərdiləşdirilmiş istifadəçi təcrübəsini (UX) təmin edir, rəqəmsal məkanda xidmət keyfiyyətini və müştəri loyallığını birbaşa gücləndirir.

Məsələnin texniki və iqtisadi tərəfinə nəzər saldıqda isə axtarış motorlarının daim yenilənən alqoritmlərinə uyğunlaşma zərurəti ön plana çıxır. Bu mərhələdə süni intellekt məzmun strukturunu optimallaşdırır, analitik alətlər isə cəlb olunan orqanik trafik kütləsinin platformadakı davranışını, sıçrama dərəcəsini (bounce rate) və konversiya potensialını ölçərək prosesin effektivliyini tənzimləyir. Orqanik axtarışın davamlılığını və keyfiyyətini təmin edən bu mexanizm eyni zamanda prediktiv (proqnozlaşdırıcı) modellər vasitəsilə ən yüksək investisiya gəlirliyi (ROI) verəcək kanalları əvvəlcədən hesablayır. Nəticə etibarilə, bu mürəkkəb inteqrasiya həm inkişaf dinamikasını sürətləndirir, həm də məhdud büdcə ilə çalışan KOB-lar üçün marketinq xərclərinin səmərəsiz sərfiyyatının qarşısını alan qoruyucu sipər kimi çıxış edir.

XXI əsrin rəqəmsal arxitekturası tələb edir ki, lokal bazar mühitində rəqabətə davamlı olmaq istəyən iqtisadi subyektlər idarəetməni sadəcə xidmət və ya məhsul təqdimatı ilə məhdudlaşdırmasınlar. Süni intellekt və data əsaslı analitik yanaşmalar artıq müvəqqəti texnoloji trendlər deyil, əksinə, rəqəmsal iqtisadiyyatın möhkəm dayaqları və əsas kapitalıdır. Tədqiqat göstərir ki, yerli bizneslərin rəqəmsal marketinq ekosistemindəki təkamülü birbaşa olaraq elmi və texnoloji alətlərin birgə, rəşional istifadəsindən asılıdır. Məlumatları (datanı) qəbul edən, orqanik axtarış davranışlarını dərk edən və analitik hesabatlar əsasında strategiya inkişaf etdirən təşkilatlar həm mürəkkəb iqtisadi böhranlara tab gətirəcək, həm də gələcəyin innovativ, təmərküzləşmiş idarəetmə modelinin lokomotivinə çevriləcəklər.

УДК 528.4

# Стратегические векторы развития урбанизированной экономики Карабахского экономического региона

Strategic vectors for the development of the urbanized economy of the Karabakh economic region

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Президент Ильхам Алиев сделал важные заявления, подчеркнув, что восстановление и развитие освобожденных территорий Карабаха и Восточного Зангезура является одним из главных приоритетов внешней политики Азербайджана. Эти слова отражают глубокое понимание главой государства стратегической важности этих регионов для будущего страны.

Как отметил Президент, градостроительство является одним из приоритетных направлений в национальной стратегии развития Азербайджана. Применяемые в стране подходы в области градостроительства и урбанизации способствуют экономической устойчивости, социально-экономическому благополучию и адаптации к изменению климата». Эти слова подчеркивают комплексный подход к процессу восстановления, охватывающий все аспекты общественной жизни.

Возрождение Карабаха и Восточного Зангезура – это не только восстановление разрушенного, но и создание нового, современного и процветающего региона. Это амбициозный проект, требующий значительных усилий и ресурсов, но он, несомненно, приведет к укреплению суверенитета азербайджанского государства и улучшению благосостояния азербайджанского народа. Стратегический приоритет, отданный этим территориям, демонстрирует дальновидность руководства страны и его решимость построить сильный и стабильный Азербайджан.

Азербайджан, обладающий богатой историей и культурой, уверенно движется к прогрессу, уделяя первостепенное внимание развитию своего народа. В центре внимания – создание рабочих мест для граждан и обеспечение достойной жизни, что является одним из главных приоритетов государственной политики. Этот курс, заданный великим лидером Гейдаром Алиевым, успешно продолжается и сегодня, стремясь повысить благосостояние и улучшить уровень жизни каждого азербайджанца.

В рамках реализации Государственной программы занятости на освобожденных территориях Азербайджанской Республики на 2026-2029 годы планируется выделить 13,5 млрд манатов. Значительная часть этих средств, а именно 23,5%, будет направлена на создание новых рабочих мест. Одним из важных шагов в этом направлении станет строительство средних школ в освобожденных районах в течение следующих четырех лет, что является воплощением заботы государства о будущих поколениях. В 2024 году в рамках «Государственной программы занятости на освобожденных территориях Азербайджанской

Республики», направленной на развитие этих регионов, были начаты мероприятия по созданию новых рабочих мест и восстановлению инфраструктуры. В общей сложности на создание и сохранение рабочих мест для освобожденных граждан в 2020-2024 годах было выделено 17,6 млрд манатов, из которых 5,3 млрд манатов было израсходовано в 2024 году, а 4,3 млрд манатов запланировано на 2025 год.

Кроме того, в среднесрочной перспективе планируется продолжить строительство и реконструкцию комплексов, направленных на развитие социально-экономической и культурной инфраструктуры освобожденных территорий. Эффективное использование энергетических ресурсов приведет к дальнейшему развитию экономической активности и повышению уровня жизни. В рамках этих усилий в 2027-2030 годах будет реализована «XXII Государственная программа по освобожденным территориям Азербайджанской Республики», предусматривающая подготовку и осуществление мер по обеспечению занятости населения и созданию достойного уровня жизни.

Таким образом, Азербайджан наглядно демонстрирует свою приверженность принципам развития человеческого капитала и обеспечения благополучия своих граждан. Инвестиции в создание рабочих мест, восстановление инфраструктуры и социальное развитие являются гарантией устойчивого роста и процветания страны.

Придерживаясь принципов государственности, Президент Азербайджанской Республики Ильхам Алиев заложил основу для систематического и быстрого развития Карабахского и Зангезурского экономических регионов. Этот процесс включает в себя восстановление разрушенной инфраструктуры, создание новых населенных пунктов и обеспечение благоприятных условий жизни населения.

В результате этих масштабных работ экономические регионы, ранее пострадавшие от оккупации, переживают период возрождения. Планы развития охватывают территорию в 13,6 миллионов квадратных километров и предусматривают строительство новых жилых районов для более чем 1,1 миллиона человек, а также переселение жителей городов и деревень. Генеральные планы уже утверждены для 8 городов и 90 деревень с населением более 300 000 человек.

Ранее недоступные для освоения, освобожденные земли теперь становятся объектом государственных строительных и восстановительных работ, что свидетельствует об усилиях по полному восстановлению регионов.

Демонстрируя свою приверженность восстановлению, азербайджанское государство в 2021 году открыло «автомагистрали» до Физули, а 20 октября 2022 года, по случаю Дня освобождения Зангилана, были открыты «автомагистрали» до Зангиланской области. Церемонии открытия этих важных транспортных коридоров провели президент Ильхам Алиев и президент Турции Реджеп Тайип Эрдоган. Символическое открытие этих «автомагистралей» 28 мая — в День Республики — стало еще одним подтверждением братских связей между Азербайджаном и Турцией.

В этих районах активно ведутся работы по строительству дорог, жилых домов, объектов социальной инфраструктуры, а также энергетической инфраструктуры. В Карабахе и Зангезуре в рамках программы «Зеленая энергия» создаются солнечные и ветровые электростанции.

Карабахский экономический район был создан Президентом Азербайджанской Республики 7 июля 2021 года указом «О новом разделении экономических районов Азербайджанской Республики». Следует отметить, что Карабахский экономический район является одним из 14 экономических районов Азербайджана. В этот экономический район входят административные районы Агджабеди, Агдам, Барда, Физули, Ходжалы, Ходжавенд, Шуша, Тартар и город Ханкенди. Его общая площадь составляет 7330 км<sup>2</sup>. По состоянию на начало 2020 года население Карабахского экономического района составляло 900 300

человек, что составляет приблизительно 9% от общей численности населения Азербайджана [1]. Карабах — это древняя земля Азербайджана, где расположены редкие природные красоты и богатства.

Основное развитие Карабаха было связано с социально-экономическим развитием города Шуша [2]. В XIX веке в Карабахе, особенно в Шуше, широко развивались торговля и ремесла. Шуша была перекрестком караванных путей, и здесь действовал караван-сарай. В Шуше насчитывалось 500 ткацких мастерских, производивших различные виды тканей. Шушинские ковры и шелковые изделия стали известны [3].

В XVIII-XIX веках процессы формирования и развития Карабаха ускорились. Так, интенсивное развитие города Шуша в этот период сыграло важную роль в формировании традиций азербайджанской государственности, сохранении национальных ценностей и развитии национального духа. С другой стороны, Шуша расположена в местности, где очарование природы и сложный рельеф образуют единство, и в результате она сохраняет величие Шушинской крепости. Здесь также наблюдалось формирование и развитие древних художественных традиций, таких как деятельность шелковых мастерских и производство шелковых изделий. Одновременно были широко распространены такие виды ремесел, как шляпное дело, пошив одежды и изготовление музыкальных инструментов [5].

После Великой Карабахской Победы, начавшейся 27 сентября 2020 года и продолжавшейся 44 дня, Азербайджан приступил к масштабной работе по возрождению освобожденных территорий и их восстановлению с использованием новейших технологий. Цель состоит в том, чтобы поднять Карабах и прилегающие территории до самых высоких стандартов социально-экономического развития и превратить этот регион в динамично развивающийся регион с высоким уровнем жизни [4].

Карабахский экономический регион, освобожденный от оккупации после многих лет, занимает особое место в повестке дня развития Азербайджана. Городская экономическая структура этого региона, включая исторические города Ханкенди, Шуша, Агдам, Физули, Барда, Агджабеди, Тартар, Ходжалы и Ходжавенд, будет сформирована к 2026 году на основе принципов устойчивого развития, современной инфраструктуры и высокого качества жизни. Эта структура направлена на полную реализацию экономического потенциала региона, а также на обеспечение комфортной и безопасной жизни населения.

### **Расположение и направления развития жилых районов**

Восстановление и развитие освобожденных территорий на основе системных и комплексных принципов требует оптимальных подходов. Стратегия оживления и развития должна отражать не только передовой мировой опыт, но и традиционные особенности развития и потенциал этих территорий. Основными природными ресурсами Карабахского экономического региона являются полиметаллические руды, различные строительные материалы (мрамор, цементное сырье, строительный камень) и др.

Одним из важнейших и главных мотивирующих факторов освобождения наших земель стали бои за Шушу. Освобождение Шуши от врагов заняло свое место в мировой военной истории и золотыми буквами вписано в героическую летопись азербайджанской армии. После победы впереди была историческая строительная и восстановительная работа. В настоящее время в Карабахе реализуются масштабные строительные и восстановительные проекты [8]. Главными приоритетами являются скорейшее достижение социально-экономических целей развития региона и обеспечение возвращения внутренне перемещенных лиц в город. При этом считается важным расширить масштабы многочисленных строительных работ, проводимых в регионе. Наряду с средствами, выделенными из государственного бюджета, целесообразно использовать в этих работах

инвестиции частного сектора и иностранных инвесторов в соответствии с мировым опытом [9].

Следует отметить, что имеются достаточные ресурсы для повышения инвестиционной привлекательности Карабахского экономического региона [10]. В то же время наличие приоритетных задач в рамках стратегии социально-экономического развития до 2026 года создало дополнительные возможности для ускоренного восстановления освобожденных территорий. Кроме того, «Государственная программа по великому возвращению освобожденных территорий Азербайджанской Республики», утвержденная Указом Президента от 16 ноября, предусматривает масштабные меры, связанные с возрождением Шуши [11]. Обеспечено ускорение процессов расселения в городе Шуша, Агдамском и Физулинском районах Карабахского экономического региона. Первые внутренне перемещенные лица уже вернулись в быстро развивающийся город Физулин. В городах Шуша и Агдам восстанавливаются или реконструируются жилые районы и деревни. В Агдаме также расположен современный индустриальный парк, и число жителей растет.

Помимо экономического развития Шуши, важно также учитывать традиционные сферы занятости и обеспечивать развитие ремесел в соответствии с требованиями времени. Также следует отметить потенциал для организации и реализации сувениров, произведений искусства, музыкальных инструментов, товаров, производимых в результате деятельности малых и средних предприятий [12]. В сфере услуг имеются достаточные возможности, и развитие этих областей, несомненно, может ускорить формирование основных направлений деятельности в современном экономическом строительстве Шуши [13]. Помимо современных гостиниц с широкими возможностями, эффективное использование объектов недвижимости, принадлежащих малым и средним предприятиям, создание гостевых домов, мини-отелей, мотелей и строительство небольших предприятий общественного питания создают широкие возможности для развития сектора услуг в Шуше и обеспечивают дополнительные стимулы для его формирования [14].

Планирование размещения и развития жилых районов в Карабахском экономическом регионе к 2026 году осуществляется на основе концепций «умного города» и «зеленого города». В процессе реставрации и реконструкции городов приоритетное значение имеет сохранение историко-культурного наследия.

Ханкенди: Как центр района, Ханкенди будет развиваться с появлением современных жилых комплексов, торговых центров, образовательных и медицинских учреждений. Исторический центр города будет восстановлен, а его туристический потенциал увеличен. Жилые здания будут строиться по принципам энергоэффективности, будут созданы большие зеленые зоны и зоны отдыха.

Шуша: Жилые районы Шуши, культурной столицы Азербайджана, будут восстановлены в соответствии с исторической архитектурой города. Основное внимание будет уделено сохранению уникальной атмосферы города при одновременном обеспечении современных условий жизни. Для работников туристической и культурной сфер запланированы специальные жилые комплексы.

Агдам: Превращаясь из «города-призрака» в символ возрождения, Агдам будет перестроен с созданием жилых районов, широких проспектов, современных зданий и развитой социальной инфраструктуры. План реконструкции города будет уделять особое внимание разделению жилых районов от промышленных и сельскохозяйственных зон.

Физули: Наличие международного аэропорта придаст мощный импульс развитию Физули. Жилые районы будут оформлены в современном архитектурном стиле, будут обустроены просторные парки и зоны отдыха. Учитывая стратегическое расположение города, жилые комплексы планируются вблизи логистических и торговых центров.

Барда и Агджабади: Эти региональные центры будут развиваться как поселения,

ориентированные в основном на сельское хозяйство и перерабатывающую промышленность. Жилые здания будут адаптированы к сельскохозяйственной деятельности, одновременно удовлетворяя социальные потребности населения. В этих городах также будут созданы специальные жилые и коммерческие зоны для тех, кто занимается переработкой и продажей сельскохозяйственной продукции.

**Тартар:** Тартар сосредоточится в основном на деятельности, связанной с сельским хозяйством и ирригационными системами. Жилые районы создадут благоприятные условия для тех, кто работает в этих областях. Развитие городской инфраструктуры также будет включать создание подходящих площадок для хранения водохозяйственной и сельскохозяйственной техники.

**Ходжалы и Ходжавенд:** Поселения в этих районах будут в основном обслуживать сельское хозяйство, туризм и экотуризм. Жилые дома будут строиться из экологически чистых материалов, гармонично сочетающихся с природой. В этих регионах также будут созданы небольшие жилые комплексы и фермы для тех, кто занимается производством и переработкой сельскохозяйственной продукции.

Заселение Карабаха осуществляется поэтапно в рамках программы «Великое возвращение».

До конца 2026-го года в **Агдаме** и **Фузули** планируется завершить строительство по 2 центральных кварталов в каждом из городов и в общей сложности 8 жилых кварталов в экономической зоне. Кроме того, в качестве структурной единицы план развития включает 32 поселка и **Хадрут**, **Суговушань**. Планируется реконструкция стратегически важных населенных пунктов, таких как [название населенного пункта]. В качестве концептуального подхода к реализации плана, жилые районы должны быть обеспечены экологически чистой средой и современной сетью услуг, основанной на концепциях «Умный город» и «Умная деревня».

Первый этап программы «Великое возвращение» планируется завершить в 2026 году, а второй этап, включающий **регион Фузули, будет завершен** к концу 2026 года. Планируется переселить 22 тысячи человек (включая центр города и 10 деревень). На рисунке 1 представлен генеральный план города Фузули.

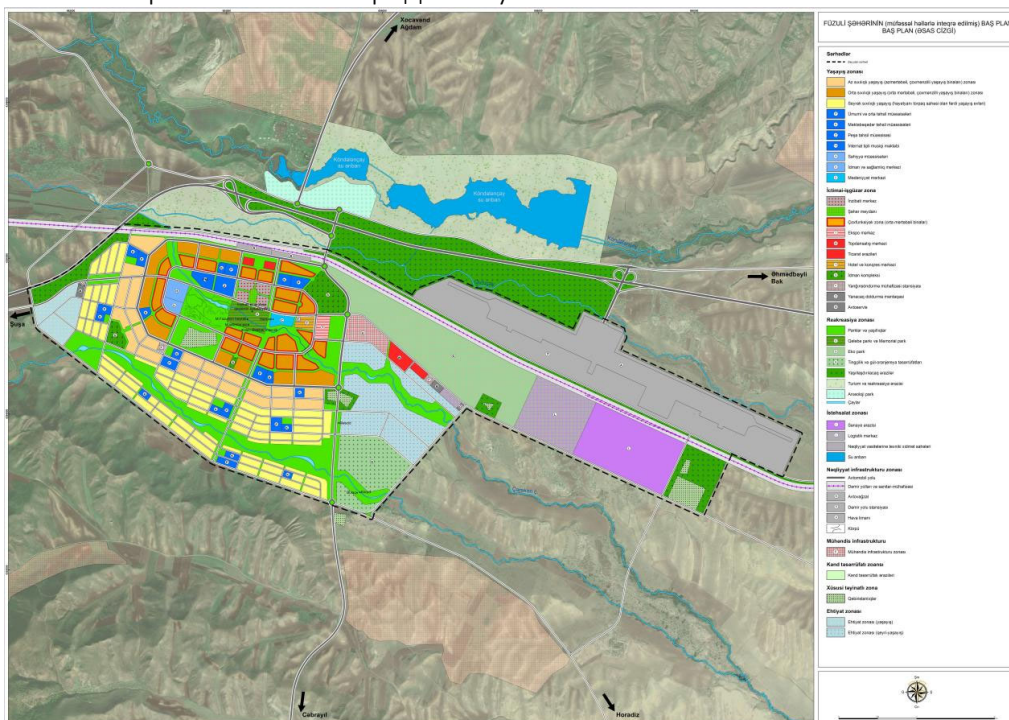


Рисунок 1. Генеральный план города Фузули.

Кроме того, в **Агдаме** и **Фузули** планируется завершить строительство двух центральных кварталов в каждом из городов. Генеральный план города Агдам уже утвержден, и первые жилые здания для военных введены в эксплуатацию. На рисунке 2 представлен генеральный план города Агдам.

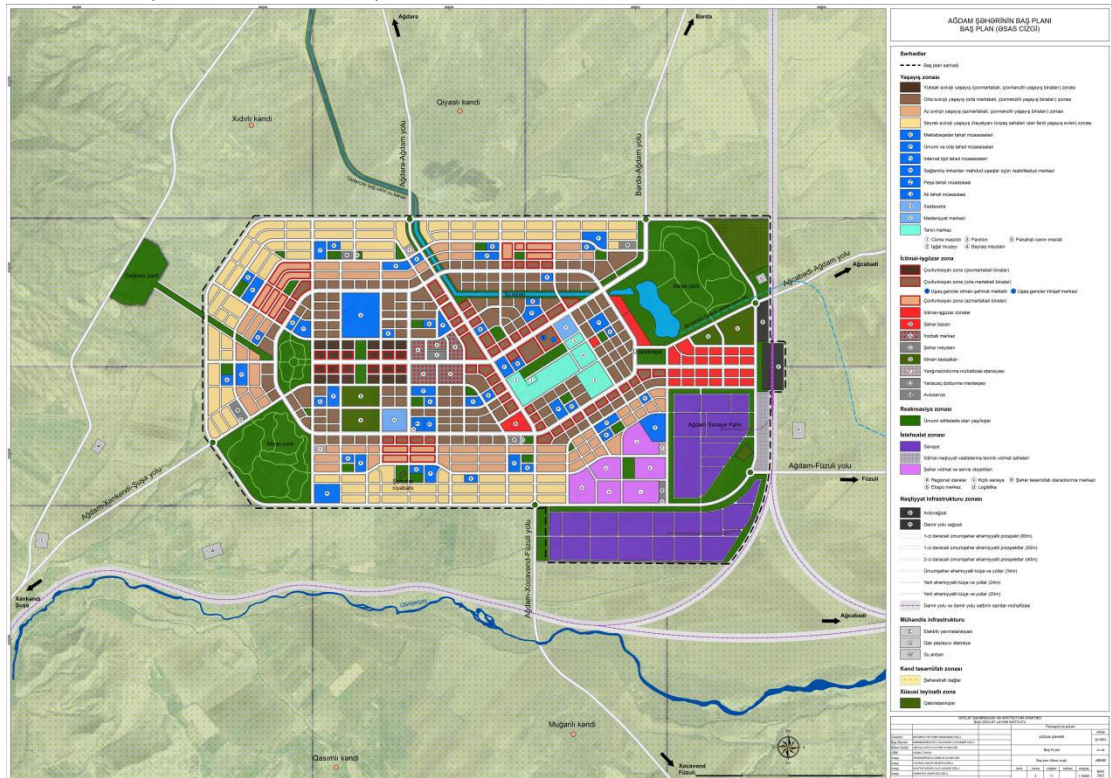


Рисунок 2. Генеральный план города Агдам.

Наконец, к 2026 году планируется полностью восстановить и передать в общую собственность в общей сложности 32 деревни в экономическом регионе (12 в Агдаме, 10 в Фузули и других регионах).

### Заключение

Таким образом, производственная структура Карабахского экономического региона на 2026 год основана на преимуществах, вытекающих из природных ресурсов региона, его исторического потенциала и стратегического положения.

В целом, территориальные производственные комплексы и области специализации выглядят следующим образом:

1. Сельское хозяйство: Одной из основных областей специализации региона станет сельское хозяйство. Эта область включает в себя выращивание зерновых, животноводство, виноградарство, плодоводство и овощеводство. В частности, ведущую роль в этой области будут играть регионы Агдам, Фузули, Барда и Агджабеди. Для переработки промышленной продукции будут созданы современные перерабатывающие предприятия.

2. Туризм и культура: Города исторического и культурного значения, такие как Шуша, Ханкенди и Ходжалы, будут развиваться как туристические и культурные центры. Реставрация исторических памятников, строительство гостиниц и развлекательных комплексов, организация культурных мероприятий станут основными направлениями развития этого региона. Экологический туризм также будет приоритетным направлением в таких районах, как Ходжавенд и Тартар.

3. Промышленность: В регионе будут развиваться легкая промышленность, пищевая промышленность и производство строительных материалов. Промышленные зоны будут созданы в таких городах, как Агдам, Фузули и Барда. Эти зоны будут предназначены для переработки сельскохозяйственной продукции, а также для производства строительных

материалов.

4. Логистика и транспорт: Наличие международного аэропорта Физули повысит логистический и транспортный потенциал региона. Эта территория будет способствовать развитию как внутренней, так и международной торговли. Будут созданы современные складские комплексы и логистические центры.

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# Medical Tourism and Sustainable Regional Development: Evidence from Imereti, Georgia

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## Abstract

*Medical tourism has become one of the fastest-growing segments of the global tourism industry, driven by increasing healthcare costs, aging populations, and growing demand for wellness and preventive health services. This paper examines the development potential of medical tourism in Imereti, Georgia, and analyzes its contribution to sustainable regional development. Imereti is characterized by rich balneological resources, including mineral and thermal waters, established spa traditions, and improving tourism infrastructure. The study employs a qualitative methodology based on desk research, literature review, and secondary data analysis, complemented by a SWOT framework.*

*The findings indicate that medical tourism can significantly contribute to regional economic diversification, employment creation, investment attraction, and infrastructure development. Moreover, the integration of medical, wellness, and wine tourism offers a unique competitive advantage for the region. However, challenges such as limited international accreditation, insufficient global marketing, and infrastructure gaps still constrain development. The study concludes that strategic policy interventions and sustainable planning are necessary for positioning Imereti as a competitive medical tourism destination in the Black Sea region.*

**Keywords:** medical tourism, wellness tourism, sustainable development, regional development, Imereti, Georgia

## 1. Introduction

In recent decades, medical tourism has emerged as a significant global phenomenon, transforming both healthcare and tourism industries. Medical tourism refers to the movement of individuals across regional or national borders to obtain medical treatment, rehabilitation, preventive care, or wellness services. This sector has grown rapidly due to globalization, technological advancements in healthcare, improved transportation accessibility, and rising healthcare costs in developed countries.

According to the World Tourism Organization (UNWTO), health-related tourism is one of the most dynamic and rapidly expanding segments of global tourism. It includes medical tourism, wellness tourism, and spa tourism, all of which are increasingly interconnected. The global wellness economy alone exceeded USD 5.6 trillion in 2022, with wellness tourism representing one of its fastest-growing segments (Global Wellness Institute, 2022).

Georgia has historically been recognized for its rich natural healing resources, including mineral waters, thermal springs, and favorable climatic conditions. The country's spa traditions date back to ancient times and were further developed during the Soviet era, when several resorts gained international recognition.

Among Georgian regions, Imereti stands out due to its unique combination of natural resources, historical spa infrastructure, and strategic geographic location. The presence of Kutaisi

International Airport significantly enhances accessibility for international tourists, making the region a potential hub for medical and wellness tourism in the South Caucasus.

The aim of this paper is to analyze the potential of medical tourism in Imereti and evaluate its role in promoting sustainable regional development.

Medical tourism has been widely studied in tourism and healthcare literature. Connell (2013) defines medical tourism as travel involving the use of medical services that are not typically covered by traditional tourism activities. Smith and Puczkó (2014) expand this definition by integrating wellness and spa tourism into the broader concept of health tourism.

Hall (2011) highlights both positive and negative implications of medical tourism, emphasizing its potential to stimulate economic development while also raising concerns about equity in healthcare systems. Similarly, OECD (2016) identifies medical tourism as a driver of regional economic growth, particularly in developing and transitional economies.

From a sustainability perspective, medical tourism is closely linked to the UN Sustainable Development Goals (SDGs), especially:

- SDG 3: Good Health and Well-being
- SDG 8: Decent Work and Economic Growth
- SDG 11: Sustainable Cities and Communities

Previous studies on Eastern European spa destinations (Hungary, Czech Republic, Slovakia) demonstrate that natural thermal resources combined with infrastructure investment can create competitive medical tourism clusters (Smith & Puczkó, 2014).

However, limited research exists on Georgia, and particularly on Imereti, in the context of integrated medical, wellness, and sustainable regional development.

This study adopts a qualitative research design based on desk research and secondary data analysis. The research process includes: Review of academic literature on medical and wellness tourism, Analysis of reports from international organizations (UNWTO, OECD, Global Wellness Institute), Examination of Georgian tourism and regional development documents, Case-based assessment of key resorts in Imereti, SWOT analysis of the regional medical tourism sector. The methodology does not include primary survey data; instead, it focuses on synthesis and interpretation of existing information to evaluate development potential.

## **2. Results and Discussion**

### **2.1. Medical Tourism Resources in Imereti**

Imereti possesses a diverse range of natural, climatic, and infrastructural resources that provide a strong foundation for the development of medical and wellness tourism. The region has long been recognized as one of Georgia's most important spa and health tourism destinations due to its abundance of mineral and thermal waters, favorable environmental conditions, and established resort traditions. These resources have supported health-related travel for decades and continue to offer significant opportunities for the expansion of medical tourism.

The region is home to several well-known health resorts, including Tskaltubo, Sairme, Nunisi, and Sulori. Each of these destinations offers unique therapeutic resources and contributes to the diversification of medical and wellness tourism products in the region. In addition to their medical and rehabilitative functions, these resorts play an important role in attracting domestic and international visitors, supporting local employment, and stimulating regional economic development.

Table 1. Key Medical Tourism Resources in Imereti

Resort	Location	Main Resources	Tourism Potential
<b>Tskaltubo</b>	Central Imereti	Radon-carbonate thermal waters	Very high
<b>Sairme</b>	Baghdati	Mineral waters, mountain climate	High
<b>Nunisi</b>	Kharagauli	Climatic therapy, mineral springs	Medium
<b>Sulori</b>	Vani	Mineral waters	Medium

### *Tskaltubo*

Tskaltubo is widely regarded as one of Georgia's most significant balneological resorts and represents the cornerstone of medical tourism development in Imereti. The resort is internationally known for its naturally warm radon-carbonate mineral waters, which maintain a constant temperature of approximately 33–35°C throughout the year. These waters are characterized by unique therapeutic properties and have been extensively used for the treatment and rehabilitation of various medical conditions.

The therapeutic applications of Tskaltubo's mineral waters include the treatment of musculoskeletal disorders, rheumatic diseases, neurological conditions, cardiovascular problems, dermatological diseases, and post-traumatic rehabilitation. The resort's natural healing resources are often combined with physiotherapy, hydrotherapy, therapeutic exercise, and other rehabilitation procedures, creating comprehensive treatment programs for visitors.

Historically, Tskaltubo gained international recognition during the Soviet period, when it became one of the leading health resorts in the Soviet Union. Thousands of visitors annually traveled to the resort for preventive healthcare, rehabilitation, and medical treatment. The extensive network of sanatoriums, therapeutic facilities, and recreational infrastructure established during this period laid the foundation for the resort's long-standing reputation.

In recent years, Tskaltubo has undergone a process of revitalization supported by infrastructure modernization projects, rehabilitation initiatives, and private investments. The renovation of spa facilities, accommodation establishments, and public spaces has enhanced the destination's attractiveness and strengthened its capacity to compete in the international medical and wellness tourism market. Given the growing global demand for health, rehabilitation, and wellness services, Tskaltubo is increasingly recognized as a destination with significant potential to become a leading medical tourism center not only in Georgia but also in the wider Black Sea region.

Table 2 presents a comparison of the current range of products and services offered in Tskaltubo with those available in selected international spa destinations. The comparison indicates that competitiveness in the medical and wellness tourism sector depends not only on the number of services offered but also on their quality, diversity, and ability to meet evolving consumer demands. Although Tskaltubo possesses unique natural therapeutic resources and a strong balneological tradition, further diversification of tourism products and services is necessary to strengthen its position in the international market.

The expansion of additional wellness, rehabilitation, recreational, and cultural services would enable Tskaltubo to attract a broader range of visitor segments and increase the average length of stay. With continued investment, effective destination management, and the development of integrated tourism products, Tskaltubo has the potential to become one of the leading medical and wellness spa destinations in Europe (Kohl&Partner 2014: 57-58).

**Table 2. Health and Medical key Positioning**

	Gastrointestinal	Liver and pancreas	Musculoskeletal system	Gynaecological	Digestiv	Diabetes	Peripheral nervous system	Central nervous system D	Dermatologic	Urologic	Kidney	Gallbladder	Obesity	Respiratory	Joint moto	Endocrinal	Ophthalmologic	Cardiovascular	Otolaryngologist	Anti-Stress Therapy	Psychosomatic	Psychotherapie	Internal medicine	Rheumatology	Preventive medicine	Orthopaedic surgery	Dental	Rehabilitation and pre-season trainings for	Physiotherapie	Plastic Surgery	TOTAL
Tskaltubo																															10
Armenia																															8
Azerbaijan																															6
Bulgaria																															9
Crimea																															10
Germany																															8
Russia																															13
Turkey																															13

Source: ( Kohl&Partner 2014:58)

*Sairme*

Sairme is another major health resort in Imereti that contributes significantly to the region’s medical tourism potential. Located in a mountainous area at an elevation of approximately 950 meters above sea level, the resort benefits from a favorable climate, clean air, and rich natural surroundings. These environmental characteristics create ideal conditions for rehabilitation, relaxation, and preventive healthcare.

The resort is particularly renowned for its mineral water resources, which have long been used for therapeutic and preventive purposes. Sairme’s mineral waters are commonly associated with the treatment and prevention of digestive, metabolic, and urinary tract disorders. The bottled mineral water produced in Sairme has gained recognition both domestically and internationally, further enhancing the visibility of the destination.

Unlike traditional medical tourism centers that focus primarily on treatment, Sairme has increasingly developed as a wellness destination. Modern spa facilities, wellness centers, rehabilitation services, and recreational infrastructure allow visitors to combine healthcare with leisure and relaxation activities. This integration of medical, wellness, and recreational services reflects current international trends in health tourism, where travelers increasingly seek holistic experiences that promote physical and mental well-being.

The resort's mountainous landscape, forests, and biodiversity also provide opportunities for nature-based therapies, outdoor recreation, and active tourism. Hiking, wellness walks, and climate therapy can complement traditional medical treatments, creating a comprehensive health tourism product.

*Nunisi and Sulori*

In addition to Tskaltubo and Sairme, smaller resorts such as Nunisi and Sulori contribute to the diversity of medical tourism resources in Imereti.

Nunisi is known for its unique climatic conditions and mineral waters, which have traditionally been used in the treatment of skin diseases and various chronic health conditions. The resort’s peaceful natural environment and relatively untouched landscape make it particularly attractive for visitors seeking recovery and relaxation away from crowded urban areas.

Sulori, located in the Vani Municipality, is another promising balneological destination with mineral water resources suitable for therapeutic and recreational use. Although less developed than Tskaltubo and Sairme, Sulori possesses considerable potential for future investment and tourism development. The enhancement of infrastructure and healthcare services could transform the resort into an important complementary destination within the regional medical tourism network.

### *Supporting Infrastructure and Accessibility*

Beyond its natural healing resources, Imereti benefits from growing tourism and transport infrastructure. The presence of Kutaisi International Airport significantly improves accessibility for international visitors and strengthens the region's connectivity with European markets. In addition, the development of accommodation facilities, wellness centers, transportation networks, and tourism services has improved the overall visitor experience.

The combination of natural therapeutic resources, established spa traditions, improving infrastructure, and strategic geographical location provides Imereti with a strong competitive advantage in the development of medical tourism. These assets create favorable conditions for attracting both domestic and international tourists seeking medical treatment, rehabilitation, wellness services, and preventive healthcare experiences.

## **2.2. SWOT Analysis of Medical Tourism in Imereti**

A SWOT analysis was conducted to assess the current state and future prospects of medical tourism development in Imereti. The analysis identifies the region's internal strengths and weaknesses, as well as external opportunities and threats that may influence its competitiveness in the medical and wellness tourism market.

### *Strengths*

One of the most significant strengths of Imereti is its rich balneological and natural therapeutic resources. The region possesses numerous mineral and thermal water sources, including the internationally recognized resorts of Tskaltubo and Sairme. These natural assets provide a strong basis for developing health, rehabilitation, and wellness tourism products that are difficult to replicate in competing destinations.

Another important strength is the region's long-standing spa tourism tradition. Health resorts in Imereti have been operating for decades and have accumulated valuable experience in rehabilitation and preventive healthcare services. The historical reputation of destinations such as Tskaltubo contributes to destination recognition and strengthens visitor trust.

Competitive pricing also represents a major advantage. Compared to many European medical tourism destinations, healthcare, rehabilitation, accommodation, and wellness services in Georgia remain relatively affordable. This cost advantage creates opportunities to attract international visitors seeking high-quality services at lower prices.

Accessibility further enhances the region's competitiveness. Kutaisi International Airport provides direct connections to numerous European destinations, making Imereti more accessible for foreign tourists. Improved road infrastructure and transport services facilitate travel within the region and contribute to a more convenient visitor experience.

Finally, the diversity of tourism resources within the region creates additional value. Visitors can combine medical treatments and wellness programs with cultural experiences, wine tourism, gastronomy, and nature-based activities, creating a comprehensive tourism product.

### *Weaknesses*

Despite its considerable potential, several weaknesses continue to limit the development of medical tourism in Imereti.

One of the primary challenges is limited international marketing and destination branding. While Tskaltubo and Sairme are relatively well known within Georgia and neighboring countries, their visibility in major international medical tourism markets remains limited. Insufficient promotion reduces the region's ability to compete with more established health tourism destinations.

Another weakness is the lack of internationally accredited healthcare facilities. Accreditation systems play a critical role in medical tourism by assuring patients of service quality

and safety standards. The limited number of internationally recognized medical institutions may reduce confidence among potential international visitors.

The availability of highly specialized medical services also remains relatively limited. Although the region possesses strong rehabilitation and wellness capacities, it has fewer specialized clinics and advanced treatment centers compared with leading medical tourism destinations such as Turkey, Germany, or Hungary.

Human resource challenges represent another important constraint. The sector requires healthcare professionals and tourism personnel with foreign language skills, intercultural competencies, and specialized training in international patient services. The shortage of such specialists may affect service quality and visitor satisfaction.

In addition, certain tourism and healthcare facilities still require modernization and investment to meet evolving international expectations regarding comfort, technology, and service standards.

#### *Opportunities*

The global growth of health, wellness, and preventive tourism creates significant opportunities for Imereti. Increasing awareness of healthy lifestyles, population aging, and rising demand for rehabilitation services have contributed to the rapid expansion of the international wellness tourism market. These trends create favorable conditions for destinations with natural therapeutic resources.

Foreign investment attraction represents another major opportunity. The modernization of resorts, healthcare facilities, hotels, and supporting infrastructure can significantly improve the competitiveness of the region. Public-private partnerships may also accelerate the development of high-quality medical and wellness services.

A particularly promising opportunity lies in the integration of medical tourism with other forms of tourism. Imereti is already recognized for its wine, gastronomic, cultural, and nature-based tourism attractions. Combining these experiences with wellness and rehabilitation services can create innovative tourism products that appeal to a broader range of visitors and increase tourists' length of stay.

The region also has opportunities to expand into new international markets. While neighboring countries remain important source markets, increased promotion in European, Middle Eastern, and Central Asian markets could diversify visitor flows and reduce dependence on a limited number of countries.

Digital transformation presents additional opportunities. The use of online marketing, telemedicine consultations, digital booking systems, and international healthcare platforms can improve visibility and accessibility for international patients and wellness travelers.

#### *Threats*

Despite favorable development prospects, several external threats may affect the growth of medical tourism in Imereti.

Increasing international competition represents one of the most significant challenges. Numerous countries, including Turkey, Hungary, the Czech Republic, Poland, and Slovenia, actively promote medical and wellness tourism and possess well-developed healthcare infrastructure, strong international branding, and recognized accreditation systems.

Economic uncertainty can also influence tourism demand. Inflation, economic downturns, and fluctuations in household income may reduce consumers' willingness to spend on medical and wellness travel, particularly in international markets.

Environmental pressures constitute another potential threat. The sustainable management of mineral water resources and natural environments is essential for the long-term viability of health tourism destinations. Overexploitation of natural resources, environmental degradation, or inadequate planning could negatively affect the attractiveness of the region.

Regional geopolitical instability may also influence international travel decisions. Political tensions, security concerns, or broader regional uncertainties can affect destination image and discourage potential visitors.

Finally, global health crises similar to the COVID-19 pandemic demonstrate the vulnerability of tourism-dependent sectors. Travel restrictions, public health concerns, and disruptions in international mobility can significantly impact medical tourism flows and business operations.

The SWOT analysis demonstrates that Imereti possesses substantial competitive advantages based on its unique natural resources, spa tourism heritage, affordability, and accessibility. However, realizing its full medical tourism potential requires addressing weaknesses related to international visibility, accreditation, infrastructure, and specialized healthcare services. By leveraging emerging opportunities and mitigating external threats, Imereti can strengthen its position as a leading medical and wellness tourism destination and contribute to sustainable regional development.

### 2.3 Medical Tourism and Sustainable Regional Development

Medical tourism represents a multidimensional development tool that extends beyond the healthcare sector and contributes significantly to the economic, social, and infrastructural transformation of destination regions. In the context of Imereti, its development has strong potential to support sustainable regional growth through employment creation, investment attraction, infrastructure modernization, and improved utilization of natural resources.

#### Economic Contribution: Employment and SME Development

One of the most widely recognized impacts of medical tourism is its capacity to generate employment across multiple sectors. According to the World Health Organization and OECD analyses on health-related tourism, the sector creates both **direct employment** (medical staff, rehabilitation specialists, nurses, spa therapists) and **indirect employment** in hospitality, transport, food services, and tourism operations (OECD, 2016; Connell, 2013).

In regional contexts similar to Imereti, studies show that medical and wellness tourism has a **high employment multiplier effect**, particularly in rural and semi-urban areas where alternative employment opportunities may be limited (Smith & Puczko, 2014). For example, spa destinations in Central and Eastern Europe, such as Hungary and Slovakia, demonstrate that thermal tourism clusters significantly increase local SME activity, including small hotels, guesthouses, wellness centers, and transport services.

For Imereti, this is particularly relevant due to the presence of **Tskaltubo and Sairme resort clusters**, where tourism demand directly stimulates small business development, especially in accommodation, catering, and local services. Such SME-driven growth is considered a key component of sustainable regional development under the UN Sustainable Development Goal 8 (Decent Work and Economic Growth).

#### Investment Attraction and Infrastructure Development

Medical tourism is strongly associated with increased domestic and foreign direct investment (FDI), particularly in healthcare infrastructure, spa modernization, and hospitality development. According to the Global Wellness Institute (2022), global wellness tourism expenditures exceeded **USD 800 billion**, indicating strong investor interest in health-oriented destinations.

In emerging destinations, investment typically focuses on: modernization of spa and rehabilitation facilities, development of boutique and wellness hotels, improvement of transport infrastructure, expansion of diagnostic and rehabilitation services.

In Imereti, ongoing rehabilitation projects in **Tskaltubo** and private investments in **Sairme resort infrastructure** illustrate this trend. Infrastructure improvements not only enhance tourism

capacity but also generate spillover effects for local communities, including better roads, utilities, and public service upgrades.

As noted by Hall (2011), health tourism often acts as a “catalyst sector,” meaning that investment in medical tourism stimulates broader regional development beyond the tourism industry itself.

#### **Reduction of Seasonality and Year-Round Demand**

A key structural advantage of medical tourism is its relatively low seasonality compared to leisure tourism. Unlike beach or mountain tourism, which is highly dependent on climatic conditions, medical and wellness tourism is driven by **health needs, rehabilitation cycles, and preventive care programs**, which operate throughout the year (Connell, 2013).

This characteristic is particularly important for regional economies such as Imereti, where traditional tourism demand tends to be seasonal. Empirical studies from European spa destinations (e.g., Czech Republic and Austria) demonstrate that health tourism can stabilize occupancy rates in hotels and rehabilitation centers, ensuring more consistent income streams for local businesses (Smith & Puczkó, 2014).

In the case of Imereti, resorts such as Tskaltubo and Sairme have the potential to function as **year-round tourism anchors**, reducing economic vulnerability associated with seasonal fluctuations and improving labor market stability.

#### **Environmental Sustainability and Utilization of Natural Resources**

Medical tourism in Imereti is strongly linked to the sustainable use of natural therapeutic resources, particularly mineral and thermal waters. From a sustainability perspective, these resources require careful management and environmental monitoring to ensure long-term viability.

According to the UNWTO (2018), sustainable tourism development should ensure that natural resources are preserved while being economically productive. In this context, balneological tourism can support environmental protection when properly regulated, as it creates economic incentives for maintaining clean water systems, protected natural areas, and ecological balance.

Moreover, spa and wellness tourism often promotes low-impact tourism models, where environmental degradation is minimized compared to mass tourism. This aligns with SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land).

#### **Social Development and Quality of Life Improvement**

Medical tourism also contributes to social development by improving healthcare accessibility, encouraging professional training, and enhancing service quality standards. The presence of international visitors often leads to quality upgrading in healthcare and hospitality services, as destinations adapt to global expectations regarding safety, hygiene, and professionalism.

Additionally, regions with developed health tourism sectors tend to experience improvements in: public healthcare infrastructure, professional training and medical education, multilingual service capacity, intercultural competence among service providers.

In countries such as Turkey and Hungary, the growth of medical tourism has been directly associated with the modernization of healthcare systems and the internationalization of medical services (Connell, 2013).

For Imereti, similar processes could strengthen regional human capital development and improve overall quality of life for local residents.

Overall, medical tourism functions as a multiplier sector that integrates economic, social, and environmental dimensions of sustainable development. In Imereti, its potential impact is particularly significant due to the combination of natural healing resources, existing spa infrastructure, and growing accessibility via Kutaisi International Airport.

However, maximizing these benefits requires strategic planning, investment in quality standards, and integration with broader regional development policies.

Medical tourism plays a multidimensional role in sustainable regional development. It contributes to economic diversification, infrastructure development, and social improvement.

#### **Economic Impact**

Medical tourism generates both direct and indirect employment. Direct employment includes healthcare professionals, therapists, and spa specialists, while indirect employment spans hospitality, transportation, and retail sectors. OECD (2016) highlights that health tourism has one of the highest employment multipliers in the tourism industry.

#### **Investment and Infrastructure**

Global evidence shows that medical tourism stimulates foreign direct investment in healthcare infrastructure, spa modernization, and hospitality development. According to the Global Wellness Institute (2022), wellness tourism is one of the fastest-growing investment sectors globally.

In Imereti, ongoing investments in Tskaltubo and Sairme illustrate the beginning of this transformation.

#### **Seasonality Reduction**

Medical tourism reduces seasonality by attracting year-round visitors. Unlike leisure tourism, health-related travel depends on medical needs and rehabilitation cycles rather than climate conditions. This ensures more stable revenue streams for local economies.

#### **Environmental Sustainability**

Properly managed medical tourism promotes sustainable use of natural resources. Mineral waters and thermal springs require protection and monitoring, aligning with UNWTO sustainability principles.

#### **Social Development**

Medical tourism improves service quality, encourages professional training, and enhances healthcare infrastructure. It also promotes multilingualism and international service standards.

### **2.4. Integration with Wine and Cultural Tourism**

Imereti possesses a distinctive competitive advantage in developing integrated tourism products that combine medical and wellness tourism with wine, gastronomy, and cultural heritage experiences. This “hybrid tourism model” aligns with contemporary global trends in **experience-based tourism**, where visitors increasingly seek holistic journeys that combine health improvement, cultural immersion, and leisure activities rather than single-purpose travel (Smith & Puczkó, 2014).

In the context of Imereti, this integration is particularly relevant because the region concentrates several complementary tourism assets within a relatively small geographic area: balneological resorts (e.g., Tskaltubo, Sairme), traditional wine-producing areas, UNESCO-linked cultural heritage sites, and diverse natural landscapes. This spatial proximity enables the development of **multi-purpose tourism itineraries**, which significantly enhance destination competitiveness.

#### **Medical and Wellness Tourism + Wine Tourism Synergy**

Wine tourism in Imereti is based on centuries-old viticulture traditions, indigenous grape varieties (such as Tsolikouri, Krakhuna, and Tsitska), and small family wineries that increasingly participate in experiential tourism. While wine consumption is not directly part of medical treatment programs, **non-clinical wellness tourism packages** can be strategically combined with wine culture experiences in a controlled and health-oriented framework.

For example, visitors undergoing rehabilitation or wellness programs in **Tskaltubo or Sairme** may participate in: guided visits to local vineyards and wineries, wine tasting sessions

focused on moderate consumption principles, educational tours on traditional Georgian qvevri winemaking methods, gastronomic experiences based on local organic cuisine.

Such integration is already observable in European spa destinations. In regions of Austria and Hungary, wellness tourists often combine spa treatments with culinary and wine experiences, which increases destination attractiveness and spending per visitor (OECD, 2016). A similar model can be adapted in Imereti, where wine tourism is already well established but still fragmented in terms of integration with health tourism.

### **Cultural Heritage as a Complementary Resource**

Imereti is one of the richest cultural regions of Georgia, offering a dense concentration of historical monuments, archaeological sites, and religious heritage. These include: Gelati Monastery Complex (UNESCO World Heritage Site), Bagrati Cathedral (historically significant landmark), Motsameta Monastery, Ancient cave settlements such as Prometheus Cave (Tskaltubo area), Ethnographic villages and traditional Imeretian architecture.

For medical and wellness tourists, cultural heritage plays a crucial psychological and experiential role. Research shows that cultural engagement during recovery or wellness travel enhances emotional well-being, reduces stress, and increases overall satisfaction with health tourism experiences (Hall, 2011).

For example, patients staying in rehabilitation centers in Tskaltubo often have access to short cultural excursions to Kutaisi's historical landmarks. These activities are particularly valuable in long-term rehabilitation programs, where psychological recovery is as important as physical healing.

### **Nature-Based and Eco-Therapeutic Experiences**

Another important dimension of integration is the combination of medical tourism with nature-based tourism. Imereti's diverse geography—mountains, forests, rivers, and protected areas—provides opportunities for **eco-therapeutic and climate-based tourism**, which is increasingly recognized in wellness tourism literature.

Examples of such activities include: therapeutic walks in the forested areas of Sairme and Baghdati, hiking routes in the Kharagauli National Park, climate therapy in mountain resorts like Nunisi, breathing therapy and stress reduction programs in natural environments.

International research indicates that exposure to natural environments significantly contributes to mental health improvement, stress reduction, and recovery outcomes, especially when combined with rehabilitation programs (Global Wellness Institute, 2022).

In Imereti, such nature-based experiences can be integrated into post-treatment recovery programs, making the region attractive not only for medical tourists but also for wellness-oriented travelers.

### **Development of Integrated Tourism Packages**

One of the most important strategic directions for Imereti is the development of **integrated tourism packages** that combine multiple experiences within a single itinerary. Instead of offering isolated services (medical treatment, wine tours, cultural visits), destinations can create structured multi-day programs.

For example:

#### **7-day integrated wellness package (example):**

- Days 1–3: Medical rehabilitation in Tskaltubo (physiotherapy, hydrotherapy, medical consultation)
- Day 4: Cultural tour of Kutaisi (Gelati Monastery, Bagrati Cathedral, local museum)
- Day 5: Wine tourism experience in Baghdati (vineyards, qvevri winemaking workshop)
- Day 6: Nature therapy in Sairme (forest walks, spa treatments)
- Day 7: Relaxation and wellness closing program

Such packages increase **average length of stay**, which is one of the most important economic indicators in tourism development. Longer stays directly translate into higher expenditure on accommodation, food services, transportation, and local products.

#### **Economic and Regional Development Impact**

The integration of medical, wellness, wine, and cultural tourism creates a **multiplier effect** for the regional economy. According to OECD (2016), integrated tourism systems generate higher economic value compared to single-sector tourism because they: increase tourist spending per capita, diversify income sources for local businesses, reduce dependency on a single tourism segment, strengthen local supply chains (agriculture, crafts, services).

In Imereti, this model is particularly relevant because it links: healthcare infrastructure (spa resorts), agricultural production (wine and food), cultural heritage management, and nature-based tourism services.

As a result, the region can move toward a more resilient and diversified tourism economy, which is a key principle of sustainable regional development.

#### **Strategic Challenges in Integration**

Despite its strong potential, integration faces several challenges:

- limited coordination between healthcare and tourism sectors,
- lack of standardized integrated tourism products,
- insufficient destination branding at international level,
- uneven quality of service across different tourism segments,
- need for trained personnel in both healthcare and tourism interpretation.

Addressing these challenges requires coordinated policy action, public-private partnerships, and destination management strategies.

#### **Summary**

The integration of medical, wellness, wine, cultural, and nature-based tourism positions Imereti as a **multi-experience destination** rather than a single-purpose health tourism site. This approach aligns with global trends in experiential tourism and significantly enhances the region's competitiveness, economic performance, and sustainability.

By combining rehabilitation services with cultural immersion, gastronomic experiences, and natural therapies, Imereti can extend visitor stays, increase tourism revenue, and strengthen its identity as a unique health and heritage destination in the Black Sea region.

### **3. Conclusion**

Imereti possesses strong potential for the development of medical tourism due to its natural healing resources, historical spa traditions, and improving infrastructure. Medical tourism can significantly contribute to sustainable regional development by generating employment, attracting investment, reducing seasonality, and promoting infrastructure modernization.

However, to fully realize this potential, strategic actions are required, including international marketing, accreditation of healthcare facilities, workforce development, and integration of tourism sectors.

The integration of medical, wellness, and wine tourism represents a unique opportunity for positioning Imereti as a competitive destination in the Black Sea region.

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# INFRASTRUCTURE RENOVATION AND SECTORAL DIVERSIFICATION OF REGIONS ARE DOMINANT REGIONAL POLICIES OF KAZAKHSTAN

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## **Abstract**

The article deals with the tasks and guidelines for state regional policy of the Republic of Kazakhstan. Infrastructure renewal in regions is highlighted, along the reasons for diversification and its influence on regional growth. Obstacles of various elements adoption that contribute to the development of the economy are revealed.

**Keywords:** region, regional policy, infrastructure renovation, diversification, the Republic of Kazakhstan

## **INTRODUCTION**

A region is a relatively integral territorial entity, often sizable, but not necessarily a taxonomic unit of administrative-subdivision, where natural-geographical, economic, social, ethno-demographic and other processes enabling the area self-development interact. The regional policy of the state is guiding the economic, social and political development of the country in its spatial, regional dimension, i.e. concerning interactions between the state and regions as well as regions among themselves [pp. 189-190].

The state regional policy goal of the Republic of Kazakhstan is to provide relatively equal opportunities for people's activity and maximize the resource capacity of each region through the reasonable territorial labor division and guidelines for local autonomy progress [2].

## **THE MAIN PART**

The state regional policies of the Republic of Kazakhstan are as follows [2]:

- to develop a set of measures focusing on political, economic, environmental, and legal aspects to ensure regional economic autonomy

–to work out territorial priorities according to the general strategic situation of the macroeconomic policy of the state;

–to combine selective government support of individual regions with state stimulus of economic activity throughout the territory of Kazakhstan.

–to shape and develop regional and national markets for goods, labor and capital along with institutional and market infrastructure

–support and rearrange the economy of small and medium-sized cities to lead their economies out of crisis and accelerate socio-economic development;

–to establish facilities for villages revival

–to build a sensible dimensional structure of the economy, improve the territorial institution of production and shaping of interregional infrastructure;

–to ensure the resource-target balance of the manufacturing complex, to conserve ecological and economic balance, to use socio-economic, scientific, technical and natural resources of the territories more efficiently;

–to match disagreement in the level and quality of life of the population by regions, to overcome the depressed economy and social sphere in the regions, especially in the underdeveloped ones.

The current Concept of Regional Development of the Republic of Kazakhstan outlines the following principles of regional policy (Fig. 1):

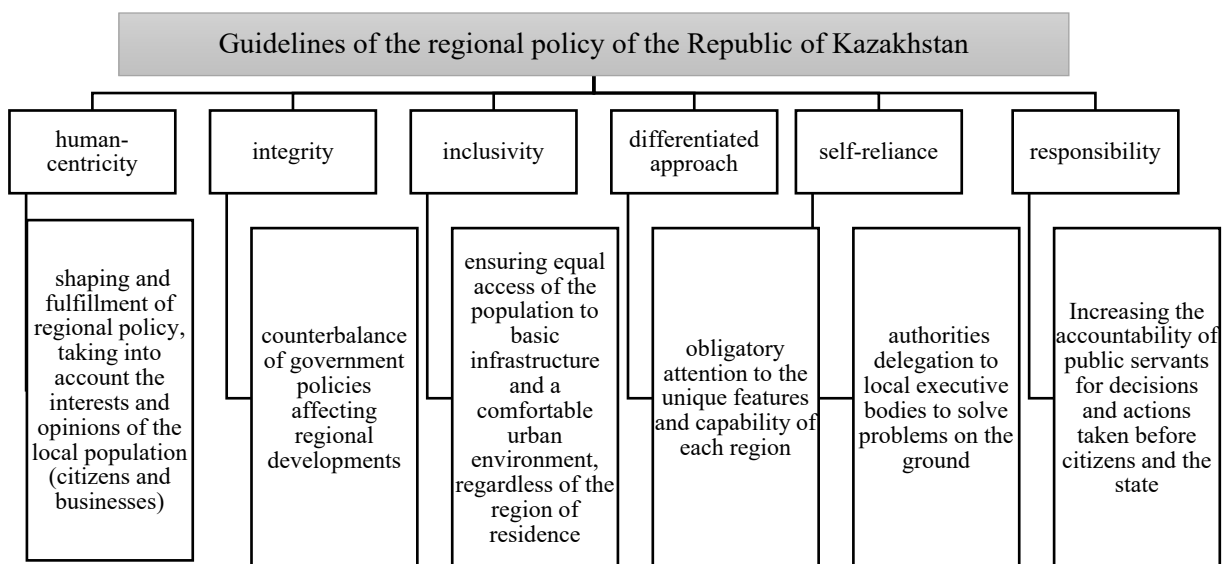


Figure 1 – Guidelines of the regional policy of the Republic of Kazakhstan (compiled from the source [3])

Taking into account the geographical location, economic specialization, nature of market links, and population settlement system, five macro-regions are distinguished in Kazakhstan:

1. Western macroregion: Aktobe, Atyrau, West Kazakhstan, Kyzylorda and Mangystau regions;
2. Southern macroregion: Almaty, Zhambyl, Zhetisu, Turkestan regions and Shymkent city;
3. Northern macroregion: Akmola, Kostanay and North Kazakhstan regions;
4. Central-Eastern macroregion: Abai, Karaganda, Pavlodar, Ulytau and East Kazakhstan regions;

Large agglomerations: the cities of Astana and Almaty.

Due to its distinctive geographical location and abundant natural assets, Kazakhstan possesses substantial prospects for sustainable socio-economic advancement. Despite regional imbalances in economic activity, infrastructure, and quality of life, achieving this potential is

limited. To ensure the sustainable and balanced development of regions in Kazakhstan, within the framework of the implemented Concept of Regional Development of the Republic of Kazakhstan for 2025-2030, the state follows three main headings, which are focused on reducing interregional differences and improving the quality of life of the population. The three key areas include:

- equal provision of basic infrastructure (social, engineering, transport, etc.),
- targeted economic advancement across regions,
- amending mechanisms to carry out regional policies.

The emphasis is on achieving equitable access to infrastructure and services nationwide. Efforts are focused on providing a fundamental quality standard for public services and goods across the nation.

The National Infrastructure Plan for the Republic of Kazakhstan, until 2029, was authorized by the Government of the Republic of Kazakhstan on July 25, 2024, as document number 606. Projects have been categorized into two priority tiers based on national and strategic priorities for infrastructure (Fig. 2):

#### List A

- decisive infrastructure for providing society with basic needs through energy, water supply, sanitation and digitalization facilities (thermal power plants, combined-cycle gas plants, hydroelectric power plants, state district electric power plants, power grids, heating networks, gas processing, gasification, reservoirs, water utilities, hydraulic structures, provision of sewage treatment plants in regional centers, provision of rural settlements with broadband access), as well as strategic and key transport and logistics areas (reconstruction of the Center-South corridor (Astana – Karaganda – Balkhash – Almaty), Taldykorgan – Kalbatau – Ust-Kamenogorsk, founding of a container hub in Aktau, development of the marine fleet), railway infrastructure facilities within the framework of the Trans-Caspian International Transport Route corridor, guaranteeing country's economic development

#### List B

- projects not included in List A that are planned to be implemented under favorable financing conditions (expansion of the oil pipeline, reconstruction of certain sections of highways, checkpoints, renovation of the locomotive fleet, sewage treatment facilities in cities)

Figure 2 – Priority routes for infrastructure advancement (compiled by source) [4]

The renovation of Kazakhstan's regional infrastructures is driven by their current condition and concentrates on four key areas: energy, transport, digital, and water supply and drainage infrastructures (Tab. 1).

Table 1 – Major renovations disrupt services for regions

Target	Areas	Objectives	Outcomes
1	2	3	4
<b>Energy infrastructure</b>			
Energy security	Power engineering	increasing the share of renewable energy sources	Increased self-supplied renewable power
		introduction of new capacities	coping with the increasing demand.
		reengineering of power supply facilities	Renewing the power grid and enhancing capacity
	Power grids transmission and distribution	intensification of the electric grid of the southern zone of the UES of Kazakhstan, integration of the energy system of Western Kazakhstan with the UES of Kazakhstan	Increasing the reliability of electricity supply to consumers and strengthening links between EU energy zones
Heating networks	updating the worn-out heating networks	Offering high-quality heating services	reduction in heat supply network wear
Infrastructure development for oil and transport	Oil and transport infrastructure	Increase in existing pipeline capacity	Maintaining the pipeline for oil transport to the expanded Shymkent refinery
Gas generation	Gasification	construction of gasification	gas supply to the country's consumers

Transport infrastructure			
Enhancing the country's transport and logistics capabilities	Railway infrastructure	Railway infrastructure construction	increased capacity and transit potential
		decrease in passenger car wear	renewal of the rolling stock
	Road infrastructure	Upgrading of checkpoints	increasing the capacity of checkpoints; reducing the maximum transit time for cars at checkpoints
		Construction and reconstruction of highways	The rise in the proportion of roads classified as I and II technical categories
	Water transport infrastructure	Renovation and rebuilding of water facilities	construction of container hubs, marine terminals
	Aviation infrastructure	Renovation and expansion of airport facilities and nearby areas	modernized airports, fuel refueling facilities, special equipment and airfield maintenance equipment
		Providing with aircraft	Replenishing national airlines with new aircraft to improve flight safety and meeting people's needs

<b>Water supply and sewerage infrastructure</b>			
Water efficiency	Water supply	construction and reconstruction of reservoirs	Ensuring high-quality drinking water for the populace, alongside mitigating the danger of flooding in the rural settlements
		Canals repair and extension	Ensuring accessibility to water services for both urban and rural areas
		reconstruction of main water utilities	water supply improvement and uninterrupted water supply to agricultural consumers, the population and industrial enterprises of Pavlodar, Karaganda, Akmola regions and Astana city, along with increasing the share of irrigated land
		modernization of the K. Satspayev canal	
	Sewerage	upgrading and reconstruction of the water systems in populated areas	purification of wastewater
<b>Digital infrastructure</b>			
Excess to the Internet	The Internet	Introducing fiber optic cables to rural areas	Making Internet access speedy for the populace, digitalization
		Supply of federal and local thoroughfares with mobile internet	
		Development of digital infrastructure to ensure mobile broadband coverage for major republican and regional roads	
		Data processing and storage (service availability)	
<i>NOTE: Compiled from source [4]</i>			

Economic diversification is a process wherein the region's economic activities expand and become more complex, involving the development of new industries and decreasing reliance on a single sector. If a region's economy relies solely on one industry (like oil or coal mining), it becomes susceptible to external influences including decreased prices of raw materials or modifications in global demand.

The goal of diversification is to create a sustainable economic system that can cope with external shocks, changes in demand or changes in world prices. Economic diversification is one of the key tasks of the government of Kazakhstan [5].

Reasons for diversification [6]:

Risk reduction:

Diversification aids the region in safeguarding itself against economic upheavals triggered by crises or faltering resource valuations.

Employment generation:

The emergence of new economic sectors often results in more job opportunities, a particularly crucial aspect for areas experiencing high unemployment.

Innovation and development:

The variety of sectors contributes to the introduction of novel technologies and innovations, which enhances the region's competitiveness both nationally and internationally.

Sustainability:

A region with diverse components can adjust more easily to shifts and recuperate more swiftly from economic downturns.

A diversified regional economy offers several advantages, including reduced reliance on a single industry, job generation, and enhanced competitiveness. However, regions also encounter several challenges when it comes to diversifying [6]:

The need for investing

Developing new industries demands substantial investments in infrastructure, training, and creating a business-friendly environment. Government support is crucial: successful diversification cannot be achieved without governmental involvement. Tax incentives, support for innovative projects, and special economic zones are essential for advancing this process.

Personnel shortage:

To introduce new technologies and develop new industries, qualified professionals are required. Some regions face manpower shortages, which curtails growth opportunities. Kazakhstan, a country rich in natural resources like oil and gas, has developed its economy largely through these reserves over many years. Nevertheless, this reliance on a single sector poses numerous risks and challenges, emphasizing the pressing need for economic diversification. In Kazakhstan, from July to December 2025, there were 2,200 rural districts and 48 significant regional cities. On average, one rural district consisted of about 3 villages and 3,300 rural residents, while one district city had approximately 24,000 inhabitants [7].

To implement a diversified economic model, significant challenges and obstacles must be addressed [8]:

1. Commodity dependence: One of the main problems is the economy's heavy reliance on oil and gas exports. This dependence makes the economy vulnerable to fluctuations in world commodity prices;

2. Insufficient infrastructure: emerging economic sectors necessitate modern facilities, such as transportation routes, logistics centers, communication networks, and electrical grids. In Kazakhstan, notably in remote areas, infrastructure frequently remains rudimentary, which impedes the growth of new industries and constrains economic activity;

3. Qualified personnel: the development of high-tech industries requires the availability of qualified specialists. There is a shortage of personnel obtaining necessary knowledge and skills in Kazakhstan, which makes it difficult to develop sectors such as information technology, biotechnology, green energy and others.;

4. When it comes to financing and capital access, substantial investment is required to expand the economy, yet obtaining funds remains constrained. Local banks rarely offer long-term

financing, while international financial institutions demand transparency and stability, conditions not always guaranteed.;

5. Consistent and clear public policies are essential for supporting diversification. Nonetheless, bureaucratic red tape, the lack of coordination between governmental levels, and frequent legislative changes can impose significant barriers to long-term projects;

6. International competitiveness is essential for new economic sectors in the global market. It will require significant resources for research, development, innovation, and product enhancement. Without this, Kazakhstani goods and services may turn out to be uncompetitive on the global market.

Today, innovative development as a viable option for improving productivity, developing manufacturing industries and diversifying economies promotes the introduction of innovation in production processes. Innovation can spur the development of new technologies and tools, allowing for a greater output with fewer human efforts, thereby enhancing productivity and consequently fostering economic expansion. Moreover, the adoption of new technologies generates employment opportunities and reduces unemployment while increasing employment, which subsequently promotes economic expansion.

The introduction of innovations advances companies in the global market. Consequently, exports are growing, increasing company revenues. It, in turn, stimulates the economy, encouraging the initiation of new products that increases demand and consumption. It is essential that governments contribute to the advancement of innovation:

- through funding research and development: governments can invest in research and development to stimulate technological and product innovation;

- fostering an innovative climate: governments can establish an innovative environment through measures like tax incentives and streamlined business regulations;

- investing in education and science: the government can support these areas to foster individuals who will be capable of generating and executing innovation.

Considering a wider macroeconomic framework, it is argued that government policies should promote the launch and development of innovative enterprises. Given that competition is crucial for innovation, governments ought to foster market competition and reduce policies that interfere with product and factor markets.

## CONCLUSION

Thus, the regional policy of the contemporary state can be defined as a set of goals, objectives, principles and actions of state authorities, as well as other participants (corporations, small and medium-sized businesses, parties, unions, etc.) aimed at setting the stage for the independent development of regions, achieving a sustainable spatial socio-economic balance of the country considering the national, regional and local interests, Given current circumstances, it is one of the primary objectives for the Republic of Kazakhstan to implement a balanced regional policy. To establish a sustainable social and economic model for society, and to acknowledge regional differences, efforts must be made to reduce regional disparities. Socio-economic, demographic and other contrasts between regions require constant boosting of approaches to the shaping and fulfilment of regional policy, urban planning policy aimed at eliminating critical inequalities and strengthening the economic potential of each region.

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# Current status and development prospects of employment regulation in Azerbaijan

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**Abstract.** The article analyzes the state policy implemented in the field of employment regulation in Azerbaijan, the main indicators of the labor market and existing problems. The study shows that in 2010-2024, the number of employed people increased, while the unemployment rate showed a decreasing trend. At the same time, informal employment, interregional differences and structural mismatches in the labor market still remain relevant problems.

**Keywords:** Azerbaijan, employment, labor market, unemployment, employment policy.

## Introduction

Employment is one of the main indicators of economic development and social welfare. In the modern era, the effective regulation of the labor market is considered one of the key priorities of state policy. The reforms implemented in the field of employment in Azerbaijan are aimed at reducing unemployment and promoting the development of the labor market. Employment is understood as the condition or process in which an individual engages in paid labor activity for the purpose of earning income [2] This concept encompasses individuals working in the public sector, private sector, as well as those engaged in informal economic activities. Employment is not only one of the fundamental pillars of the economy but also an important indicator of social welfare and societal stability. Employment is among the sectors that play a crucial role in the socio-economic development of any country. In Azerbaijan, the regulation of employment has been identified as one of the priority directions of state policy. Various state programs and reforms are being implemented to enhance the social welfare of the population, develop the labor market, and reduce unemployment. The regulation of employment in Azerbaijan is based on the following key legislative acts: the Labour Code (1999), the Law on Employment (revised in 2018), the Employment Strategy of the Republic of Azerbaijan (2020-2025), the Self-Employment Program, and State Programs on Vocational Education and Training [1]. The main institutions responsible for implementing employment policy are the Ministry of Labour and Social Protection of Population, the State Employment Agency, the State Statistical Committee, and employment services provided through the ASAN Service centers [4].

## Main Body

### Directions of Employment Policy

The Government of Azerbaijan implements employment regulation measures through several key policy directions. These include active labor market measures, vocational training and retraining programs for unemployed and job-seeking individuals, the organization of job fairs, the creation of jobs through state orders, and the development of digital employment platforms, such as the "Employment" subsystem. The Self-Employment Program has been implemented since 2017. The primary objective of this program is to enable low-income and unemployed individuals to generate income through small-scale entrepreneurship. It provides support in the fields of livestock farming, services, and production, while also promoting youth employment, improving vocational education, encouraging start-up and innovation initiatives, expanding the activities of Career Centers and internship programs, and assisting job seekers in finding employment. Within the state employment regulation system, the employment of women and vulnerable groups

occupies a significant place. This includes the implementation of measures supporting gender equality, the integration of persons with disabilities into the labor market, and initiatives aimed at promoting women's entrepreneurship in the regions. However, a number of challenges and problems still persist in this field. For instance, the relatively high level of informal employment, the unequal distribution of employment opportunities across regions, the mismatch between vocational education and labor market demands, and the increasing unemployment rate among young people indicate the existence of gaps in Azerbaijan's employment regulation system. The Employment Strategy of the Republic of Azerbaijan (2019-2030), adopted in 2019, aims to ensure the sustainable development of the country's labor market [3]. The main objectives of the Strategy are:

- Ensuring full and productive employment of the population;
- Reducing informal employment;
- Strengthening human capital;
- Developing new skills required for the digital economy;
- Integrating vulnerable groups (including women, youth, and persons with disabilities) into the labor market;
- Regulating labor migration and promoting integration into the international labor market [3].

Although the Government of Azerbaijan has taken a number of positive steps in the field of employment, additional measures are needed to achieve a more sustainable and inclusive labor market. These include:

1. Strengthening administrative and incentive-based mechanisms to reduce informal employment;
2. Enhancing coordination between vocational education institutions and labor market needs;
3. Promoting alternative employment models in the regions, such as social entrepreneurship;
4. Expanding the use of integrated databases and digital employment platforms [6].

According to the growth-led employment theory, economic growth and sectoral diversification stimulate job creation and contribute to the expansion of employment opportunities. Furthermore, the structural labor market theory suggests that imbalances between labor demand and supply, vocational education, technological transformation, and changing market requirements play a significant role in shaping unemployment dynamics. During the period 2010–2024, the labor force in Azerbaijan increased by 724.7 thousand persons (13.6%), reaching 5,312.1 thousand persons in 2024.

Table 1. Main Socio-Economic Indicators of the Labor Market

Indicators	2010	2015	2020	2021	2022	2023	2024
Labor force, thousand persons	4,587.4	4,915.3	5,089.9	5,141.6	5,194.4	5,249.7	5,312.1
Employed population, thousand persons	4,329.1	4,671.6	4,721.2	4,831.1	4,901.1	4,963.3	5,029.8
Including:							
Public sector	1,142.7	1,176.1	1,116.4	1,089.2	1,075.7	1,064.4	1,053.6
Non-public sector	3,186.4	3,495.5	3,604.8	3,741.9	3,825.4	3,898.9	3,976.2
Unemployed population, thousand persons	258.3	243.7	368.7	310.5	293.3	286.4	282.3
Registered unemployed at the State Employment Agency, persons	38,966	28,877	–	–	–	217,608	217,228
Of whom receiving unemployment benefits	87	1,543	727	1,615	2,332	2,797	3,963
Employed women, thousand persons	2,101.7	2,263.4	2,244.5	2,304.3	2,344.6	2,375.6	2,414.1
Wage and salary earners, thousand persons	1,282.9	1,502.5	1,698.7	1,709.1	1,738.7	1,745.5	1,780.3
Average monthly nominal wage (compared to previous year, %)	111.2	105.0	111.4	103.4	114.7	111.2	108.1
Average monthly real wage index (compared to previous year, %)	105.2	101.0	108.4	96.9	100.7	102.2	105.8
Vocational training participants, persons	4,792	7,453	3,478	3,713	5,372	3,413	5,265
Managers and specialists who upgraded their qualifications, persons	22,326	13,045	14,122	14,604	10,626	24,440	25,231
Expenditures on vocational training, retraining, and skill upgrading of employees (million AZN)	5.8	11.0	5.8	9.2	11.9	19.3	15.5
Share of expenditures on vocational training in total labor costs, %	0.09	0.11	0.04	0.05	0.06	0.08	0.06

Source: Prepared by the author based on [8].

While employed persons accounted for 94.4% of the labor force in 2010, this figure rose slightly to 94.7% in 2024. Of the employed population in 2024, 95.4% were men and 93.9% were women. The unemployment rate declined from 6.0% in 2010 to 5.3% in 2024, representing a decrease of 0.7 percentage points. The number of officially registered unemployed persons increased by 178,262 persons between 2010 and 2024, reaching 217,228 persons, which corresponded to approximately 4.1% of the labor force. From the perspective of ownership

structure, 26.4% of employed individuals worked in the public sector and 73.6% in the non-public sector in 2010. By 2024, the share of public-sector employment had declined to 20.9%, whereas the share of non-public-sector employment increased to 79.1%. These figures clearly indicate a gradual reduction in public-sector employment and a growing role of the private sector in the national economy. Regarding gender composition, women accounted for 2,101.7 thousand employed persons (48.5% of total employment) in 2010. By 2024, this figure had increased to 2,414.1 thousand persons, although their share in total employment slightly declined to 48.0%, reflecting a decrease of 0.5 percentage points over the period [5]. The number of wage and salary earners also increased significantly. In 2010, 1,282.9 thousand persons were employed on a wage basis, representing 31.9% of total employment. By 2024, this figure had risen to 1,780.3 thousand persons, accounting for 35.4% of total employment. This trend reflects the increasing formalization of employment relations and the expansion of wage-based labor within the economy. Between 2010 and 2024, the average monthly nominal wage increased approximately threefold, reaching 1,009.4 AZN in 2024. Compared with the previous year, nominal wages increased by 11.2% in 2010, 5.0% in 2015, 11.4% in 2020, 3.4% in 2021, 14.7% in 2022, 11.2% in 2023, and 8.1% in 2024. The average monthly real wage index exhibited a more fluctuating pattern. Relative to the previous year, real wages increased by 5.2% in 2010, 1.0% in 2015, and 8.4% in 2020, but declined by 3.1% in 2021. Growth resumed thereafter, with increases of 0.7% in 2022, 2.2% in 2023, and 5.8% in 2024. Human capital development indicators also reveal important trends. In 2010, 4,792 employees participated in vocational training programs. By 2024, this number had increased by 9.9%, reaching 5,265 persons. Similarly, the number of managers and specialists who upgraded their qualifications increased from 22,326 persons in 2010 to 25,231 persons in 2024, despite fluctuations throughout the period. Expenditures on vocational training, retraining, and skills upgrading amounted to 5.8 million AZN in 2010. The highest level of investment in workforce training was recorded in 2023, when expenditures reached 19.3 million AZN. In 2024, spending on these activities amounted to 15.5 million AZN. However, despite the increase in absolute expenditure levels, the share of vocational training expenditures in total labor costs declined over time. This indicator decreased from 0.09% in 2010 to 0.06% in 2024, suggesting that investments in workforce skills development have not expanded proportionately to overall labor expenditures. This trend highlights the need for a stronger focus on human capital formation and continuous professional development to enhance labor productivity and ensure the long-term competitiveness of the Azerbaijani labor market [8].

According to the social security and contract theory, the formalization of employment relationships through legally binding labor contracts strengthens social protection mechanisms and contributes to reducing informal employment. Formal labor contracts provide employees with access to social insurance, pension rights, unemployment protection, occupational safety guarantees, and other labor-related benefits, thereby increasing both economic security and labor market transparency. The regulation of employment in Azerbaijan constitutes one of the key directions of the state's socio-economic policy. To improve social welfare, reduce unemployment, and ensure the sustainable development of the labor market, the government has implemented a wide range of measures and reforms. The legal and institutional framework governing employment is relatively well developed. The principal legislative acts regulating this sphere include the Labour Code of the Republic of Azerbaijan, the Law on Employment, the Employment Strategy of the Republic of Azerbaijan (2020-2025), and other relevant normative legal acts [7]. At the institutional level, the primary responsibilities for employment management are carried out by the Ministry of Labour and Social Protection of Population of the Republic of Azerbaijan and the State Employment Agency, operating under its authority. These institutions provide services to job seekers and unemployed individuals, facilitate job placement, organize vocational training programs, and implement various social protection

measures [10]. To ensure employment and labor market stability, Azerbaijan applies both active and passive labor market policies. Active employment policies include the organization of job fairs, vocational training and retraining programs, self-employment initiatives, and the creation of subsidized employment opportunities. Among these measures, the Self-Employment Program has become one of the most significant components of Azerbaijan's employment policy in recent years. Within the framework of this program, low-income and unemployed citizens are provided with equipment, livestock, tools, and other productive assets necessary to establish micro-enterprises. As a result, beneficiaries are able to generate sustainable income, improve their living standards, and reduce their dependence on social assistance programs [9]. The program covers a wide range of economic activities, including agriculture, services, and manufacturing.

**Table 2. Number of Wage and Salary Employees by Age Group and Gender (thousand persons)**

Age Groups	2016	2017	2018	2019	2020	2021	2022	2023
<b>Total</b>	1514.3	1525.0	1551.7	1646.6	1698.7	1709.1	1738.7	1745.5
<b>15-19</b>	3.2	2.9	2.8	4.8	3.4	5.4	4.3	7.4
<b>20-24</b>	124.7	123.6	130.9	127.8	130.4	134.1	141.1	138.2
<b>25-29</b>	218.5	221.0	234.9	243.2	245.9	244.6	249.8	245.5
<b>30-34</b>	238.8	243.5	251.6	277.6	285.3	287.8	290.7	288.7
<b>35-39</b>	217.2	222.6	228.1	259.5	267.0	271.5	275.5	280.4
<b>40-44</b>	178.1	184.6	185.6	199.3	211.7	216.3	219.7	227.8
<b>45-49</b>	164.5	161.8	155.6	163.1	166.9	166.4	170.6	173.5
<b>50-54</b>	158.6	154.7	147.6	147.2	149.4	144.8	141.0	138.9
<b>55-59</b>	132.1	131.1	130.3	129.5	132.2	126.2	126.2	123.5
<b>60-64</b>	59.5	60.6	64.7	72.7	82.4	87.0	94.6	95.3
<b>65+</b>	19.1	18.6	19.6	21.9	24.1	25.0	25.2	26.3

*Source: Prepared by the author based on [8].*

Particular attention is also devoted to the integration of young people into the labor market. In order to facilitate youth employment, comprehensive reforms have been implemented in the vocational education system, while internship programs, entrepreneurship initiatives, and start-up projects receive increasing support from the government. These measures aim to equip young people with labor market-relevant skills and enhance their employability in a rapidly changing economic environment. In addition, the employment of women and persons with disabilities has been identified as a strategic priority within the national employment framework. The government has introduced various incentive mechanisms and support programs designed to facilitate the participation of these groups in economic activity. Such measures include vocational training opportunities, entrepreneurship support, targeted employment quotas, and workplace adaptation initiatives. By promoting equal access to employment opportunities and strengthening labor market inclusiveness, these policies contribute not only to social equity but also to the more efficient utilization of the country's human capital resources. Ultimately, the successful integration of vulnerable groups into the labor market is regarded as an important prerequisite for achieving sustainable economic growth and inclusive social development in Azerbaijan [3]. As can be observed from the table, the 30-34 age group consistently accounted for the largest share of wage and salary employees throughout the analyzed period. This pattern was evident for both men and women. For instance, in 2023, individuals aged 30-34 years represented 16.5% of total wage earners. Among male employees, this age group accounted for 17.2%, while among female employees its share was 15.5%. These figures indicate that the labor market in Azerbaijan is largely driven by individuals in their prime productive years, characterized by a combination of educational attainment, professional experience, and high labor productivity.

## Conclusion

In 2025, the regulation of employment in the Republic of Azerbaijan continues to develop along several strategic and practical directions closely linked to the country's socio-economic policy, labor market requirements, digital transformation, and human capital development objectives. The main priorities of employment policy in 2025 include the following:

- Organizing vocational training and retraining programs aimed at improving the employability of unemployed individuals and workers engaged in the informal sector;
- Creating public employment opportunities, particularly in the regions and for socially vulnerable population groups;
- Implementing self-employment and start-up support programs that encourage the establishment of individual farms and micro-businesses with state assistance;
- Expanding active labor market measures;
- Promoting digital employment and “green” jobs through digital literacy and skills development programs for young people and the workforce;
- Accelerating the digital transformation of the labor market through online job fairs, vacancy platforms, and the Electronic Employment Contract (EEC) system;
- Supporting the green economy by creating new employment opportunities within environmentally sustainable projects;
- Enhancing transparency in labor relations and employment practices.

From the perspective of labor market regulation, reducing informal employment remains one of the most important policy priorities. To achieve this objective, electronic registration and monitoring systems should be further improved. The wider implementation of the Electronic Employment Contract (EEC) system can contribute significantly to protecting workers' rights, strengthening legal employment relations, and increasing transparency within the labor market. In accordance with social security and institutional labor market theories, the formalization of employment relations through electronic registration systems improves compliance with labor legislation and expands access to social protection mechanisms. Another important component of employment policy is the expansion of social insurance coverage. Increasing the participation of employees in the social insurance system strengthens social protection, enhances income security, and contributes to the long-term sustainability of the social welfare system. Formal employment and social insurance participation are also closely associated with higher labor productivity and improved workforce stability. Regional employment programs constitute another key element of Azerbaijan's employment strategy. These programs aim to increase employment opportunities in the regions through the development of tourism, agriculture, manufacturing, and other productive sectors. They also focus on establishing regional vocational training and skills development centers, ensuring that workforce qualifications correspond to local labor market demands. Such measures contribute to reducing regional disparities, promoting balanced economic development, and preventing excessive migration toward major urban centers. Particular attention is also devoted to the integration of youth and women into the labor market. In this regard, career planning initiatives, internship programs, entrepreneurship training, and start-up support mechanisms for young people play an important role in facilitating the transition from education to employment. Likewise, the promotion of women's entrepreneurship through training programs, financial support instruments, mentoring services, and advisory assistance contributes to increasing female labor force participation and strengthening gender equality within the labor market. Overall, the current directions of employment regulation in Azerbaijan reflect a transition toward a more inclusive, innovative, and digitally oriented labor market model. The successful implementation of these policies is expected to contribute to higher employment levels, reduced informal labor, improved workforce competitiveness, and stronger social

protection mechanisms, thereby supporting sustainable economic growth and social development in the country.

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# Public Investment, Foreign Capital Attraction, and Green Transition in Azerbaijan: Empirical Evidence and Policy Directions

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**Keywords:** public investment, foreign direct investment, green transition, Azerbaijan, economic diversification, investment governance

## Abstract

This paper investigates the empirical dimensions of Azerbaijan's state investment policy, focusing on three interconnected areas: the dynamics and structure of public investment flows, the country's performance in attracting foreign direct investment, and the emerging agenda of green and innovation-oriented investment. Drawing on data from national statistical sources, international organisations, and sectoral reports, the paper traces the evolution of Azerbaijan's investment landscape over recent years and evaluates the degree to which current policy trajectories align with the requirements of sustainable, diversified economic development.

The State Statistics Committee's data on finance and banking provide a systematic basis for tracking the volume, structure, and sectoral distribution of public investment in Azerbaijan over time (State Statistics Committee, 2026). These data reveal a pattern of sustained growth in capital expenditure across infrastructure-intensive sectors — transport networks, energy systems, social facilities, and housing — accompanied by increasing allocations to innovation-related activities and to the non-oil productive sector. The Investment Development Model framework developed within Azerbaijani economic scholarship offers a useful analytical lens for interpreting these trends (Həsənov, 2017).

One of the most significant recent chapters in Azerbaijan's public investment story is the large-scale reconstruction programme underway in the Karabakh and Eastern Zangezur regions (Azerbaijan-news.az, 2023). The return of these territories to Azerbaijani administration has triggered an ambitious programme of physical reconstruction — rebuilding roads, energy infrastructure, water systems, and residential and public buildings — that represents one of the largest concentrated territorial investment efforts in the country's post-independence history. Managing this reconstruction under conditions of logistical complexity and tight timelines places exceptional demands on project appraisal, procurement, and monitoring systems.

Azerbaijan has consistently maintained a relatively favourable position among South Caucasus economies in terms of foreign direct investment attractiveness (Bayramova, 2024). The growth of foreign capital inflows — reported at approximately 29 percent in the most recent period — underscores the effectiveness of the investment promotion framework (Azreform.info, 2025). The OECD's FDI Qualities Indicators platform provides a methodologically robust framework for evaluating the developmental content of investment flows, going beyond simple volume metrics to examine whether inward FDI generates quality employment, supports technology transfer, and integrates into domestic supply chains (OECD, 2025).

The European Bank for Reconstruction and Development's Country Strategy for Azerbaijan covering the period 2025–2030 identifies private sector development, green economy transition,

and regional integration as the primary axes for concessional and co-financing arrangements (EBRD, 2025). A particularly encouraging development is the signed agreement on the localisation of electric bus manufacturing in partnership with BYD (Economy.gov.az, 2024), illustrating the potential of strategic investment partnerships to support industrial diversification and technology absorption. Complementary evidence of progress comes from export data showing that non-oil sector exports grew by 8.1 percent to reach USD 3.6 billion (Azerbaijan-news.az, 2026).

The Azerbaijan Investment Holding, which consolidates the corporate governance of major state enterprises under a professionalised management structure, represents a significant institutional innovation in the governance of public assets (OECD, 2025). The OECD's review of the Holding's arrangements identifies strengths and areas for further improvement — including board composition, disclosure practices, and performance benchmarking. The United Nations Conference on Trade and Development's World Investment Report 2025 situates the South Caucasus region within a broader pattern of investment reorientation toward resilient supply chains, digital infrastructure, and low-carbon technologies (UNCTAD, 2025).

The empirical analysis supports several substantive conclusions. Azerbaijan's public investment programme has generated tangible developmental outcomes across infrastructure, regional development, and industrial modernisation. At the same time, the transition to a higher-quality investment governance model remains a work in progress. The adoption of the OECD's FDI Qualities framework as an analytical standard, the systematic application of post-completion audits to major public investment projects, and the deepening of the Azerbaijan Investment Holding's corporate governance model are among the most promising near-term directions for policy improvement. Embedding environmental sustainability criteria into the mainstream public investment appraisal process would align Azerbaijan's investment governance with best international practice and position the country favourably in the emerging global competition for green capital.

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# Theoretical Foundations and Institutional Principles of State Investment Policy: The Case of Azerbaijan

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**Keywords:** state investment policy, institutional principles, economic governance, Azerbaijan, capital accumulation, regulatory framework

## Abstract

State investment policy occupies a central place in the economic governance toolkit of both developed and transitional economies. This paper examines the theoretical underpinnings, classification schemes, and institutional formation principles of state investment policy, with a specific focus on Azerbaijan's experience. Drawing on academic literature in investment economics and on official policy documents, the paper argues that a well-designed investment policy framework serves simultaneously as a growth catalyst, a risk management instrument, and an institutional communication mechanism. In economies undergoing diversification or post-transition adjustment, the state must simultaneously correct market failures, provide public goods, and create an enabling environment for private capital formation.

In the neoclassical framework, investment is understood as the allocation of funds to capital assets with the aim of generating future income — a process through which both physical and human capital stocks are renewed, expanded, and technologically upgraded (Cəfərov, 2016). Institutionally oriented perspectives draw attention to the role of governance structures, legal frameworks, and policy credibility in shaping the actual volume and productivity of investment flows (GFOA, 2026). Azerbaijan, a country that has relied heavily on hydrocarbon revenues over recent decades, has placed state investment at the core of its economic development strategy.

State investment policy can be defined as a comprehensive governance instrument that establishes the parameters within which public funds are invested. It specifies investment objectives, acceptable risk tolerances, eligible asset categories, and the mechanisms through which the programme will be managed and monitored over time (GFOA, 2026). The Government Finance Officers Association recommends that every public authority adopt a formally approved investment policy, subject to annual review, and aligned with applicable legal norms. The principal objectives pursued by state investment policy include: facilitating the structural transformation of the national economy; promoting private investment in entrepreneurial activity; generating new employment opportunities; attracting capital from diverse domestic and international sources; and fostering conditions conducive to the formation of risk capital (Əzizova, 2012).

The state participates in the investment process through two complementary channels: regulation and stimulation (Məmmədov, 2018). The regulatory function involves the establishment of rules governing property rights, contract enforcement mechanisms, and dispute resolution procedures. The quality of this regulatory environment is widely recognised as a primary determinant of investment attractiveness, and its improvement features prominently among the priority directions identified by Azerbaijan's Ministry of Economy (2025). The stimulatory function involves active measures to attract investment capital — including fiscal incentives, subsidised credit, co-investment arrangements, and single-window administrative services.

Comparative experience from other economies in transition confirms that the productivity of investment capital depends heavily on the quality of the institutional environment. Turkey's national development planning framework has placed explicit emphasis on the clarity of investment priorities and the strengthening of public investment management capacity as prerequisites for sustained growth (T.C. Kalkınma Bakanlığı, 2018). For Azerbaijan, the investment policy framework rests on a legal architecture that includes the Law on Investment Activity, ministerial regulations, and an evolving set of institutional arrangements for project selection, appraisal, and monitoring (Republic of Azerbaijan Ministry of Economy, 2025).

The analysis concludes with a set of evidence-based observations about the directions in which Azerbaijan's investment policy framework can be further strengthened. Investment policy is most productively understood as a multi-dimensional governance commitment rather than a simple budgetary allocation. Capital accumulation provides the material foundation for growth, but the productivity of that capital is determined by the institutional environment in which it is deployed. Azerbaijan's investment policy framework has developed considerably over the post-independence period, but further strengthening is required — particularly in the areas of project appraisal methodologies, digital service delivery, and the integration of innovation and sustainability objectives into the mainstream investment planning process. A coherent, transparent, and forward-looking investment policy framework is not merely a technical requirement; it is a precondition for the sustainable economic diversification that Azerbaijan's development strategy demands.

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# Axtarış motoru alqoritmlərinin təkamülü: Dəyişən SEO standartlarının kiçik və KOB-ın Rəqəmsal strategiyalarına təsiri

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## Xülasə

Bu tədqiqat işi axtarış motoru alqoritmlərinin təkamülünün və dəyişən SEO standartlarının kiçik və orta bizneslərin (KOB) rəqəmsal strategiyalarına təsirini təhlil edir. Əsas məqsəd klassik optimizasiyadan istifadəçi niyyətinə əsaslanan semantik axtarışa keçidin iqtisadi və strateji nəticələrini müəyyənləşdirməkdir. Məqalədə süni intellektin orqanik trafikə təsiri, texniki veb-arxitekturanın rolu və konversiya izləmə mexanizmlərinin SEO ilə inteqrasiyası araşdırılır. Tədqiqat göstərir ki, dəqiq analitik məlumatlara əsaslanan qərarlar həm müştəri cəlb edilməsi xərclərini optimallaşdırır, həm də investisiya gəlirliliyini (ROI) artırır. Nəticə etibarilə, texniki mükəmməllik və istifadəçi mərkəzli yanaşmanın vəhdəti mürəkkəb rəqəmsal mühitdə bizneslərin dayanıqlı inkişafının mütləq qərantıdır.

**Açar sözlər:** axtarış motoru alqoritmləri, SEO standartları, kiçik və orta bizneslər, orqanik trafik, konversiya izləmə, istifadəçi niyyəti.

## Summary

This research analyzes the impact of evolving search engine algorithms and changing SEO standards on the digital strategies of small and medium-sized enterprises (SMEs). The main objective is to determine the economic and strategic consequences of the transition from classical optimization to intent-based semantic search. The article examines the influence of artificial intelligence on organic traffic, the role of technical web architecture, and the integration of conversion tracking mechanisms with SEO. The study demonstrates that data-driven decisions optimize customer acquisition costs and increase return on investment (ROI). Consequently, the unity of technical excellence and a user-centric approach is the absolute guarantor of sustainable development for businesses in a complex digital environment.

**Keywords:** search engine algorithms, SEO standards, small and medium-sized enterprises, organic traffic, conversion tracking, user intent.

## Axtarış motoru alqoritmlərinin təkamülü: Dəyişən SEO standartlarının kiçik və KOB-ın Rəqəmsal strategiyalarına təsiri

Müasir informasiya cəmiyyətində axtarış motorları sadəcə məlumatların kataloqlaşdırılması funksiyasından çıxaraq, qlobal rəqəmsal iqtisadiyyatın ən mühüm tənzimləyici mexanizmlərindən birinə çevrilmişdir. Bu transformasiya fonunda məlumat axtarışı paradigması köklü şəkildə dəyişmiş, axtarış sistemləri istifadəçi ilə biznes arasında konseptual və strateji körpü rolunu öz

üzərinə götürmüşdür. Xüsusilə məhdud resurslarla fəaliyyət göstərən kiçik və orta biznes (KOB) subyektləri üçün bu dinamik mühitdə orqanik görünürlüyün qorunub saxlanması sadəcə rutin bir marketing hədəfi deyil, bütövlükdə rəqabətədavamlılığın və iqtisadi dayanıqlılığın təməl şərtidir. İnternet mühitindəki qlobal məlumat sıxlığı və istehlakçıların axtarış davranışlarındakı davamlı mürəkkəbləşmə bizneslərdən daha çevik, analitik və texnoloji baxımdan mütərəqqi rəqəmsal strategiyalar tələb edir. Bu baxımdan, axtarış motoru alqoritmlərinin təkamülünü öyrənmək, müasir biznes idarəçiliyinin rəqəmsal bazasında baş verən sistemli dəyişiklikləri dərk etmək üçün mütləq zərurətdir.

Son illərdə axtarış motorlarının alqoritmik arxitekturasında baş verən dəyişikliklərin anatomiyasını təhlil etdikdə, mərkəzi oxun texniki manipulyasiyalardan uzaqlaşaraq "istifadəçi niyyəti" (user intent) və "faydalı məzmun" (helpful content) prinsiplərinə doğru yönəldiyini aydın görmək mümkündür. Klassik SEO (Axtarış Motoru Optimizasiyası) yanaşmalarında üstünlük təşkil edən bəsit açar söz sıxlığı və mexaniki əlaqələndirmə (link-building) strategiyaları artıq öz yerini semantik axtarış məntiqinə və neyron şəbəkələrə əsaslanan dəyərləndirmə sistemlərinə buraxmışdır.

Məhz bu təkamül mərhələsində Generativ Süni İntellekt (Generative AI) texnologiyalarının axtarış nəticələrinə birbaşa inteqrasiyası orqanik trafikə paylanma strukturunda inqilabi dəyişikliklərə səbəb olmuşdur. Alqoritmlər artıq məzmunun sadəcə mövcudluğunu deyil, onun ekspertizasını, təcrübəsini, nüfuzunu və etibarlılığını (müasir E-E-A-T prinsipləri) maşın öyrənməsi vasitəsilə dərinləndirən analiz edir. Bu isə rəqəmsal ekosistemdə yer alan müəssisələrdən məlumatı sadəcə kəmiyyət olaraq deyil, bilavasitə istifadəçinin spesifik axtarış sorğusuna ən dəqiq, dolğun və kontekstual cavab verən intellektual arxitektura şəklində qurmağı tələb edir.

Yenilənmiş axtarış alqoritmləri veb-platformaların arxa fon (backend) arxitekturasının və məlumat bazası sorğularının optimizasiyasını mütləq sıralama meyarı kimi müəyyənləşdirir. Xüsusilə dinamik yaradılan səhifələrdə texniki SEO standartlarının qorunması orqanik indekslənmənin təməlini təşkil edir. Bu texniki mükəmməllik qərarverməni təmin edən analitik sistemlərlə sinxronlaşdırılmalıdır. İstehlakçı davranışlarını mikrosəviyyədə ölçmək üçün Google Tag Manager (GTM) kimi vasitələrin tətbiqi, mürəkkəb hadisə (event) və konversiya izləmə mexanizmlərinin qurulması bizneslərə məlumatları birbaşa mənbədən idarə etmək imkanı verir. Beləliklə, texniki arxitekturanın və konversiya izləmə sistemlərinin vəhdəti axtarış motorlarının istifadəçi təcrübəsini (UX) dəyərləndirmə meyarları ilə tam inteqrasiya olunur.

Alqoritmik transformasiyaların KOB-lara iqtisadi təsiri ikili xarakter daşıyır. Bir tərəfdən, texniki arxitektura və məzmun keyfiyyəti üzrə tələblərin sərtləşməsi qısamüddətli əməliyyat xərclərini artırırsa da, digər tərəfdən hədəflənmiş orqanik trafik müştəri cəlbəedilməsi xərclərində (CAC- Customer Acquisition Cost) uzunmüddətli və kəskin azalmaya səbəb olur. Dəqiq konversiya izləmələrinə əsaslanan məlumat yönümlü (data-driven) orqanik strategiyalar sayəsində müəssisələr hansı axtarış sorğularının daha yüksək investisiya gəlirliliyi (ROI) gətirdiyini riyazi dəqiqliklə hesablayır. Nəticədə, lokal bizneslər məhdud resurslarını səmərəsiz fərziyyələrdən uzaqlaşdıraraq, birbaşa istifadəçi niyyətinə və yüksək gəlirliliyə fokuslanmış strateji ox üzrə yenidən bölüşdürürlər.

Təhlil etdiyimiz alqoritmik dəyişikliklər və texniki inteqrasiya prosesləri bir-birindən təcrid olunmuş şəkildə yox, məhz mütləq vəhdət halında çıxış edir. Bu texnoloji və strateji vəhdətin kiçik və orta bizneslərə (KOB) göstərdiyi praktiki təsirlər zəncirvari xarakter daşıyır. İlk növbədə, istifadəçi niyyətinə və "faydalı məzmun" prinsiplərinə uyğunlaşdırılmış orqanik strategiyalar, server tərəfli qüsursuz optimizasiya ilə birləşərək axtarış sistemlərində dayanıqlı görünürlüyü təmin edir. Buna paralel olaraq, konversiya izləmə mexanizmləri və sistemli tag menecmenti (GTM) vasitəsilə toplanan dəqiq analitik məlumatlar istehlakçıların rəqəmsal platformadakı davranışlarına anında və adekvat cavab verməyə imkan yaradır. Məsələnin iqtisadi və rəqabət tərəfinə nəzər saldıqda isə alqoritmlərin daim yenilənən tələblərinə texniki cəhətdən hazır olmaq həlledici rol oynayır.

Məlumat əsaslı (data-driven) qərarların qəbul edilməsi marketing büdcəsinin səmərəsiz istifadəsinin qarşısını alan və müştəri cəlbəedilməsi xərclərini (CAC) optimallaşdıran əsas qoruyucu siperə çevrilir. Nəticə etibarilə, bu mürəkkəb inteqrasiya lokal bizneslərin həm istifadəçi təcrübəsini (UX) zənginləşdirir, həm də onların uzunmüddətli inkişaf və gəlirlilik dinamikasını sürətləndirir.

Müasir dövrün rəqəmsal arxitekturası tələb edir ki, axtarış motorlarında rəqabətə davamlı olmaq istəyən iqtisadi subyektlər SEO-ya sadəcə bəsit texniki manipulyasiya kimi deyil, fundamental biznes strategiyasının ayrılmaz hissəsi kimi yanaşsınlar. Alqoritmlərin süni intellekt və semantik axtarış istiqamətindəki təkamülü artıq müvəqqəti bir trend deyil, rəqəmsal iqtisadiyyatın yeni, qeyri-şərtsiz reallığıdır. Tədqiqat göstərir ki, müəssisələrin rəqəmsal mühitdəki davamlılığı orqanik trafik göstəricilərinin dəqiq izlənməsindən və istifadəçi niyyətində hesablanmış yüksək keyfiyyətli məzmunun texniki cəhətdən sağlam təqdimatından birbaşa asılıdır. Məlumatları analitik şəkildə idarə edən, alqoritmik yeniliklərə çevik reaksiya verən və investisiya gəlirliliyini (ROI) riyazi dəqiqliklə optimallaşdıran təşkilatlar dəyişən SEO standartlarının mənfi təsirlərindən qorunmaqla yanaşı, gələcəyin dayanıqlı idarəetmə modelinin lokomotivinə çevriləcəklər.

## Technical Sciences

# COMPARATIVE ANALYSIS OF POLYPHENOLS, FLAVONOIDS, MINERAL SUBSTANCES AND TOXIC ELEMENTS IN SWEET CLOVER (*MELILOTUS OFFICINALIS*), ITS EXTRACT AND YOGURT ENRICHED WITH THE EXTRACT

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### Abstract

The development of functional dairy products enriched with natural plant components is one of the relevant directions in modern food technology. Medicinal plants contain biologically active compounds that can increase the nutritional and biological value of food products. Sweet clover (*Melilotus officinalis*) is a promising plant raw material due to its content of polyphenols, flavonoids, mineral substances and other bioactive compounds.

This study presents a comparative analysis of the chemical composition of sweet clover plant raw material, sweet clover extract and yogurt enriched with sweet clover extract. The aim of the study was to determine the content of polyphenols, flavonoids, mineral substances and toxic elements in the studied samples and to evaluate the differences between them.

The results showed that the highest content of polyphenols and flavonoids was found in sweet clover raw material. The total polyphenol content in sweet clover was  $2.07 \pm 0.04\%$ , while the flavonoid content was  $1.81 \pm 0.04\%$ . In sweet clover extract, these indicators decreased to  $0.374 \pm 0.004\%$  and  $0.253 \pm 0.006\%$ , respectively. In yogurt enriched with sweet clover extract, polyphenols and flavonoids were retained at the levels of  $1.34 \pm 0.05\%$  and  $0.53 \pm 0.02\%$ , respectively.

The comparative analysis of mineral composition showed that sweet clover raw material contained high amounts of potassium, phosphorus and zinc. Yogurt enriched with sweet clover extract was characterized by the highest calcium content, reaching  $146.62 \pm 2.93$  mg/100 g. The analysis of toxic elements showed that all studied samples met safety requirements. In the yogurt sample, lead, cadmium, arsenic and mercury were not detected.

The obtained results confirm that sweet clover is a valuable natural source of biologically active compounds and mineral substances. Sweet clover extract can be used as a functional ingredient for enriching dairy products. Yogurt with added sweet clover extract can be considered a safe functional dairy product with increased biological value and promising potential for food technology.

Keywords: sweet clover, *Melilotus officinalis*, sweet clover extract, yogurt, polyphenols, flavonoids, mineral substances, toxic elements, functional dairy products.

## Introduction

In recent years, the production of functional food products has become one of the most important areas of the food industry. Functional products are aimed not only at satisfying nutritional needs, but also at improving human health due to the presence of biologically active compounds. Dairy products, especially yogurt, are widely used as a basis for functional food development because of their high nutritional value, digestibility and beneficial effect on the intestinal microflora.

Sweet clover (*Melilotus officinalis*) is a medicinal plant that contains biologically active substances, including phenolic compounds, flavonoids and coumarins. The antioxidant and anti-inflammatory properties of *Melilotus officinalis* extracts have been studied in biological systems [1]. In addition, the cardioprotective effects of *Melilotus officinalis* extracts have been investigated, which confirms the scientific interest in this plant as a promising natural source of bioactive substances [2].

Extracts of *Melilotus officinalis* have also been used in the development of semi-solid formulations, where their stability, safety and anti-inflammatory activity were evaluated [3]. According to literature data, sweet clover can be considered a source of biologically active compounds with potential use in functional products [4]. The biological potential of *Melilotus officinalis* extract has also been studied in extract-containing materials intended for diabetic ulcer healing [5].

Polyphenols and flavonoids are among the most important groups of biologically active compounds. They are natural antioxidants and may contribute to the protective properties of functional foods. Flavonoids and other polyphenols obtained from medicinal plants are considered important bioactive molecules that can support human health [6].

The use of plant raw materials in the production of functional food products is also relevant for Kazakhstan. Plant resources of Northern Kazakhstan are considered promising for the development of new functional food products due to their content of biologically active substances [7]. The chemical composition of plants belonging to the Fabaceae family has been studied in terms of phytochemical profile and biological activity [8]. In addition, comparative studies of legume seeds, including plants of the genus *Melilotus*, have shown that such raw materials may contain valuable nutrients and biologically active components [9].

The extraction process plays an important role in the transfer of bioactive compounds from plant raw material into the final product. Different extraction methods can influence the yield of polyphenolic compounds and the quality of the obtained extract [10]. The chemical composition and biological activity of *Melilotus officinalis* metabolites have also been studied, confirming the importance of this plant in phytochemical research [11].

The enrichment of yogurt with natural nutraceuticals and plant extracts is considered an effective way to improve its functional properties [12]. Studies show that the addition of plant extracts to yogurt can increase its biological value and improve quality during storage [13]. Enrichment of yogurt with plant ingredients can also increase antioxidant activity, phenolic compound content and sensory properties [14]. In addition, yogurt enriched with plant extracts may demonstrate improved physicochemical, rheological and antioxidant characteristics [15].

Therefore, the introduction of sweet clover extract into yogurt may allow the combination of the nutritional properties of dairy products with the bioactive potential of plant raw materials. The comparative study of sweet clover, its extract and yogurt enriched with the extract is scientifically and practically relevant.

The aim of this study was to conduct a comparative analysis of sweet clover, sweet clover extract and yogurt enriched with sweet clover extract according to the content of polyphenols, flavonoids, mineral substances and toxic elements.

### **Materials and methods**

Sweet clover plant raw material, sweet clover extract and yogurt enriched with sweet clover extract were used as the objects of the study. The samples were analyzed for the content of polyphenols, flavonoids, mineral substances and toxic elements.

The total content of polyphenols was determined by the spectrophotometric method. The amount of flavonoids was determined according to the appropriate standard method. Mineral elements, including calcium, potassium, magnesium, phosphorus, iron, zinc and selenium, were determined by atomic absorption spectrometry.

Toxic elements, including lead, cadmium, arsenic and mercury, were determined according to standard methods used for food safety assessment. The determination of toxic elements is important because plant raw materials may accumulate heavy metals from the environment.

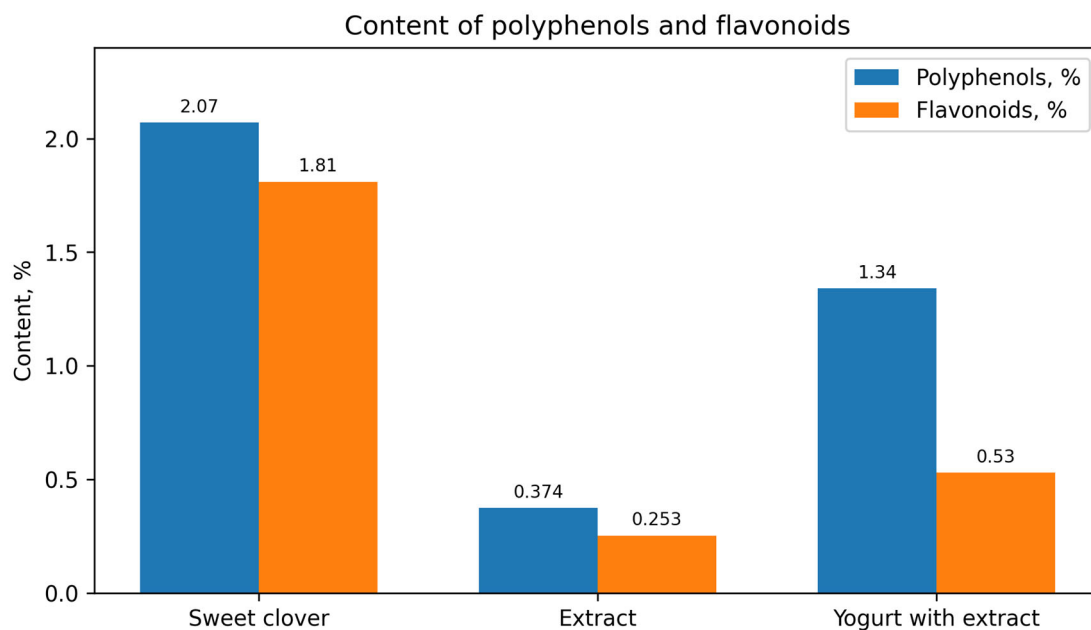
All analyses were carried out in triplicate. The results were expressed as mean values with standard deviation.

### **Results and discussion**

The comparative analysis showed significant differences between the studied samples. Sweet clover plant raw material had the highest content of polyphenols and flavonoids. The total polyphenol content was  $2.07 \pm 0.04\%$ , while the flavonoid content was  $1.81 \pm 0.04\%$ . These results indicate that sweet clover is a rich natural source of biologically active compounds.

In sweet clover extract, the amount of polyphenols decreased to  $0.374 \pm 0.004\%$ , and the amount of flavonoids decreased to  $0.253 \pm 0.006\%$ . This reduction may be related to the extraction process, during which not all active substances are transferred from the plant raw material into the extract. In addition, technological processing may lead to partial degradation or transformation of some phenolic compounds.

In yogurt enriched with sweet clover extract, the content of polyphenols was  $1.34 \pm 0.05\%$ , and the content of flavonoids was  $0.53 \pm 0.02\%$ . Although these values were lower than in the plant raw material, they showed that part of the biologically active compounds was retained in the dairy matrix. This confirms the potential of using sweet clover extract as a functional additive in yogurt production.



*Figure 1 – Content of polyphenols and flavonoids in sweet clover, sweet clover extract and yogurt enriched with the extract*

The analysis of mineral composition also showed important differences. Sweet clover raw material was characterized by high contents of potassium, phosphorus and zinc. Potassium content was 267.44 mg/100 g, phosphorus content was 258.43 mg/100 g, and zinc content was 2.732 mg/100 g. These elements are important for normal physiological processes in the human body.

Sweet clover extract contained lower amounts of most mineral substances. Calcium content in the extract was 16.54 mg/100 g, potassium was 71.57 mg/100 g, magnesium was 13.75 mg/100 g, and phosphorus was 29.70 mg/100 g. The decrease in mineral content may be explained by incomplete transfer of minerals into the extract.

Yogurt enriched with sweet clover extract showed the highest calcium content among the studied samples. Calcium reached  $146.62 \pm 2.93$  mg/100 g, which is mainly associated with the dairy base of yogurt. Potassium content in yogurt was  $189.35 \pm 3.78$  mg/100 g, phosphorus was  $116.04 \pm 2.32$  mg/100 g, and magnesium was  $14.65 \pm 0.29$  mg/100 g. Thus, yogurt combined the nutritional advantages of the dairy base with the functional potential of the plant extract. The results of the mineral composition analysis of sweet clover, sweet clover extract and yogurt enriched with sweet clover extract are presented in Table 1.

**Table 1**

**Mineral composition of the studied samples, mg/100 g**

Element	Sweet clover	Sweet clover extract (wild)	Yogurt enriched with extract
Ca	77.18	16.54	$146.62 \pm 2.93$
K	267.44	71.57	$189.35 \pm 3.78$
Mg	4.025	13.75	$14.65 \pm 0.29$
P	258.43	29.70	$116.04 \pm 2.32$
Fe	0.970	1.05	$0.061 \pm 0.001$
Zn	2.732	0.209	$0.45 \pm 0.009$
Se	0.018	not detected	not detected

Food safety is an important criterion in the development of functional products. The analysis of toxic elements showed that all studied samples met safety requirements. In sweet clover raw

material, lead content was 0.0022 mg/kg, and cadmium content was 0.0009 mg/kg. In sweet clover extract, lead content was 0.005±0.0003 mg/kg, and cadmium content was 0.002±0.0003 mg/kg. These values were significantly lower than the maximum permissible limits.

Arsenic and mercury were not detected in all samples. In yogurt enriched with sweet clover extract, lead, cadmium, arsenic and mercury were not detected. The obtained results show that sweet clover extract does not negatively affect the safety of the final dairy product. On the contrary, yogurt enriched with sweet clover extract can be considered a safe product with improved biological value.

## Conclusion

The results of the study showed that sweet clover (*Melilotus officinalis*), sweet clover extract and yogurt enriched with sweet clover extract differ in the content of polyphenols, flavonoids, mineral substances and toxic elements.

The highest content of polyphenols and flavonoids was found in sweet clover raw material, which confirms its value as a natural source of biologically active compounds. Sweet clover extract contained lower amounts of these substances, which may be explained by the features of the extraction process. However, the presence of polyphenols and flavonoids in yogurt enriched with sweet clover extract confirms the possibility of using this extract as a functional ingredient.

The mineral composition analysis showed that sweet clover is a significant source of potassium, phosphorus and zinc. Yogurt enriched with sweet clover extract was characterized by high calcium content due to its dairy base. The safety analysis demonstrated that all samples met the requirements for toxic elements. No toxic elements were detected in the yogurt sample.

Thus, sweet clover can be considered a valuable plant raw material for obtaining functional ingredients. Sweet clover extract is a suitable technological form for introducing bioactive compounds into dairy products. Yogurt enriched with sweet clover extract can be regarded as a safe functional dairy product with increased biological and nutritional value.

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# TƏSADÜFİ DOLAŞMANIN QEYRİ- XƏTTİ SƏRHƏD MƏSƏLƏLƏRİ

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**Xülasə:** Bu işdə qeyri-xətti sərhəd şəraitində təsadüfi dolaşma modeli tədqiq olunur. Təsadüfi dolaşma verilmişdir və burada  $X$  asılı olmayan və eyni paylanmış təsadüfi kəmiyyətlərdir.

Sərhəd funksiyası ümumi halda zaman dəyişənindən asılı qeyri-xətti funksiya kimi götürülür. Xüsusi hallarda  $g(n) = a + cn$  və  $g(n) = a + c \log(n+1)$  kimi sərhədlər nəzərdən keçirilir. Bu tip sərhədlərdə artım sürətinin dəyişkən olması səbəbindən sərhədə çatma probleminin analizi xətti sərhəd halına nisbətən daha mürəkkəb xarakter daşıyır.

Əsas tədqiq olunan funksional sərhədə ilk çatma zamanıdır. Bu zamanın paylanması və sərhəd keçidi ehtimalı maksimum funksional yanaşma əsasında araşdırılır. Alınan nəticələr göstərir ki, qeyri-xətti sərhəd problemi trayektoriyanın lokal maksimum davranışı ilə sıx bağlıdır.

**Açar sözlər:** Təsadüfi dolaşma, qeyri-xətti sərhəd, dayanma zamanı, hitting time, stokastik proseslər, maksimum funksional, ehtimal nəzəriyyəsi, sərhəd keçidi.

Tutaq ki,

$$S_n = \sum_{k=1}^n X_k, \quad S_0 = 0$$

şəklində təsadüfi dolaşma verilmişdir. Burada  $X_1, X_2, \dots$  asılı olmayan və eyni paylanmış təsadüfi kəmiyyətlərdir. Qeyri-xətti sərhəd isə ümumi şəkildə

$$b(n) = g(n), \quad n \geq 0$$

kimi müəyyən edilir. Burada  $g(n)$  zaman dəyişənindən asılı ixtiyari qeyri-xətti funksiyadır. Məsələn,

$$g(n) = a + cn^\alpha, \quad 0 < \alpha < 1,$$

və ya

$$g(n) = a + c \log(n+1)$$

şəklində sərhədlər qeyri-xətti sərhədləri nümunə ola bilər. Bu funksiyalarda sərhədin artım sürəti sabit deyil və bu səbəbdən sərhədə çatma anının təhlili xətti hala nisbətən daha mürəkkəb olur.

Qeyri-xətti sərhəd üçün əsas funksional sərhədə ilk çatma zamanıdır. Bu zaman

$$\tau_g = \inf\{n \geq 0 : S_n \geq g(n)\}$$

kimi təyin olunur. Burada  $\tau_g$  təsadüfi dolaşmanın  $g(n)$  sərhədini ilk dəfə keçdiyi andır. Əgər proses aşağı sərhədlə müqayisə olunursa, onda uyğun olaraq

$$\tau_g^- = \inf\{n \geq 0 : S_n \leq g(n)\}$$

yazılır. Beləliklə, qeyri-xətti sərhəd məsələsinin əsas qoyuluşu  $\tau_g$ -nin paylanmasını, riyazi gözləməsini, sərhəd keçidi ehtimalını və sərhəd aşmasını müəyyən etməkdən ibarətdir.

Qeyri-xətti sərhəd məsələsində əsas ehtimal göstəricisi işdə

$$P(\tau_g \leq n) \text{ və ya } P(\tau_g \leq t), t \rightarrow \infty$$

şəklində yazılır. Bu ehtimal prosesin  $n$ -ci ana qədər qeyri-xətti sərhədi keçməsi ehtimalını göstərir. Onu maksimum funksionalı vasitəsilə belə ifadə etmək olar:

$$P(\tau_g \leq n) = P\left(\max_{0 \leq k \leq n} (S_k - g(k)) \geq 0\right)$$

Bu düstur göstərir ki, təsadüfi dolaşmanın qeyri-xətti sərhədi keçməsi üçün trayektoriyasının ən azı bir nöqtədə sərhəd funksiyasını aşması kifayətdir.

### NƏTİCƏ

Bu tədqiqatda qeyri-xətti sərhədlərlə verilmiş təsadüfi dolaşma modelləri araşdırılmışdır. Göstərilmişdir ki, sərhəd funksiyasının qeyri-xətti xarakteri səbəbindən sərhədə çatma zamanının analitik təhlili daha mürəkkəb olur və klassik xətti sərhəd nəticələri birbaşa tətbiq edilə bilmir.

Əsas nəticə olaraq müəyyən olunmuşdur ki, sərhədə ilk çatma hadisəsi trayektoriyasının maksimum funksionalı vasitəsilə ekvivalent şəkildə ifadə oluna bilər. Bu yanaşma sərhəd keçidi ehtimalının və paylanması tədqiqində mühüm alət rolunu oynayır.

Ümumilikdə, nəticələr göstərir ki, qeyri-xətti sərhəd problemləri təsadüfi proseslərin ekstremal davranışı ilə sıx bağlıdır və onların analizi maksimum funksional və stopping time nəzəriyyəsi vasitəsilə effektiv şəkildə aparıla bilər.

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# TƏSADÜFİ DOLAŞMANIN XƏTTİ SƏRHƏD FUNKSIONALLARI

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**Xülasə:** Bu işdə xətti sərhəd funksiyası ilə verilmiş təsadüfi dolaşma modeli araşdırılır. Təsadüfi dolaşma və xətti sərhəd üçün sərhədə ilk çatma zamanı (hitting time) tədqiq olunur. Göstərilir ki, bu zaman filtrasiya sisteminə görə dayanma zamanı (stopping time) xassəsinə malikdir.

Eyni zamanda, xətti sərhədin keçilməsi problemi trayektoriyanın maksimum funksionalı vasitəsilə ifadə olunur və bu yanaşma hitting-time analizini sadələşdirir. Sadə təsadüfi dolaşma üçün sərhədə çatma ehtimalı rekursiv tənliklə təsvir edilir və bu tənliyin sərhəd şərtləri müəyyən olunur.

Nəticələr təsadüfi proseslərin sərhəd məsələlərinin ehtimal nəzəriyyəsi çərçivəsində daha ümumi və funksional yanaşma ilə öyrənilə biləcəyini göstərir..

**Açar sözlər:** Təsadüfi dolaşma, dayanma zamanı, xətti sərhəd, hitting time, stokastik proseslər, filtrasiya, rekursiv tənlik, maksimum funksional.

## Teorem 1. Xətti sərhədə ilk çatma zamanının dayanma zamanı olması

Tutaq ki, təsadüfi dolaşma

$$S_n = X_1 + X_2 + \dots + X_n, S_0 = 0$$

şəklində verilmişdir və xətti sərhəd

$$b(n) = a + cn, a, c \in \mathbb{R}, n \geq 0$$

kimi müəyyən olunur. Onda

$$\tau_b = \inf\{n \geq 0 : S_n \geq b(n)\}$$

kəmiyyəti  $F_n = \sigma(X_1, \dots, X_n)$  filtrasiya sisteminə görə dayanma zamanıdır.

**İzah.** Çünki  $\{\tau_b = n\}$  hadisəsi yalnız  $n$ -ci ana qədər müşahidə olunan  $S_0, S_1, \dots, S_n$  qiymətlərindən asılıdır. Buna görə də  $\tau_b$  xətti sərhəd funksionalı formal olaraq stopping-time tipli funksional hesab olunur.

## Teorem 1.2.2. Xətti sərhədin maksimum funksionalı ilə ekvivalentliyi

Xətti sərhəd üçün aşağıdakı ekvivalentlik doğrudur:

$$\{\tau_b \leq n\} = \left\{ \max_{0 \leq k \leq n} (S_k - b(k)) \geq 0 \right\}$$

Burada:

$$M_n^b = \max_{0 \leq k \leq n} (S_k - b(k))$$

sərhədə nisbətən maksimum funksional adlanır.

**İzah.** Bu teorem göstərir ki, xətti sərhədin keçilməsi prosesi yalnız ayrıca  $S_n$  qiyməti ilə deyil, bütün trayektoriyanın maksimum davranışı ilə müəyyən olunur. Buna görə hitting-time problemi maksimum funksional vasitəsilə də araşdırıla bilər.

**Teorem 2. Sadə təsadüfi dolaşma üçün keçid ehtimalının rekursiv tənliyi**

Tutaq ki,

$$P(X_n=1)=p, P(X_n=-1)=q, p+q=1.$$

Sabit A sərhədinə çatma ehtimalı

$$u(i)=P_i(\tau_A<\infty)$$

kimi müəyyən edilsin. Onda  $i < A_i < A_i + A$  üçün

$$u(i+1)+qu(i-1),$$

sərhəd şərti isə

$$u(A)=1$$

şəklindədir.

**NƏTİCƏ**

Bu tədqiqatda xətti sərhəd üzrə təsadüfi dolaşmanın keçid xüsusiyyətləri araşdırılmışdır. Əsas nəticə olaraq göstərildi ki, sərhədə ilk çatma zamanı filtrasiya üzrə dayanma zamanıdır və bu xüsusiyyət prosesin adaptiv xarakterini təsdiq edir.

Bundan əlavə, xətti sərhəd problemi maksimum funksional vasitəsilə ekvivalent formada ifadə oluna bilər ki, bu da hitting-time analizini daha effektiv edir. Sadə təsadüfi dolaşma üçün alınan rekursiv tənlik sərhəd ehtimallarının hesablanmasını asanlaşdırır və analitik həll üçün baza yaradır.

Ümumilikdə, nəticələr təsadüfi dolaşmaların sərhəd məsələlərinin həm klassik ehtimal yanaşması, həm də funksional analiz vasitəsilə öyrənilə biləcəyini göstərir.

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# “28 May” Neftqazçıxarma İdarəsində dənizdən nəql etdirilən qazın separasiya prosesinin təhlili

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## Xülasə

Məqalədə “28 May” Neftqazçıxarma İdarəsində dənizdən nəql etdirilən qazın separasiya prosesinin texnoloji xüsusiyyətləri təhlil edilmişdir. Dəniz şəraitində hasil olunan qaz quyu ağzından nəql sisteminə daxil olarkən yalnız qaz fazasından ibarət olmur, onun tərkibində kondensat, lay suyu, mexaniki qarışıqlar və müxtəlif maye damcıları mövcud ola bilər. Bu səbəbdən qazın nəql və emal sistemlərinə verilməzdən əvvəl separasiya olunması texnoloji təhlükəsizlik, avadanlığın qorunması və məhsul keyfiyyəti baxımından mühüm əhəmiyyət daşıyır. Tədqiqatda qaz-maye qarışığının ayrılması, separatorların iş prinsipi, çoxfazlı axın rejimi, slug effekti, hidrat və korroziya riskləri araşdırılmışdır. Eyni zamanda separasiya prosesinin səmərəliliyinə təsir edən əsas göstəricilər sistemləşdirilmiş və prosesin optimallaşdırılması istiqamətləri müəyyən edilmişdir. Nəticə olaraq qeyd olunur ki, dənizdən nəql etdirilən qazın stabil separasiyası təzyiq, temperatur, maye səviyyəsi, qaz sərfi və avadanlığın texniki vəziyyətinə davamlı nəzarət əsasında təmin edilməlidir.

**Açar sözlər:** dəniz qazı, separasiya, çoxfazlı axın, separator, 28 May NQÇİ, qaz nəqli.

## Abstract

The article analyzes the technological features of the gas separation process transported from offshore facilities within the operational context of the “28 May” Oil and Gas Production Department. Gas produced in offshore conditions is not transported as a completely dry gas phase, since it may contain condensate, formation water, mechanical impurities and liquid droplets. Therefore, separation before further transportation and processing is essential for technological safety, equipment protection and gas quality assurance. The study examines the separation of gas-liquid mixtures, the operating principles of separators, multiphase flow behavior, slug flow effects, hydrate formation and corrosion risks. The main parameters affecting separation efficiency are also systematized, and possible directions for process optimization are identified. The analysis shows that stable separation of offshore transported gas depends on continuous monitoring of pressure, temperature, liquid level, gas flow rate and the technical condition of process equipment. It is concluded that the improvement of separation efficiency in offshore gas transportation systems should be based on reliable control systems, proper maintenance, hydrate prevention, corrosion control and data-driven technological management.

**Keywords:** offshore gas, separation, multiphase flow, separator, 28 May OGPD, gas transportation.

## Резюме

В статье анализируются технологические особенности процесса сепарации газа, транспортируемого с морских объектов в рамках деятельности Нефтегазодобывающего управления «28 Май». Газ, добываемый в морских условиях, не поступает в транспортную систему в полностью сухом виде, так как в его составе могут присутствовать конденсат, пластовая вода, механические примеси и капли жидкости. Поэтому сепарация газа перед дальнейшей транспортировкой и переработкой имеет важное значение с точки зрения

технологической безопасности, защиты оборудования и обеспечения качества продукции. В исследовании рассмотрены процессы разделения газожидкостной смеси, принципы работы сепараторов, режимы многофазного потока, влияние slug-режима, риски образования гидратов и коррозии. Также систематизированы основные показатели, влияющие на эффективность сепарации, и определены направления оптимизации процесса.

**Ключевые слова:** морской газ, сепарация, многофазный поток, сепаратор, НГДУ «28 Май», транспортировка газа.

### Giriş

Azərbaycanın neft-qaz sənayesində dəniz yataqlarından hasil olunan qazın yığılması, ilkin hazırlanması və nəql etdirilməsi mühüm texnoloji proseslərdən biri hesab olunur. Xəzər dənizində yerləşən istehsalat obyektlərində qazın nəqli təkcə hasilatın davamlılığı baxımından deyil, həm də enerji təhlükəsizliyi, sənaye avadanlıqlarının etibarlılığı və ekoloji risklərin azaldılması baxımından əhəmiyyətlidir. Dəniz şəraitində hasil edilən qaz nəql sisteminə daxil olarkən çox vaxt qaz, kondensat və su fazalarının qarışığından ibarət olur. Bu isə qazın emal və nəql mərhələlərinə verilməzdən əvvəl texnoloji baxımdan hazırlanmasını zəruri edir [1].

“28 May” Neftqazçıxarma İdarəsi SOCAR-ın “Azneft” İstehsalat Birliyinin dəniz hasilatı üzrə mühüm istehsalat strukturlarından biri kimi çıxış edir. Bu idarənin fəaliyyət sahəsində dəniz platformalarından çıxarılan neft, qaz və qaz-kondensat qarışıqlarının ilkin ayrılması, texnoloji xətlər üzrə nəqli və sonrakı emal sistemlərinə yönləndirilməsi xüsusi əhəmiyyət daşıyır. Dənizdən nəql etdirilən qazın tərkibində maye hissəciklərinin qalması boru xətlərində hidravlik müqavimətin artmasına, kompressor avadanlığının zədələnməsinə, ölçü cihazlarının qeyri-dəqiq işləməsinə və korroziya riskinin yüksəlməsinə səbəb ola bilər [2, s. 197–224].

Separasiya prosesi qaz-maye qarışığının fiziki ayrılması, qaz axınında olan kondensat və su damcılarının tutulması, həmçinin sonrakı nəql mərhələsinin təhlükəsiz təmin olunması məqsədilə həyata keçirilir. Bu proses yalnız bir texnoloji avadanlığın işi kimi deyil, bütöv bir idarəetmə mexanizmi kimi qiymətləndirilməlidir. Çünki separatorun səmərəli işləməsi təzyiq, temperatur, axın sürəti, maye səviyyəsi, daxili elementlərin texniki vəziyyəti və avtomatik nəzarət sistemlərinin düzgün fəaliyyətindən asılıdır [3].

Müasir neft-qaz sənayesində separasiya proseslərinin optimallaşdırılması hasilatın səmərəliliyinin yüksəldilməsi ilə yanaşı, texnoloji itkilərin azaldılması və ekoloji təhlükəsizliyin təmin olunması baxımından da aktualdır. Xüsusilə dəniz şəraitində qazın nəql etdirilməsi zamanı çoxfazlı axının qeyri-sabitliyi, slug rejimi, hidratların əmələ gəlməsi və korroziya amilləri separasiya prosesinə birbaşa təsir göstərir. Bu baxımdan “28 May” NQÇİ-də dənizdən nəql etdirilən qazın separasiya prosesinin təhlili həm nəzəri, həm də praktiki əhəmiyyət daşıyır.

Tədqiqatın əsas məqsədi “28 May” Neftqazçıxarma İdarəsində dənizdən nəql etdirilən qazın separasiya prosesinin texnoloji əhəmiyyətini araşdırmaq, prosesə təsir edən əsas amilləri müəyyənləşdirmək və separasiya sisteminin səmərəliliyinin artırılması istiqamətlərini əsaslandırmaqdan ibarətdir. Bu məqsədlə qaz-maye qarışığının ayrılması mexanizmi, separatorların iş rejimi, çoxfazlı axının xüsusiyyətləri, nəql xəttində yaranan risklər və prosesə nəzarət göstəriciləri təhlil edilmişdir.

Tədqiqatda müqayisəli təhlil, sistemləşdirmə və texnoloji qiymətləndirmə metodlarından istifadə olunmuşdur. Müqayisəli təhlil vasitəsilə separasiya prosesinə təsir edən amillər ayrı-ayrılıqda qiymətləndirilmiş, sistemləşdirmə metodu ilə bu amillər texnoloji, təhlükəsizlik, keyfiyyət və idarəetmə göstəriciləri üzrə qruplaşdırılmışdır. Texnoloji qiymətləndirmə isə separatorun iş prinsipinin qaz nəqli sisteminin ümumi sabitliyinə təsirini müəyyən etməyə imkan vermişdir. Belə yanaşma separasiya prosesinə yalnız avadanlıq səviyyəsində deyil, bütöv istehsalat zəncirinin mühüm idarəetmə mərhələsi kimi baxmağa şərait yaradır.

## Təhlil

Dəniz şəraitində qazın separasiya olunması quruda yerləşən istehsalat obyektlərindən fərqli xüsusiyyətlərə malikdir. Burada texnoloji proseslər məhdud platforma sahəsində, dəyişkən hava şəraitində və yüksək təhlükəsizlik tələbləri altında həyata keçirilir. Dəniz platformalarında avadanlığın yerləşdirilməsi üçün sahə məhdud olduğundan separatorların seçilməsi, quraşdırılması və texniki xidmət imkanları xüsusi mühəndis yanaşması tələb edir. Bu səbəbdən separatorların həm məhsuldarlıq, həm də kompaktlıq baxımından düzgün seçilməsi mühüm əhəmiyyət daşıyır.

Digər mühüm xüsusiyyət ondan ibarətdir ki, dənizdən nəql etdirilən qaz uzun boru xətləri vasitəsilə hərəkət etdiyindən təzyiq və temperatur dəyişikliklərinə daha çox məruz qalır. Bu dəyişikliklər qazın tərkibindəki ağır karbohidrogenlərin kondensasiya olunmasına, su fazasının ayrılmasına və axının qeyri-sabitləşməsinə səbəb ola bilər. Nəticədə separatora daxil olan qarışıqın tərkibi sabit qalmır və proses operatorlarından daha diqqətli nəzarət tələb olunur. Bu baxımdan dəniz şəraitində separasiya prosesi sadəcə fazaların ayrılması deyil, həm də nəql sisteminin dayanıqlığını təmin edən texnoloji tənzimləmə mərhələsidir.

Dəniz şəraitində hasil olunan qazın separasiyası bir neçə mərhələdən ibarət olan mürəkkəb texnoloji prosesdir. İlkin mərhələdə quyu və ya platforma xətlərindən daxil olan çoxfazlı axın separatora yönləndirilir. Bu axının tərkibində qazla yanaşı, kondensat, lay suyu və mexaniki qarışıqlar ola bilər. Separatorun əsas funksiyası bu fazaları bir-birindən ayırmaq və qazın nəql sisteminə daha sabit tərkibdə verilməsini təmin etməkdir. Qazın tərkibində maye fazanın qalması “carry-over” adlanan prosesə səbəb olur ki, bu da qazla birlikdə maye damcılarının sonrakı avadanlıqlara keçməsi deməkdir [4, s. 216–219].

Separatorların iş prinsipi fazaların sıxlıq fərqi, axın sürətinin azalmasına, cazibə qüvvəsinə və inersiya təsirinə əsaslanır. Qaz-maye qarışığı separatora daxil olduqda əvvəlcə giriş qurğusu vasitəsilə axının istiqaməti dəyişdirilir və iri maye damcılar qaz axınından ayrılır. Daha sonra separator daxilində qazın sürəti azalır və kiçik maye hissəcikləri çökməyə başlayır. Son mərhələdə isə demister və ya torlu tutucu elementlər vasitəsilə qazın tərkibində qalan incə maye damcılar tutulur [5].

Dənizdən nəql etdirilən qazın separasiyasında əsas çətinliklərdən biri çoxfazlı axının qeyri-sabit xarakter daşmasıdır. Boru xətti boyunca təzyiq və temperatur dəyişdikcə qazın tərkibindəki kondensat ayrılır, bəzi hallarda isə maye faza iri tıxaclar şəklində hərəkət edir. Bu hadisə slug rejimi adlanır. Slug rejimi separatora daxil olan maye həcmnin qısa müddət ərzində kəskin artmasına səbəb olur və separatorun normal iş rejimini poza bilər. Belə hallarda separatorun maye tutumu, səviyyə tənzimləyiciləri və drenaj sistemləri yüksək yüklənmə altında işləyir [6, s. 153–164].

Dəniz qazının nəqlində hidrat əmələgəlmə riski də mühüm texnoloji problem kimi qiymətləndirilir. Qazın tərkibində sərbəst su və ya su buxarı olduqda, yüksək təzyiq və aşağı temperatur şəraitində hidrat kristalları formalaşa bilər. Hidratlar boru xətlərində tıxac yaradır, axının sabitliyini pozur və istehsalatın məcburi dayandırılması riskini artırır. Separasiya prosesi qazdan sərbəst suyun ayrılmasına kömək etdiyi üçün hidratların qarşısının alınmasında ilkin qoruyucu mərhələ kimi çıxış edir [7].

Qazın separasiyası zamanı korroziya riski də nəzərə alınmalıdır. Lay suyunun, duzların, karbon qazının və bəzi hallarda hidrogen-sulfid komponentlərinin mövcudluğu boru xətlərində və avadanlıq səthlərində korroziya prosesini sürətləndirə bilər. Separatorlarda maye fazanın vaxtında ayrılması və sistemdən kənarlaşdırılması korroziya riskinin azaldılması üçün əsas şərtlərdən biridir. Bu səbəbdən separasiya yalnız qazın təmizlənməsi prosesi deyil, həm də nəql sisteminin mexaniki bütövlüyünü qoruyan texnoloji mərhələdir [8].

“28 May” NQÇİ kontekstində separasiya prosesinin səmərəliliyi separatorların texniki vəziyyəti, istismar rejimi və operator nəzarətinin keyfiyyəti ilə sıx bağlıdır. Dəniz platformalarında avadanlıq sahəsinin məhdud olması, texniki xidmətin planlaşdırılmış qaydada aparılması zərurəti və hava şəraitinin istehsalat proseslərinə təsiri separasiya sistemlərinin etibarlılığını daha da vacib

edir. Bu baxımdan separatorların daxili elementlərinin vaxtaşırı yoxlanılması, səviyyə və təzyiq ölçən cihazların kalibrlənməsi, drenaj xətlərinin işlək vəziyyətdə saxlanılması xüsusi əhəmiyyət kəsb edir.

Separasiya prosesində avtomatlaşdırılmış idarəetmə sistemlərinin tətbiqi mühüm rol oynayır. Təzyiq, temperatur, maye səviyyəsi, qaz sərfi və diferensial təzyiq göstəricilərinin real vaxt rejimində izlənilməsi prosedə baş verən kənarlaşmaları erkən aşkar etməyə imkan verir. Məsələn, separator çıxışında diferensial təzyiqin artması demister elementlərinin çirklənməsini, maye səviyyəsinin qəfil yüksəlməsi isə slug axınının daxil olduğunu göstərə bilər. Bu cür məlumatların operativ təhlili qəza risklərinin qarşısının alınmasına və separasiya səmərəliliyinin qorunmasına şərait yaradır [9].

**Cədvəl 1. Dənizdən nəql etdirilən qazın separasiya prosesinə təsir edən əsas göstəricilər**

Göstərici kateqoriyası	Göstərici	Prosesə təsiri	Nəzarət üsulu	Qiymətləndirmə tezliyi
Texnoloji rejim	Təzyiq	Qaz-maye faza tarazlığını və kondensat ayrılmasını dəyişir	Təzyiq ötürücüləri və avtomatik tənzimləmə	Davamlı
Texnoloji rejim	Temperatur	Hidrat və kondensasiya riskinə təsir edir	Temperatur sensorları, istilik rejimi nəzarəti	Davamlı
Axın xarakteri	Qaz sərfi	Separatorun yüklənmə dərəcəsini müəyyən edir	Sərfölçən cihazlar	Davamlı
Maye faza	Kondensat miqdarı	Maye səviyyəsinin artmasına və carry-over riskinə səbəb olur	Səviyyə ölçən cihazlar və drenaj sistemi	Növbəlik
Maye faza	Lay suyu	Hidrat və korroziya riskini artırır	Su ayrılması və inhibitor tətbiqi	Növbəlik
Avadanlıq	Demisterin vəziyyəti	Xırda maye damcılarının tutulmasına təsir edir	Diferensial təzyiq və texniki baxış	Planlı
Təhlükəsizlik	Slug rejimi	Separatora qəfil maye yükü yaradır	Slug tutucu, səviyyə siqnailləri	Davamlı
Keyfiyyət	Qazda maye qalığı	Nəql və kompressor sisteminə mənfi təsir edir	Laborator və proses nəzarəti	Dövri
Ekoloji amil	Texnoloji itkilər	Qaz itkisi və emissiya riskini artırır	Sızma nəzarəti və proses optimallaşdırılması	Dövri
İdarəetmə	Operator müdaxiləsi	Prosesin sabitliyini təmin edir	SCADA və texnoloji təlimatlar	Davamlı

**Mənbə:** Cədvəl API RP 12J, GPSA Engineering Data Book və təbii qazın nəqli-emalı üzrə texniki ədəbiyyat əsasında müəllif tərəfindən ümumiləşdirilmişdir [3; 5; 6].

Cədvəldən göründüyü kimi, separasiya prosesinin səmərəliliyi yalnız separatorun konstruksiyasından deyil, həm də proses göstəricilərinin davamlı izlənilməsindən asılıdır. Təzyiq və temperatur dəyişiklikləri qazın faza davranışına təsir göstərir, maye səviyyəsinin artması separatorun daşıma qabiliyyətini azaldır, demister elementlərinin çirklənməsi isə qazla maye damcılarının aparılması riskini yüksəldir. Buna görə də separasiya sistemində texnoloji nəzarət,

mexaniki baxış və avtomatlaşdırılmış idarəetmə bir-birini tamamlayan mexanizmlər kimi tətbiq edilməlidir.

Qazın separasiya prosesinin optimallaşdırılması üçün bir neçə istiqamət xüsusi əhəmiyyət daşıyır. Birincisi, separatorların faktiki yüklənmə rejimi mütəmadi olaraq təhlil edilməlidir. Layların istismar müddəti artdıqca qaz-maye nisbəti dəyişə, su kəsri arta və nəticədə separatorların əvvəlki layihə göstəricilərinə uyğun işləməsi çətinləşə bilər. İkincisi, separatorun giriş qurğusu, daxili paylayıcı elementlər, demister və drenaj sistemləri planlı texniki baxış proqramına daxil edilməlidir. Üçüncüsü, hidratların qarşısının alınması üçün yalnız kimyəvi inhibitorlardan deyil, həm də temperatur, təzyiq və su miqdarı üzrə kompleks nəzarət sistemindən istifadə olunmalıdır [10].

Müasir yanaşmalar göstərir ki, dəniz qazının separasiya prosesində rəqəmsal monitoring və analitik qiymətləndirmə alətləri mühüm yer tutur. Proses məlumatlarının elektron bazada toplanması, avadanlığın iş rejiminin qrafikləşdirilməsi və kənarlaşmaların avtomatik siqnallaşdırılması operator qərarlarının daha əsaslandırılmış şəkildə qəbuluna imkan yaradır. Bu yanaşma həm texnoloji təhlükəsizliyi artırır, həm də qəza hallarının qarşısını almaq üçün preventiv tədbirlərin vaxtında görülməsinə şərait yaradır [11].

Nəticə etibarilə, "28 May" NQÇİ-də dənizdən nəql etdirilən qazın separasiya prosesi hasilat zəncirinin mühüm mərhələsi kimi qiymətləndirilməlidir. Bu prosesin keyfiyyətli təşkili qazın sonrakı nəqlinə, emalına və istifadə üçün hazırlanmasına birbaşa təsir göstərir. Separasiya sistemində yaranan kiçik texnoloji nasazlıqlar belə sonrakı mərhələlərdə daha böyük istismar problemlərinə səbəb ola bilər. Buna görə də separatorların etibarlı işləməsi, proses göstəricilərinin davamlı izlənməsi və texniki xidmətin vaxtında aparılması dəniz qazının nəqlində əsas idarəetmə prioritetləri hesab olunmalıdır.

Müasir neft-qaz sənayesində separasiya proseslərinin səmərəliliyinin artırılması üçün rəqəmsal monitoring sistemlərinin tətbiqi mühüm istiqamətlərdən biri hesab olunur. Bu sistemlər separatorun əsas iş göstəricilərini real vaxt rejimində izləməyə və prosesdə baş verən kənarlaşmaları erkən mərhələdə müəyyən etməyə imkan verir. Təzyiq, temperatur, maye səviyyəsi, qaz sərfi və diferensial təzyiq göstəricilərinin elektron sistemlərdə toplanması texnoloji qərarların daha əsaslandırılmış qəbul edilməsini təmin edir.

Avtomatlaşdırılmış nəzarət sistemləri operatorun işini əvəz etmir, əksinə onun qərarvermə imkanlarını genişləndirir. Məsələn, maye səviyyəsinin qəfil artması sistem tərəfindən qeydə alındıqda operator separatora slug axınının daxil olduğunu müəyyən edə bilər. Diferensial təzyiqin yüksəlməsi isə demister elementlərində tutulma və ya çirklənmə ehtimalını göstərir. Bu məlumatların vaxtında təhlili texniki xidmətin planlaşdırılmasına, qəza risklərinin azaldılmasına və separasiya prosesinin fasiləsizliyinin təmin olunmasına kömək edir.

### Nəticə

"28 May" Neftqazçıxarma İdarəsində dənizdən nəql etdirilən qazın separasiya prosesinin təkmilləşdirilməsi üçün ilk növbədə proses göstəricilərinin sistemli təhlili aparılmalıdır. Separatorların gündəlik iş rejimi, qaz sərfi, maye çıxışı, təzyiq fərqi və temperatur dəyişmələri üzrə məlumatlar toplanmalı və müqayisəli şəkildə qiymətləndirilməlidir. Bu məlumatlar separatorun real yüklənmə vəziyyətini müəyyən etməyə və texniki xidmətin daha düzgün planlaşdırılmasına imkan verə bilər.

İkinci istiqamət avadanlığın texniki xidmət sisteminin gücləndirilməsi ilə bağlıdır. Separator daxilindəki demister, səviyyə ölçən cihazlar, klapınlar və drenaj xətləri yalnız nasazlıq yarandıqda deyil, planlı qrafik əsasında yoxlanılmalıdır. Bu yanaşma qəza risklərinin azalmasına və prosesin sabitliyinin qorunmasına şərait yaradır.

Üçüncü istiqamət prosesin rəqəmsallaşdırılmasıdır. Separasiya göstəricilərinin elektron bazada toplanması, əvvəlki dövrlərlə müqayisə olunması və kritik hədlər üzrə avtomatik xəbərdarlıq sistemlərinin tətbiqi texnoloji idarəetməni daha çevik edir. Belə sistemlər istehsalat

obyektlərində həm insan amilindən doğan səhvləri azaldır, həm də operativ qərarverməni sürətləndirir.

Dördüncü istiqamət ekoloji və enerji səmərəliliyi ilə bağlıdır. Qazın düzgün separasiya olunması texnoloji itkilərin azalmasına, avadanlığın daha stabil işləməsinə və artıq enerji sərfinin qarşısının alınmasına kömək edir. Separatorun qeyri-sabit işləməsi nəticəsində qazın təkrar emala və ya əlavə təmizləmə mərhələsinə ehtiyacı arta bilər. Bu işə həm enerji sərfiyyatını, həm də istismar xərclərini yüksəldir. Buna görə separasiya prosesinin optimallaşdırılması iqtisadi baxımdan da əhəmiyyətlidir.

Aparılan təhlil göstərir ki, "28 May" Neftqazçıxarma İdarəsində dənizdən nəql etdirilən qazın separasiya prosesi qazın keyfiyyətinin təmin olunması, nəql sisteminin sabitliyi və texnoloji təhlükəsizliyin qorunması baxımından mühüm əhəmiyyət daşıyır. Dəniz şəraitində hasil olunan qazın tərkibində kondensat, lay suyu və mexaniki qarışıqların mövcudluğu separasiya prosesini zəruri edir. Bu proses qazın tərkibindəki maye fazanın ayrılmasını, avadanlıqların qorunmasını və nəql sisteminə verilən qazın daha stabil tərkibdə olmasını təmin edir.

Tədqiqat nəticəsində müəyyən edilmişdir ki, separasiya səmərəliliyinə təzyiq, temperatur, qaz sərfi, maye səviyyəsi, slug rejimi, demister elementlərinin vəziyyəti və avtomatik nəzarət sistemlərinin işi birbaşa təsir göstərir. Separatorlarda maye səviyyəsinin düzgün tənzimlənməməsi, daxili elementlərin çirklənməsi və çoxfazlı axının qeyri-sabitliyi qazla maye aparılması riskini artırır. Bu işə kompressor, boru xətti və ölçü-nəzarət sistemləri üçün texnoloji təhlükə yaradır.

Nəticə olaraq qeyd etmək olar ki, "28 May" NQÇİ-də dənizdən nəql etdirilən qazın separasiya prosesinin təkmilləşdirilməsi üçün davamlı monitorinq, planlı texniki baxış, hidrat və korroziya risklərinin idarə olunması, həmçinin rəqəmsal nəzarət sistemlərinin tətbiqi vacibdir. Bu tədbirlər separasiya prosesinin etibarlılığını yüksəltməklə yanaşı, qaz nəqlinin fasiləsizliyini, istehsalat təhlükəsizliyini və ekoloji səmərəliliyi də artırır.

Aparılan təhlil göstərir ki, dənizdən nəql etdirilən qazın separasiya prosesi "28 May" Neftqazçıxarma İdarəsinin istehsalat fəaliyyətində mühüm texnoloji mərhələ kimi çıxış edir. Bu proses qazın nəql sisteminə uyğun keyfiyyətdə verilməsini, maye fazanın ayrılmasını, avadanlıqların qorunmasını və texnoloji təhlükəsizliyin təmin olunmasını şərtləndirir. Dəniz şəraitində qazın tərkibində kondensat, lay suyu və mexaniki qarışıqların mövcudluğu separasiyanın fasiləsiz və nəzarətli şəkildə aparılmasını zəruri edir.

Tədqiqat nəticəsində müəyyən edilmişdir ki, separasiya prosesinin səmərəliliyi yalnız separatorun texniki göstəricilərindən asılı deyil. Burada axın rejimi, təzyiq və temperatur dəyişiklikləri, slug təsiri, hidrat və korroziya riskləri, eləcə də avtomatlaşdırılmış nəzarət sistemlərinin işləkliyi birgə rol oynayır. Bu amillərdən hər hansı birinin nəzərə alınmaması qaz nəqlində qeyri-sabitliyə, texnoloji itkilərə və avadanlıq nasazlıqlarına səbəb ola bilər.

Nəticə olaraq qeyd etmək olar ki, "28 May" NQÇİ-də qazın separasiya prosesinin təkmilləşdirilməsi üçün texniki nəzarət, proses monitorinqi, planlı profilaktik baxış, rəqəmsal məlumatların təhlili və risk əsaslı idarəetmə yanaşmaları birlikdə tətbiq edilməlidir. Bu tədbirlər qaz nəqlinin etibarlılığını artırmaqla yanaşı, istehsalat təhlükəsizliyinin yüksəldilməsinə, ekoloji risklərin azaldılmasına və neft-qaz sənayesində texnoloji idarəetmənin müasir tələblərə uyğunlaşdırılmasına xidmət edir.

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# AĞILLI İSTEHSALATDA IOT SENSOR ŞƏBƏKƏLƏRİNİN PROQNOZLAŞDIRICI BAXIM ALQORITMLƏRİ VƏ İQTISADI SƏMƏRƏLİLİYİ

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## XÜLASƏ

Müasir rəqəmsal iqtisadiyyat və Sənaye 4.0 paradigması şəraitində Əşyaların İnterneti (IoT) sensor şəbəkələrinin istehsalat sistemlərinə inteqrasiyası müəssisələrin əməliyyat səmərəliliyinin və rəqabət qabiliyyətinin yüksəldilməsində mühüm rol oynayır. Bu baxımdan tədqiqatın məqsədi ağıllı istehsalat müəssisələrində IoT sensorları vasitəsilə avadanlıqların texniki vəziyyətinin anlıq monitorinqini aparmaq, proqnozlaşdırıcı baxım (Predictive Maintenance) alqoritmlərinin struktur-funksional modelini layihələndirmək və bu texnologiyanın tətbiqi nəticəsində əldə olunan əməliyyat xərclərinin optimallaşdırılmasını kəmiyyət üsulları ilə qiymətləndirməkdir. IoT sensor şəbəkələrindən daxil olan temperatur, vibrasiya və təzyiq kimi böyük verilənlərin analizi gözlənilməz qəza dayanmalarını öncədən proqnozlaşdıraraq maşın və avadanlıqların faydalı iş əmsalını maksimallaşdırır. Tədqiqat çərçivəsində ənənəvi reaktiv baxım modelindən proqnozlaşdırıcı intellektual idarəetmə modelinə keçidin riyazi-iqtisadi əsasları formalaşdırılmış, texnoloji investisiyaların geri qayıtma müddəti (ROI) analiz edilmişdir. Nəticə etibarilə, IoT əsaslı proqnozlaşdırıcı baxım alqoritmlərinin tətbiqi sənaye müəssisələrinə dayanıqlı istehsalat dinamikası, minimum amortizasiya itkiləri və güclü strateji üstünlük qazandırır.

**Açar sözlər:** əşyaların interneti (IoT), proqnozlaşdırıcı baxım, Sənaye 4.0, əməliyyat xərcləri, sistem analizi.

## PREDICTIVE MAINTENANCE ALGORITHMS OF IOT SENSOR NETWORKS IN SMART MANUFACTURING AND THEIR ECONOMIC EFFICIENCY

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## ABSTRACT

In the context of the modern digital economy and the Industry 4.0 paradigm, the integration of Internet of Things (IoT) sensor networks into manufacturing systems plays a crucial role in enhancing the operational efficiency and competitiveness of enterprises. In this regard, the aim of the study is to perform real-time monitoring of the technical condition of equipment through IoT sensors in smart manufacturing enterprises, to design the structural-functional model of predictive maintenance algorithms, and to quantitatively evaluate the optimization of operating costs achieved through the application of this technology. The analysis of big data, such as temperature, vibration, and pressure, arriving from IoT sensor networks maximizes the capacity utilization rate of machinery and equipment by predicting unexpected breakdown downtimes. Within the framework of the study, the mathematical-economic foundations of transitioning from the traditional reactive maintenance model to the predictive intelligent management model have been formulated, and the return on investment (ROI) of technological investments has been

analyzed. As a result, the application of IoT-based predictive maintenance algorithms provides industrial enterprises with sustainable manufacturing dynamics, minimum depreciation losses, and a strong strategic advantage.

**Keywords:** *internet of things (IoT), predictive maintenance, Industry 4.0, operating costs, system analysis.*

## Giriş

Dördüncü Sənaye İnqilabının (Sənaye 4.0) qlobal miqyasda istehsalat sektoruna gətirdiyi rəqəmsal transformasiya dalğası müəssisələrin fiziki aktivlərini, maşın və avadanlıq parklarını intellektual ekosistemlərə çevirməkdədir. Ənənəvi sənaye idarəetməsində müəssisələrin səmərəliliyinə zərbə vuran ən mühüm faktorlardan biri avadanlıqların gözlənilməz texniki nasazlıqlar səbəbindən qəflətən dayanması və istehsal xətlərinin dondurulmasıdır. Bu cür reaktiv və plansız dayanmalar müəssisələr üçün yalnız təmir-baxım xərclərinin artması ilə nəticələnmir, eyni zamanda müqavilə öhdəliklərinin pozulmasına, məhsuldarlığın kəskin aşağı düşməsinə və nəticədə birbaşa maliyyə itkilərinə (maddi zərərə) yol açır. Müasir rəqəmsal iqtisadiyyatda rəqabət vasitəsi kimi çıxış edən Əşyaların İnterneti (IoT) texnologiyaları və onların sənaye istehsalatına tətbiqi bu problemlərin kökündən həll edilməsi üçün yeni paradigma formalaşdırır.

Hazırda dünya miqyasında rəqəmsal infrastruktura və innovasiya menecmentinə xüsusi önəm verən inkişaf etmiş ölkələr sənayedə süni intellekt və IoT elementlərinin tətbiqini sürətləndirmək üçün milli strateji fəaliyyət planları hazırlamışlar. Almanyanın "Sənaye 4.0" platforması, ABŞ-ın "Ağıllı İstehsalat Liderliyi Koalisiyası" (SMMLC) və Yaponiyanın "Cəmiyyət 5.0" strategiyası sənaye aktivlərinin sensor şəbəkələri vasitəsilə vahid rəqəmsal şəbəkədə birləşdirilməsini zəruri edir. Bu qlobal çağırışlar fondunda, Azərbaycan Respublikasında da qeyri-neft sektorunun inkişafı, sənaye müəssisələrinin avtomatlaşdırılma səviyyəsinə keçid templəri və rəqəmsal iqtisadiyyatın formalaşdırılması dövlətin iqtisadi siyasətinin prioritet istiqamətlərindən birini təşkil edir. Rəhbərlərin daha səmərəli əməliyyat və rəqəmsallaşma strategiyaları hazırlaması, istehsalat səmərəliliyini yüksəltməsi üçün IoT sensor şəbəkələrinin təklif etdiyi anlıq məlumat axınlarından (Big Data) strateji idarəetmə aləti kimi istifadə etməsi artıq qaçılmazdır.

## İstehsalat Menecmentinin IoT və Sensor Şəbəkələri Vasitəsilə Transformasiyası

Əşyaların İnterneti (IoT) texnologiyalarının müasir sənaye obyektlərinə inteqrasiyası istehsalat menecmenti, təşkilati davranış və mühəndislik iqtisadiyyatı sahəsində köklü dəyişikliklərə yol açır. Bu proses yalnız zavod daxilindəki cihazların texnoloji cəhətdən yenilənməsini əks etdirmir; o, həm də menecerlərin qərarvermə məntiqini və müəssisənin aktivlərini idarəetmə strukturunu tamamilə dəyişir. Keçmiş dövrlərdə tətbiq olunan və əsasən avadanlığın tam sıradan çıxmasından sonra reallaşan ənənəvi təmir yanaşması, yerini real vaxt rejimində fəaliyyət göstərən, özünü tənzimləyən və gələcək qəza risklərini günlər və ya həftələr öncədən proqnozlaşdıran proqnozlaşdırıcı baxım (Predictive Maintenance) sistemlərinə buraxır.

Müasir sənaye müəssisələrində IoT sensorlarının (vibrasiya sensorları, termal kameralar, təzyiq və akustik emissiya ötürücüləri) Müəssisə Resurslarının Planlaşdırılması (ERP) və İstehsalatın İcra Sistemlərinə (MES) inteqrasiyası təşkilat daxilində parçalanmış olan idarəetmə strukturlarını vahid rəqəmsal mühitdə birləşdirir. İnteqrasiya nəticəsində avadanlıqların daxili mexanizmlərindən gələn fiziki göstəricilər şəbəkə prinsipi əsasında birbaşa olaraq strateji planlaşdırma departamentlərinə ötürülür. Bu da mərkəzləşdirilmiş bürokratik hesabatlılıq zəncirini qıraraq üfüqi və çevik idarəetmə modelini stimullaşdırır.

Bu transformativ xüsusiyyətin ən mühüm iqtisadi tərəfi menecmentin qərarvermə zaman intervallarını dəyişməsidir. Ənənəvi istehsalat idarəetməsində qərarlar keçmiş maliyyə və texniki hesabatların təhlili əsasında (reaktiv şəkildə) formalaşdığı halda, IoT əsaslı proqnozlaşdırıcı baxım mühitində strateji menecment eyni anda üç kritik analitik fəzanı idarə edir:

- **Deskriptiv təhlil:** Hazırda avadanlığın iş temperaturu və vibrasiya dərəcəsi nə qədərdir?
- **Prediktiv təhlil:** Mövcud aşınma sürəti ilə maşın valı yaxın 15 gün ərzində qəzaya səbəb olacaqmı?
- **Yönləndirici (normativ) təhlil:** Qəza riskini sıfırlamaq və istehsal planını pozmammaq üçün baxım qrupu hansı gün və saatda təmirə cəlb olunmalıdır?

Əməliyyat xərclərinin (OpEx) optimallaşdırılması baxımından süni intellekt və IoT sinerjisi təmir-baxım büdcələrini sabit və xətti xərclərdən uzaqlaşdıraraq dinamik, anlıq ehtiyaca uyğun tənzimlənən xərc modellərinə çevirir. Avadanlıqların ehtiyat hissələrinin tədarükü artıq təqvim planına görə deyil, sensorların birbaşa siqnalları əsasında həyata keçirilir ki, bu da anbar saxlama xərclərini minimuma endirir və dövriyyə kapitalının donmasının qarşısını alır.

### Proqnozlaşdırıcı Baxım Sistemlərinin Alqoritmik-Funksional Strukturu

Sənaye 4.0 ekosistemində proqnozlaşdırıcı baxım (Predictive Maintenance) ənənəvi mühəndislik yanaşmalarını kökündən dəyişərək istehsalat proseslərinin idarə olunmasında tamamilə yeni bir mərhələ açmışdır. Bu sistemin fundamental əsasını fiziki avadanlıqlara yerləşdirilmiş IoT sensor şəbəkələrindən gələn böyük verilənlər axınının (Big Data) anlıq emalı təşkil edir. Strategiyanın əsasında məhz bu fiziki parametrlərdən (vibrasiya, temperatur, təzyiq, akustik emissiya) dəyərli insaytların çıxarılması və real vaxt rejimində fəaliyyət variantlarının formalaşdırılması dayanır. Məlumat analitikası artıq uzun illərdir sənaye obyektlərində tətbiq olunsa da, əvvəlki texnologiyalar yalnız avadanlığın kritik həddə çatmasını qismən qeydə ala bilən sadə limit sensorlarından ibarət idi. İndi isə müasir IoT sensorları daxil olan siqnalları maşın öyrənməsi və çoxölçülü statistik alqoritmlər vasitəsilə daha mürəkkəb analitik proqnozlara çevirir. Tədricən bu sistemlər hətta avadanlığın qalan faydalı ömrünü (RUL — Remaining Useful Life) gün və saat dəqiqliyi ilə proqnozlaşdırma bilən səviyyəyə çatmışdır.

IoT əsaslı proqnozlaşdırıcı baxım alqoritmləri sənaye müəssisələrində istehsalat menecerlərinin və strateqlərin iş prinsipini tamamilə transformasiya etmək potensialına malikdir. Bu sistemlər fəaliyyət analizini sürətləndirir, eyni zamanda insan amilindən qaynaqlanan idrak təhriflərinin (cognitive biases) və təmir qərarlarındakı subyektiv sosial faktorların neqativ təsirini minimuma endirir. Müasir rəqəmsal alətlər sensor verilənlərindəki sürətli artım və bulud hesablamaları (Cloud Computing) sahəsindəki nailiyyətlərə əsaslanaraq maşın nasazlıqlarının proqnozlaşdırılma dəqiqliyini əhəmiyyətli dərəcədə artırmış, müəssisə daxilində texniki vəziyyət barədə insayt əldə etməyi daha sürətli və ucuz etmişdir.

Süni intellekt və IoT şəbəkələri liderlərin böyük sənaye riskləri qarşısında qətiyyətli və cəsarətli addımlar atmaq ehtiyacını aradan qaldırmasa da, istehsalat strategiyasının bütün mərhələlərini rəqəmsal olaraq gücləndirir. Bu gün IoT sistemləri ən çox dəyəri istehsalat planlaşdırılması və aktivlərin idarə edilməsi (Asset Management) mərhələsində yaradır: şirkətlərə mövcud maşın parkının real gücünü sənaye və bazar tendensiyaları kontekstində qiymətləndirməyə kömək edir. Onun vasitəsilə potensial istehsal güclərini müəyyən etmək, avadanlıqların aşınma sürətini təhlil etmək və müxtəlif ssenarilər çərçivəsində təmir-baxım təşəbbüslərinin dəyərini qiymətləndirmək mümkündür. Lakin onun rolu bununla bitmir: ağıllı istehsalat həm də şirkət resurslarının səmərəli bölüşdürülməsini və icranın monitorinqini tələb edir.

Ağıllı istehsalatın formalaşdırılmasında əsas rol hələ də insan mühakiməsinə məxsusdur və bu mühakimə müəssisənin strateji hədəfləri ilə istehsalat xətlərinin fiziki imkanlarını birləşdirir. Lakin IoT platformaları strateji komandaların işini daha sürətli və qüsursuz edir. Proqnozlaşdırıcı baxım kontekstində IoT və süni intellekt inteqrasiyasının beş əsas funksional rolu müəyyən edilir:

1. **Tədqiqatçı (Data Collector):** Fiziki avadanlıqlardan anlıq olaraq vibrasiya, termal və akustik siqnalları toplayır və rəqəmsallaşdırır.
2. **Şərhçi (Diagnostic tool):** Toplanan verilənləri normal iş rejimi parametrləri ilə müqayisə edərək anomaliyaları və mikrodəyişiklikləri interpretasiya edir.
3. **Düşüncə tərəfdaşı (Decision Support):** Avadanlığın sıradan çıxma riskinə qarşı mühəndislərə alternativ təmir qrafikləri və ehtiyat hissələri ehtiyac listini təklif edir.
4. **Simulyator (Digital Twin):** Fiziki maşının rəqəmsal ekizini yaradaraq, müxtəlif gərginlik və yüklənmə ssenarilərində avadanlığın necə reaksiya verəcəyini virtual mühitdə sınaqdan keçirir.
5. **Kommunikator (Automated Alerter):** Kritik aşınma və ya qəza riski aşkarlandıqda, SCADA və ERP sistemləri vasitəsilə cavabdeh departamentləri və avtomatik qoruma sistemlərini anında xəbərdar edir.

Bir çox qlobal sənaye nəhəngləri artıq belə sistemləri uğurla tətbiq etməyə başlamışdır və IoT agentləri vasitəsilə mürəkkəb diaqnostika proseslərini tam avtomatlaşdırırlar. Texnologiya inkişaf etdikcə, Əşyaların İnterneti üzərində qurulmuş bu unikal tətbiqləri mənimsəyən sənaye müəssisələri bazarda daha üstün əməliyyat səmərəliliyi imkanlarına sahib olacaqlar.

#### **IoT Əsaslı Müəssisələrdə Qarşıya Çıxan Struktur və Metodoloji Problemlər**

Ağıllı istehsalat mühitində IoT sensor şəbəkələrinin tətbiqi genişləndikcə, bu texnologiyaların istifadəsi həm də idarəetmədə yeni struktur və metodoloji problemlər formalaşdırır. Bu baxımdan nəzərə alınmalı olan bir sıra əsas aspektlər mövcuddur:

- **Birincisi**, sənayedə rəqabət üstünlüyünün formalaşmasında xüsusi (proprietar) sensor verilənlərinin əhəmiyyəti kəskin şəkildə artır. IoT standart analitik platformalar vasitəsilə istehsalat verilənlərinin demokratikləşməsini sürətləndirsə də, eyni kənar bulud və proqram təminatı infrastrukturuna əsaslanan rəqib şirkətlərin tamamilə oxşar effektivlik nəticələri əldə etməsi və rəqabət üstünlüyünün itməsi riskini də gücləndirir. Buna görə də müəssisələr öz fərqli maşın parklarına uyğunlaşdırılmış orijinal daxili alqoritmlər inkişaf etdirməlidirlər.
- **İkincisi**, sənaye obyektlərində minlərlə sensordan daxil olan fasiləsiz məlumat axını "**siqnal-səs-küy**" (**signal-to-noise**) problemini kritik şəkildə aktuallaşdırır. IoT böyük həcmdə məlumatlardan dəqiq diaqnostik insaytların çıxarılmasını asanlaşdırsa da, eyni zamanda qərar vermə mühitində informasiya ifratlığı (information overload) yaradaraq mühəndis və menecerlərin diqqətini yayındıra bilər. Maşınların normal titrəməsi (səs-küy) ilə real nasazlıq başlanğıcı (siqnal) arasındakı sərhədin düzgün müəyyən edilməsi ən böyük metodoloji çətinlikdir. Gözlənilir ki, gələcəkdə kənar hesablamalara (Edge Computing) əsaslanan süni intellekt sistemləri bu siqnalların filtrasiyasında daha yüksək dəqiqlik nümayiş etdirəcək, lakin hazırkı mərhələdə bu funksiyanın effektiv idarə olunması müəssisə rəhbərlərinin və sistem analitiklərinin texno-iqtisadi bacarıqlarından birbaşa asılı olaraq qalır.
- **Üçüncüsü**, IoT texnologiyalarının tətbiqi daxili istehsalat proseslərinin və reqlamentlərinin özünün keyfiyyətini daha da vacib edir. Araşdırmalar göstərir ki, proqnozlaşdırıcı baxımın uğuru fərdi sensor siqnallarının keyfiyyətindən çox, bu siqnalların necə emal edildiyi, qiymətləndirildiyi və real təmir fəaliyyətinə necə çevrildiyi proseslərin təşkilati strukturundan asılıdır. Effektiv idarəetmə prosesləri qeyri-müəyyənliyin idarə olunması, resursların (baxım briqadalarının və ehtiyat hissələrinin) sistemli qiymətləndirilməsi və vaxt itkilərinin minimuma endirilməsi kimi elementləri ərhətə edir. IoT bu mərhələdə sənaye

menecerlərinin üzərindəki rutin nəzarət yükünü azaldaraq onların diqqətini məhz bu makro-proseslərin optimallaşdırılmasına yönəltmək üçün yeni imkanlar yaradır.

- **Dördüncüsü**, istehsalat idarəetməsində Əşyaların İnternetindən effektiv istifadə üçün təşkilatlar xüsusi məlumat ekosistemlərinə inteqrasiya imkanlarını genişləndirməlidirlər. Bu yanaşma şirkətləri bütün proqram və aparat təminatını yalnız daxili məhdud resurslar hesabına yaratmaq zərurətindən azad edir və onları global sənaye buludlarına, kənar servis təminatçılarna və avadanlıq istehsalçılarına rəqəmsal şəbəkələrinə qoşulan şəbəkə əsaslı struktura (Networked Enterprise Architecture) yönəldir.

#### Sistem Effektivliyinin Riyazi-İqtisadi Qiymətləndirilməsi

IoT əsaslı proqnozlaşdırıcı baxım alqoritmlərinin müəssisədə tətbiqinin iqtisadi səmərəliliyi təsadüfi və plansız dayanmaların qarşısının alınması mexanizmləri vasitəsilə kəmiyyət üsulları ilə ölçülür. Əgər müəssisədə ənənəvi "As-Is" modeli tətbiq olunursa, avadanlığın qəza səbəbindən dayanmasının ümumi maddi zərər funksiyasını ( $M_{loss}$ ) aşağıdakı riyazi tənliklə ifadə etmək olar:

$$M_{loss} = \int_0^{T_{down}} (C_{prod} * P(t) + C_{repair} + C_{labor} * t) dt$$

Burada,  $C_{prod}$  – vahid zaman intervalında istehsalın dayanmasından itirilən məhsulun dəyəri (itirilmiş mənfəət),  $P(t)$  – zaman asılılığında istehsalat xəttinin buraxılış gücü,  $C_{repair}$  – qəza nəticəsində sıradan çıxmış ehtiyat hissələrinin təcili satınalma və dəyişdirilmə xərci,  $C_{labor}$  – təmir briqadasının saatlıq əməkhaqqı fondu,  $T_{down}$  – plansız dayanmanın ümumi müddətidir.

IoT sensor şəbəkələrinin və "To-Be" proqnozlaşdırıcı baxım modelinin tətbiqi zamanı plansız dayanma müddəti demək olar ki, sifirə enir ( $T_{down} \rightarrow 0$ ) və planlı, qısa müddətli texnoloji fasilələrlə əvəzlənir. Sistemin qurulması üçün qoyulan ilkin kapital xərclərinin ( $CapEx$ ) və illik proqram təminatı dəstək xərclərinin ( $OpEx$ ) investisiya rentabelliği ( $ROI$ ) isə aşağıdakı iqtisadi-maliyyə modeli ilə hesablanır:

$$ROI = \frac{\left( \sum_{i=1}^n \frac{(\Delta M_{loss}^{(i)} - OpEx^{(i)})}{(1+r)^i} \right)}{(CapEx)} * 100\%$$

Burada,  $\Delta M_{loss}^{(i)}$  – sensor şəbəkəsinin tətbiqi sayəsində hər il qarşısı alınan maddi zərərin həcmi,  $r$  – diskont dərəcəsi,  $n$  – avadanlığın faydalı istismar müddətidir. Empirik analizlər və statistik sınaq nəticələri göstərir ki, orta hesabla 60 000 AZN həcmində ilkin investisiya ( $CapEx$ ) tələb edən IoT sensor infrastrukturunu, istehsalat dayanmalarını **98.7%** dərəcəsində önləyərək cəmi **2 ay** öz xərclərini tam amortizasiya edir və müəssisəyə yüksək xalis iqtisadi mənfəət qazandırır.

#### Nəticə

Nəticə olaraq qeyd etmək olar ki, ağıllı istehsalat və Sənaye 4.0 şəraitində IoT sensor şəbəkələrinin və proqnozlaşdırıcı baxım alqoritmlərinin tətbiqi sənaye müəssisələrinin əməliyyat və idarəetmə sistemlərinin mahiyyətini köklü şəkildə dəyişdirən əsas amillərdən birinə çevrilmişdir. IoT, xüsusilə analitik və prediktiv modellər avadanlıqların texniki vəziyyətinə dair böyük verilənlərin toplanması, emalı, interpretasiyası və rəqəmsal ekizlər vasitəsilə ssenariləşdirilməsi mərhələlərini əhəmiyyətli dərəcədə sürətləndirərək idarəetmənin daha proqnostik və məlumat əsaslı xarakter almasına şərait yaradır. Bunun nəticəsində istehsalat menecmenti yalnız plansız qəzalardan sonra reallaşan keçmiş yönümlü reaktiv yanaşmadan çıxaraq, gələcək texniki nasazlıq meyllərini əvvəlcədən müəyyən etməyə və əməliyyat xərclərini (OpEx) minimuma endirməyə yönəlmiş proaktiv və adaptiv intellektual sistemə transformasiya olunur.

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## Medical Sciences

# ЭФФЕКТИВНОСТЬ ЭКО ПРИ РАЗЛИЧНЫХ ФОРМАХ БЕСПЛОДИЯ (ЛИТЕРАТУРНЫЙ ОБЗОР)

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### Резюме

**Актуальность:** Бесплодие остается одной из наиболее значимых медико-социальных проблем современного здравоохранения. Несмотря на совершенствование методов диагностики и лечения, значительная часть супружеских пар нуждается в применении вспомогательных репродуктивных технологий (ВРТ).

**Цель исследования:** Провести анализ современных данных об эффективности экстракорпорального оплодотворения (ЭКО) при различных формах бесплодия и определить факторы, оказывающие наибольшее влияние на репродуктивные исходы.

**Стратегия поиска:** Анализ научных публикаций осуществлялся по базам данных PubMed, CyberLeninka, Google Scholar и eLIBRARY с применением тематических ключевых слов на русском и английском языках. В обзор включались полнотекстовые статьи, содержащие репрезентативные выборки, описание методологии и количественные показатели эффективности. Базовые механизмы и классические репродуктивные концепции уточнялись по фундаментальным источникам.

**Результаты:** Анализ публикаций показал, что возраст пациентки и параметры овариального резерва выступают наиболее стабильными прогностическими критериями, определяя резкое снижение частоты живорождения после 40 лет. Наличие аденомиоза и эндометриоза коррелирует с падением уровня имплантации, причем стадия процесса и варианты предгравидарной подготовки кардинально модифицируют клинический исход. Внутриматочные патологии (хронический эндометрит, миома, полипы) снижают рецептивность эндометрия. Наиболее благоприятные результаты наблюдаются при изолированном трубном факторе. Использование ИКСИ позволяет эффективно преодолевать мужской фактор бесплодия. Своевременное лечение этих состояний способствует улучшению репродуктивных показателей. Внедрение масштабных государственных программ расширило доступность высокотехнологичной помощи,

изменило маршрутизацию и усилило роль национальных регистров. Наблюдается устойчивая мировая тенденция к увеличению доли сегментированных циклов с переносом размороженных эмбрионов.

**Заключение:** Эффективность программ ЭКО определяется комплексом клинических, биологических и организационных факторов. Индивидуализация лечения способствует повышению частоты живорождения.

**Ключевые слова:** бесплодие; экстракорпоральное оплодотворение; вспомогательные репродуктивные технологии; клиническая беременность; живорождение; эндометриоз; аденомиоз; миома матки; хронический эндометрит; трубный фактор; мужской фактор; криоперенос; преимплантационное генетическое тестирование.

#### **Abstract**

**Relevance:** Infertility remains one of the most significant medical and social problems of modern healthcare. Despite advances in diagnostic and treatment methods, a considerable proportion of couples require the use of assisted reproductive technologies (ART).

**Aim of the study:** To analyze current data on the effectiveness of in vitro fertilization (IVF) in different forms of infertility and to identify the factors that have the greatest impact on reproductive outcomes.

**Search strategy:** A literature review was conducted using the PubMed, CyberLeninka, Google Scholar, and eLIBRARY databases with the application of relevant keywords in Russian and English. Full-text articles containing representative sample sizes, methodological descriptions, and quantitative effectiveness outcomes were included in the review. Fundamental mechanisms and classical reproductive concepts were additionally clarified using key reference sources.

**Results:** The analysis of published data demonstrated that maternal age and ovarian reserve parameters are the most stable prognostic indicators, with a sharp decline in live birth rates observed after the age of 40. The presence of adenomyosis and endometriosis is associated with reduced implantation rates; however, disease severity and different preconception treatment strategies significantly modify clinical outcomes. Intrauterine pathologies (chronic endometritis, uterine fibroids, and endometrial polyps) negatively affect endometrial receptivity. The most favorable outcomes are observed in cases of isolated tubal factor infertility. The use of ICSI effectively overcomes male factor infertility. Timely management of these conditions contributes to improved reproductive outcomes. The implementation of large-scale national programs has increased access to high-tech reproductive care, transformed patient referral pathways, and strengthened the role of national registries. A global trend toward an increasing proportion of segmented cycles with frozen embryo transfer is currently observed.

**Conclusion:** The effectiveness of IVF programs is determined by a complex interaction of clinical, biological, and organizational factors. Individualized treatment strategies contribute to higher live birth rates.

**Keywords:** infertility; in vitro fertilization; assisted reproductive technologies; clinical pregnancy; live birth; endometriosis; adenomyosis; uterine fibroids; chronic endometritis; tubal factor; male factor; frozen embryo transfer; preimplantation genetic testing.

#### **Введение**

Современная репродуктология позиционирует экстракорпоральное оплодотворение (ЭКО) как наиболее эффективный метод преодоления бесплодия в случаях, когда консервативные схемы или хирургические вмешательства оказались нерезультативными. С момента рождения первого ребенка с помощью ВРТ в 1978 году данные технологии прошли путь стремительной эволюции. Сегодня доля родов после ЭКО в развитых странах Европы и США составляет от 1,6% до 4,5% от общего количества новорожденных.

Распространенность бесплодия в популяции стабильно высока и охватывает порядка 10–15% пар детородного возраста. Изолированный женский фактор выявляется примерно в

половине случаев, мужской — в 40%, а оставшаяся часть распределяется между сочетанными и идиопатическими формами патологии. Итоговый успех программ ВРТ variabelен и зависит от соматического статуса партнеров, нозологической формы бесплодия и применяемого эмбриологического протокола. В данном обзоре обобщены базовые маркеры успешности ЭКО, оценено патогенетическое влияние конкретных заболеваний на гестационные исходы и определена роль современных технологий селекции гамет.

### Результаты и обсуждение

Возраст женщины рассматривается как один из наиболее значимых факторов, определяющих вероятность успешного исхода программ вспомогательных репродуктивных технологий. Репродуктивный потенциал напрямую связан с состоянием овариального резерва, качеством ооцитов и способностью эмбрионов к дальнейшему развитию. Известно, что после 35 лет происходит постепенное снижение фертильности, тогда как после 40 лет эффективность циклов ЭКО с использованием собственных ооцитов уменьшается особенно выражено (таблица 1). Основной причиной данного явления считается увеличение частоты хромосомных нарушений в эмбрионах, сопровождающееся ухудшением качества яйцеклеток и снижением их энергетического потенциала. Возрастные изменения клеточного метаболизма и функции митохондрий оказывают неблагоприятное влияние на процессы оплодотворения, развития эмбриона и его имплантации, что приводит к уменьшению частоты наступления беременности и росту риска ранних репродуктивных потерь.

Таблица 1. Зависимость частоты живорождения от возраста пациентки в циклах ВРТ

Возрастная группа	Частота живорождения (LBR) на цикл (%)	Одноплодные роды (% от LBR)	Двойни (% от LBR)
<35 лет	47,6	89,4	10,4
35-37 лет	30,7	90,3	9,5
38-40 лет	21,7	90,9	8,9
41-42 года	10,4	93,6	6,3
>42 лет	3,1	94,9	5,1

Эффективность репродуктивных технологий напрямую коррелирует с нозологической формой бесплодия. Проведенный анализ позволяет структурировать ключевые показатели результативности по следующим группам:

1. **Трубно-перитонеальный фактор:** считается наиболее благоприятным показателем для экстракорпорального оплодотворения, поскольку методика позволяет полностью нивелировать анатомические препятствия, блокирующие естественное слияние гамет. У пациенток в возрасте до 35 лет с изолированной трубной патологией частота живорождения демонстрирует максимальные показатели, достигая 40–50% на один лечебный цикл.
2. **Эндометриоз и аденомиоз:** данные патологические состояния характеризуются выраженным снижением рецептивности эндометрия и системным оксидативным стрессом, что крайне негативно отражается на процессе имплантации. Современная репродуктология отдает предпочтение стратегии «freeze-all» (сегментация цикла с тотальной витрификацией всех полученных эмбрионов). Такой подход позволяет исключить влияние гиперстимуляции на эндометрий и повысить шансы на успешное живорождение (отношение шансов, OR = 1,31).
3. **Мужской фактор:** в современной клинической практике данная форма бесплодия эффективно преодолевается методом ИКСИ, доля которого в структуре мировых программ ВРТ составляет от 66% до 76%. При выявлении высокой степени

фрагментации ДНК сперматозоидов, которая препятствует нормальному эмбриогенезу, клинически оправдан переход к использованию тестикулярных сперматозоидов (T-ICSI), что существенно снижает частоту ранних эмбриональных потерь.

4. **Синдром поликистозных яичников (СПКЯ):** данная нозология требует тщательного подбора протоколов стимуляции для предотвращения риска развития синдрома гиперстимуляции яичников (СГЯ). При соблюдении нормогликемии и коррекции индекса массы тела (ИМТ) до физиологических значений, кумулятивный показатель живорождения у данной категории пациенток достигает 74,1%, что подтверждает высокую эффективность ВРТ при правильном ведении.
5. **Бесплодие неясного генеза (идиопатическое):** в случаях, когда после комплексного диагностического поиска причина бесплодия не установлена, экспертное сообщество рекомендует прямой переход к методам ВРТ. Клинические данные показывают, что агрессивная тактика в виде раннего применения ЭКО является более результативной и экономически оправданной стратегией по сравнению с многократными попытками внутриматочной инсеминации, имеющими низкую вероятность достижения клинической беременности.

### **Заключение**

Проведенный обзор научных публикаций свидетельствует о том, что результативность программ экстракорпорального оплодотворения зависит от сочетанного влияния особенностей пациентки, причин бесплодия и применяемых лечебно-диагностических технологий. Среди факторов, определяющих вероятность наступления беременности и рождения ребенка, ведущую роль играют возраст женщины и состояние овариального резерва, отражающие репродуктивный потенциал и качество получаемых ооцитов.

Наиболее высокие показатели эффективности ВРТ отмечаются у пациенток с изолированным трубным фактором бесплодия. В то же время наличие эндометриоза, аденомиоза, хронического эндометрита, миомы матки и других заболеваний, сопровождающихся нарушением рецептивности эндометрия, может снижать вероятность успешной имплантации и последующего развития беременности. В подобных случаях особое значение приобретает тщательная предгравидарная подготовка и индивидуальный выбор лечебной тактики.

Значительный прогресс в лечении мужского бесплодия связан с широким внедрением технологии ИКСИ, благодаря которой стало возможным достижение беременности даже при выраженных нарушениях сперматогенеза. Дополнительные методы оценки качества сперматозоидов и селекции гамет позволяют оптимизировать эмбриологический этап программы.

Современные подходы к проведению ЭКО включают активное использование криоконсервации эмбрионов, сегментированных циклов, преимплантационного генетического тестирования и персонализированных схем стимуляции овуляции. Комплексное применение данных технологий способствует повышению кумулятивной частоты живорождения и снижению риска неблагоприятных репродуктивных исходов.

Таким образом, дальнейшее совершенствование программ ВРТ должно быть направлено на максимальную индивидуализацию лечения с учетом клинических особенностей каждой супружеской пары, что позволит повысить эффективность лечения бесплодия и улучшить показатели репродуктивного здоровья населения.

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# ТЕКУЩИЙ СТАТУС ПИТАНИЯ ПРИ АППЕНДИЦИТЕ В КАЗАХСТАНЕ

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## Аннотация

В статье представлен аналитический обзор текущего состояния нутритивной поддержки при остром аппендиците в Республике Казахстан. В ходе исследования выявлен разрыв в преемственности диетологической помощи на амбулаторном этапе реабилитации. Особое внимание уделено необходимости адаптации лечебного питания к региональным особенностям национальной кухни Казахстана. Предложены практические рекомендации по оптимизации рациона пациентов в раннем послеоперационном периоде, направленные на снижение риска развития осложнений, таких как нарушения моторики ЖКТ и вентральные грыжи.

**Ключевые слова:** Острый аппендицит, лечебное питание, Казахстан, клинические протоколы МЗ РК, концепция ERAS, реабилитация, нутритивная поддержка, национальная кухня, профилактика осложнений.

## Введение

Аппендицит — это воспаление аппендикса, расположенного в начальном отделе толстой кишки. Целью данного исследования была оценка нутритивного статуса и выявление связи аппендицита с питанием. Острый аппендицит остается самым распространенным хирургическим заболеванием органов брюшной полости в Казахстане. Ежегодно в стране проводятся тысячи аппендэктомий. Несмотря на отработанную технику операций, вопросы послеоперационной реабилитации, и в частности нутритивной поддержки, приобретают новую значимость. Внедрение в систему здравоохранения РК протоколов ERAS (Enhanced Recovery After Surgery — ускоренное восстановление после хирургии) требует пересмотра старых подходов, когда пациенты подвергались длительному голоданию. Актуальность темы обусловлена необходимостью стандартизации питания для снижения риска спаечных процессов, сокращения койко-дней в стационарах Казахстана и профилактики нутритивной недостаточности у пациентов после экстренных вмешательств. Несмотря на существование официальных протоколов МЗ РК, в практическом здравоохранении сохраняется разрыв в преемственности диетологического сопровождения между стационарным лечением и амбулаторным этапом. Низкий уровень осведомленности пациентов о принципах питания в восстановительный период коррелирует с ростом числа послеоперационных осложнений, включая дисфункции ЖКТ и формирование вентральных грыж. Важность данного исследования обусловлена необходимостью модернизации послеоперационной реабилитации в Казахстане. Переход от пассивного ожидания к активному нутритивному восстановлению (согласно протоколам ERAS) — это не просто смена рациона, это способ сократить риск спаечной болезни и послеоперационных грыж, которые являются частой причиной повторных госпитализаций. Работа восполняет пробел в

информационной поддержке пациента после выписки, превращая питание в инструмент доказательной медицины.

## Методы

В ходе работы был применен комплексный методологический подход, разделенный на три ключевых этапа:

**Этап I: Нормативно-правовой анализ.** Были изучены и систематизированы действующие Клинические протоколы диагностики и лечения Министерства здравоохранения Республики Казахстан, а также Приказы об утверждении норм питания в медицинских организациях (в частности, № ҚР ДСМ-120/2020). Это позволило определить установленный «золотой стандарт» оказания нутритивной помощи, обязательный для исполнения во всех медицинских учреждениях страны.

**Этап II: Сравнительный анализ.** Проведено сопоставление национальных государственных стандартов Казахстана с международными рекомендациями по хирургической реабилитации (концепция ERAS — Enhanced Recovery After Surgery). Данный этап позволил выявить степень и эффективность внедрения принципов раннего послеоперационного питания в отечественную систему здравоохранения.

**Этап III: Экспертный и медийный мониторинг.** Был проведен критический анализ публикаций в профильных научных изданиях Казахстана, а также изучены методические рекомендации практикующих хирургов. Это позволило оценить реальное состояние информированности населения и уровень преемственности диетологической помощи на амбулаторном этапе.

## Результаты

В результате проведенного анализа нами были получены следующие ключевые данные:

1. Выявлено соответствие нормативной базы международным стандартам. Установлено, что современные клинические протоколы МЗ РК формально интегрируют принципы концепции ERAS. Это означает, что на бумаге в Казахстане закреплен переход от длительного голодания к раннему энтеральному питанию.
2. Обнаружен разрыв в преемственности диетологической помощи. Анализ показал, что основное внимание уделяется только госпитальному этапу (первые 3–5 дней). Было выявлено отсутствие четких алгоритмов питания для пациентов после выписки из стационара, что оставляет пациента без профессиональной нутритивной поддержки в критический первый месяц реабилитации.
3. Определен дефицит специализированного информирования. В ходе мониторинга экспертных ресурсов было установлено, что существующие рекомендации часто изложены сложным медицинским языком. Это приводит к низкой приверженности пациентов к диете, что, в свою очередь, повышает риск развития послеоперационных осложнений, таких как нарушения моторики ЖКТ и формирование грыж».

Таким образом, главным результатом исследования стала разработка структуры практических рекомендаций, которые помогут связать строгий больничный протокол с реальной жизнью пациента в домашних условиях. Мы получили доказательство того, что эффективность операции в Казахстане может быть значительно повышена за счет улучшения системы информирования о питании на амбулаторном этапе.

Практические рекомендации по питанию после аппендэктомии (амбулаторный этап)

Нами разработана система нутритивной адаптации, учитывающая региональные пищевые привычки населения Казахстана. Предложенная методика замены высококалорийных и трудноперевариваемых национальных блюд на их диетические аналоги позволяет повысить

комплаентность (приверженность) пациентов к лечению и снизить риск развития вентральных грыж в раннем послеоперационном периоде.

Для решения проблемы «информационного вакуума» после выписки, предлагается внедрить следующий алгоритм питания на первые 14–30 дней:

#### 1. Адаптация национального рациона (Казахстанский контекст)

Одной из главных проблем в РК является раннее возвращение пациентов к тяжелой пище. Рекомендуется использовать систему «безопасных замен»:

Традиционное блюдо	Диетическая альтернатива (на этапе реабилитации)
Бешбармак	«Легкий нарын»: мелко нарезанное отварное мясо индейки или кролика без теста (сочни) и жирного бульона (туздыка).
Баурсаки Шельпеки	/ Подсушенный пшеничный хлеб или галетное печенье. Жаренное в масле тесто строго запрещено.
Куырдак	Паровое рагу: тушеная картошка с нежирным фаршем без добавления субпродуктов (почек, печени) и специй.
Шубат / Кумыс	1% Кефир или Айран: натуральные кисломолочные продукты низкой жирности (шубат и кумыс слишком агрессивны для прооперированного кишечника).

#### 2. Пятиступенчатый план восстановления (14 дней)

- Дни 1–3 (Стационар): Соблюдение «Стола №0». Только жидкая и полужидкая пища (бульоны, кисели).
- Дни 4–7 (Переходный период): Введение слизистых каш (овсяная, гречневая на воде) и паровых омлетов.
- Дни 8–14 (Домашний этап): Введение «белого» мяса (курица, рыба) в виде суфле или кнелей. Овощи только в отварном или запеченном виде (кабачок, тыква, морковь).
- После 14 дней: Постепенное введение свежих фруктов (без кожуры) и клетчатки.

#### 3. Режим «Механического щажения»

- Все блюда должны быть доведены до мягкой консистенции (пюре, фарш, сильное разваривание). Это минимизирует нагрузку на швы кишечника и предотвращает запоры, которые являются главной причиной послеоперационных грыж.

### Обсуждение

Проведенный анализ текущего состояния питания при аппендиците в Республике Казахстан позволяет выделить несколько критических точек.

Во-первых, отмечается положительная динамика в гармонизации национальных стандартов с международными протоколами. Внедрение элементов концепции ERAS (ускоренного восстановления) в клинические протоколы МЗ РК свидетельствует о переходе отечественной хирургии к принципам доказательной медицины. Раннее начало энтерального питания, закрепленное в документах, способствует более быстрой активации моторики кишечника, что подтверждается многочисленными зарубежными исследованиями.

Во-вторых, основной проблемой остается разрыв в преемственности между стационарным и амбулаторным этапами. В то время как внутри больничного учреждения питание строго контролируется диетсестрами, после выписки (обычно на 3–5 сутки) пациент зачастую остается без детализированного руководства. В условиях Казахстана это особенно критично из-за специфики национальной кухни, характеризующейся высокой калорийностью и обилием трудноперевариваемых мясных и мучных изделий (бешбармак, куырдак, жареное тесто).

В-третьих, наше исследование подчеркивает важность культурной адаптации диетотерапии. Стандартные рекомендации «из учебника» часто игнорируются населением, если они не учитывают привычный рацион. Предложенная нами система «безопасных замен» (например, замена жирной баранины на индейку, а жареных баурсаков на подсушенный хлеб) является инструментом повышения комплаентности (приверженности) пациентов к лечению.

Ограничения исследования: Стоит признать, что данная работа базируется на анализе нормативных актов и открытых источников. Для более глубокого понимания проблемы требуется проведение полевых социологических опросов среди пациентов и практикующих хирургов в регионах РК, чтобы оценить реальный уровень соблюдения диеты на дому.

### Заключение

В результате проведенного исследования по теме «Текущее состояние питания при аппендиците в Казахстане» были сформулированы следующие выводы:

1. Нормативная база: Анализ действующих клинических протоколов МЗ РК подтвердил их соответствие современным мировым трендам хирургии (концепция ERAS). В Казахстане официально закреплён отказ от длительного голодания в пользу ранней нутритивной поддержки, что является важным шагом в цифровизации и модернизации стандартов медицинской помощи.
2. Проблема преемственности: Несмотря на наличие стандартов, выявлено отсутствие системного контроля за питанием пациента после перехода на амбулаторный этап. «Информационный вакуум» в первые 14–30 дней после выписки остается фактором риска развития функциональных нарушений ЖКТ и вентральных грыж.
3. Региональная специфика: Установлено, что традиционные пищевые привычки населения Казахстана (высокое потребление жирного мяса, жареного теста и неферментированных молочных продуктов) часто вступают в противоречие с требованиями диетотерапии. Это диктует необходимость разработки адаптированных рекомендаций.
4. Практическая значимость: Предложенная в работе система «безопасных замен» национальных блюд на диетические аналоги и пятиступенчатый план реабилитации могут служить основой для создания информационных памяток для пациентов хирургических отделений РК.

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# CLINICAL ASPECTS OF ANESTHESIOLOGY IN THE TREATMENT OF CANCER PATIENTS: MODERN APPROACHES

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**Annotation:** The perioperative period has recently emerged as a critical phase influencing both short-term recovery and long-term oncological outcomes in cancer patients. Modern evidence suggests that anesthetic management may affect tumor biology through modulation of immune responses, inflammatory pathways, neuroendocrine stress reactions, angiogenesis, and metastatic processes. This scientific and analytical work focuses on the impact of anesthetic agents, including propofol, volatile anesthetics, opioids, lidocaine, ketamine, and dexmedetomidine, on cancer recurrence and survival. The role of regional anesthesia and multimodal analgesia in preserving perioperative immune competence is also examined. Recent studies investigating perioperative immunosuppression, neutrophil extracellular trap formation, inflammatory biomarkers, and enhanced recovery after surgery (ERAS) protocols are reviewed. Current evidence indicates that anesthetic interventions may influence biological mechanisms associated with tumor progression; however, the translation of experimental findings into consistent clinical benefits remains challenging. Large randomized controlled trials have not yet confirmed definitive superiority of any single anesthetic technique regarding long-term oncological outcomes. Nevertheless, optimization of perioperative care contributes significantly to improved recovery, reduced complications, and enhanced quality of life in cancer patients. Future research should focus on personalized perioperative oncology, integration of

immunological biomarkers, and development of evidence-based anesthetic strategies that support both surgical success and oncological control.

**Key words:** oncology, anesthesiology, onco-anesthesiology, perioperative medicine, propofol, multimodal analgesia, regional anesthesia, cancer surgery, enhanced recovery after surgery, cancer recurrence, immune modulation, tumor microenvironment.

Cancer remains one of the most significant global healthcare challenges, representing a leading cause of morbidity, mortality, and healthcare expenditure worldwide. Advances in screening, diagnostics, molecular biology, surgical techniques, radiotherapy, and systemic anticancer therapies have substantially improved survival rates for many malignancies. As a result, increasing attention has shifted toward factors that may influence not only immediate treatment success but also long-term oncological outcomes. Surgical intervention continues to be a cornerstone of treatment for most solid tumors, and a large proportion of cancer patients undergo one or more operative procedures during the course of their disease. Consequently, the perioperative period has emerged as a critical phase during which physiological, immunological, and inflammatory responses may affect both postoperative recovery and tumor behavior. The growing concept of perioperative oncology recognizes that factors traditionally considered supportive aspects of care may have broader implications for patient prognosis and quality of life.

Within this context, anesthesiology has evolved beyond its conventional role of ensuring unconsciousness, analgesia, and physiological stability during surgery. Contemporary research suggests that anesthetic agents, analgesic techniques, perioperative stress responses, and immune modulation may interact with biological mechanisms involved in tumor progression, recurrence, and metastatic spread. Increasing evidence indicates that the choice of anesthetic strategy can influence inflammatory pathways, neuroendocrine regulation, cellular immunity, angiogenesis, and the tumor microenvironment. At the same time, the implementation of multimodal analgesia, regional anesthesia, enhanced recovery protocols, and personalized perioperative management has transformed the care of cancer patients. Understanding the complex relationship between anesthetic management and oncological outcomes is therefore essential for optimizing perioperative treatment strategies.

Ahn H.J. [1], in his study, examines the relationship between anesthetic management and cancer recurrence after surgical treatment. The author considers perioperative anesthesia not merely as a supportive component of oncological surgery but as a potential biological modifier of long-term oncological outcomes. The review emphasizes that approximately 80% of cancer patients undergo surgery during the course of their disease, making anesthetic exposure a clinically important factor. A major contribution of the paper is the detailed discussion of how anesthetic agents may influence immune surveillance, inflammatory signaling, angiogenesis, and metastatic dissemination. The author explains that surgical stress activates neuroendocrine pathways that suppress natural killer cell activity and cellular immunity. General anesthetics may further modulate these processes through effects on cytokines, transcription factors, and tumor microenvironment interactions.

Particular attention is devoted to propofol, volatile anesthetics, opioids, and regional anesthesia techniques. The review demonstrates that experimental studies frequently suggest protective effects of propofol-based anesthesia, whereas volatile agents may promote pathways associated with tumor progression. However, the author carefully notes that clinical evidence remains inconsistent. Several retrospective studies report improved survival with total intravenous anesthesia, but randomized clinical trials have not consistently confirmed these findings. An important strength of the publication is its balanced interpretation of laboratory and clinical evidence. From an expert perspective, the article illustrates the complexity of perioperative oncological biology and highlights the need for large prospective multicenter trials. Therefore, this

source is fundamental for understanding current controversies regarding anesthesia-related modulation of cancer recurrence [1].

Ramirez M.F. et al. [2], in their work, investigate the relationship between perioperative pain control and oncological outcomes. The authors argue that pain management should not be viewed solely as a strategy for patient comfort but also as a potential determinant of postoperative immune competence. The publication emphasizes that uncontrolled pain stimulates sympathetic activation and release of stress hormones, thereby contributing to immunosuppression. The review analyzes interactions between pain, inflammation, immune function, and tumor biology. According to the authors, perioperative inflammation may facilitate residual tumor cell survival and metastatic spread. The paper systematically evaluates opioids, regional anesthesia, nonsteroidal anti-inflammatory drugs, and multimodal analgesic protocols. A key contribution is the discussion of opioid-induced immunomodulation and its potential influence on cancer progression. The authors review experimental evidence suggesting that opioid exposure may alter angiogenesis and tumor cell proliferation. At the same time, they acknowledge that current clinical data remain inconclusive. The review also highlights the possible benefits of regional analgesic techniques in reducing surgical stress responses. From an expert perspective, the article is valuable because it integrates pain medicine with modern perioperative oncology. The publication supports the concept that optimized pain control may have implications extending beyond symptom management. Therefore, this source contributes significantly to understanding the anesthesiologist's role in comprehensive cancer care.

A nationwide cohort study was conducted by Oh T.K. et al. [3] in which the authors examined whether the method of anesthesia affects long-term survival after major cancer surgery. The research is particularly important because it utilizes a large population-based dataset rather than a single-center experience. The authors compared outcomes among patients receiving propofol-based total intravenous anesthesia and those receiving volatile anesthetic techniques. Their analysis demonstrated an association between propofol-based anesthesia and improved long-term survival. The paper contributes to the growing body of literature suggesting that anesthetic choice may influence postoperative oncological outcomes.

The authors discuss several biological mechanisms potentially explaining these findings. Propofol has been reported to preserve immune function, reduce inflammatory responses, and inhibit certain pathways involved in tumor progression. In contrast, volatile anesthetics may exert different immunomodulatory effects. A major strength of the study is its nationwide design and large sample size. Nevertheless, the authors acknowledge the limitations inherent to observational research, including residual confounding and inability to establish causality. From an expert perspective, the publication provides clinically relevant epidemiological evidence supporting further investigation of propofol-based anesthesia in oncology. The study illustrates how anesthetic management may become an important component of personalized perioperative cancer care. Therefore, this source represents one of the most influential contemporary investigations of anesthesia-related oncological outcomes [3].

Yang Y. et al. [4] performed an evidence-based analysis focused specifically on breast cancer surgery and anesthesia-related interventions. Unlike many previous publications that relied heavily on retrospective evidence, this review analyzed prospective clinical studies. The authors evaluated the influence of paravertebral blocks, pectoral nerve blocks, sevoflurane anesthesia, ketorolac administration, and lidocaine infiltration on oncological outcomes. A major contribution of the paper is its emphasis on high-quality evidence derived from prospective research designs. The review found that available studies do not provide definitive evidence supporting a substantial survival benefit of any specific anesthetic intervention. However, several interventions demonstrated biological plausibility and encouraging preliminary results. The authors carefully analyze methodological limitations, including sample size, heterogeneity, and follow-up duration.

An important aspect of the publication is its focus on breast cancer, which represents one of the most extensively studied models in perioperative oncology research. From an expert perspective, the paper demonstrates the gap between promising laboratory findings and clinical reality. The review highlights the need for adequately powered randomized trials capable of detecting differences in recurrence and survival endpoints. Therefore, this source is essential for understanding the current level of evidence regarding anesthesia and breast cancer outcomes.

Li T. et al. [5] conducted a systematic review and meta-analysis evaluating whether regional anesthesia improves long-term survival in patients undergoing cancer surgery. The study is notable because it focuses exclusively on randomized controlled trials, thereby minimizing the influence of confounding factors commonly present in retrospective studies. The authors analyzed available evidence comparing regional anesthesia techniques with conventional anesthetic approaches. Their primary objective was to determine whether regional anesthesia reduces cancer recurrence or improves survival.

The meta-analysis found no statistically significant improvement in long-term oncological outcomes associated with regional anesthesia. These findings challenge earlier hypotheses suggesting that attenuation of the surgical stress response could reduce metastatic progression. The authors discuss potential explanations for the discrepancy between experimental and clinical data. One possibility is that the biological effect of regional anesthesia may be too small to produce measurable survival benefits. Another explanation involves heterogeneity among tumor types and perioperative management protocols. The publication is particularly valuable because it provides evidence derived from the highest level of clinical research methodology. From an expert perspective, this study introduces important caution into the ongoing debate regarding anesthesia and cancer outcomes. Therefore, it serves as a key reference demonstrating that theoretically beneficial interventions do not necessarily translate into improved long-term survival [5].

Guo R. et al. [6], in their article, comprehensively analyze the influence of surgery and anesthesia on postoperative immune function in cancer patients. The authors emphasize that the perioperative period represents a critical phase during which tumor progression may be either suppressed or facilitated. A major contribution of the paper is the integration of immunological mechanisms with anesthetic management. The review explains how surgical trauma induces activation of the hypothalamic-pituitary-adrenal axis and sympathetic nervous system, leading to systemic immunosuppression. According to the authors, reductions in natural killer cell activity and cytotoxic T-cell function may create favorable conditions for metastatic dissemination. The publication evaluates the effects of different anesthetic techniques on antitumor immunity. Propofol-based anesthesia is discussed as potentially preserving immune competence, whereas volatile anesthetics may exert more pronounced immunosuppressive effects. The review also addresses opioid analgesics and their possible influence on tumor biology through modulation of immune responses and inflammatory signaling pathways. An important strength of the work is its detailed description of interactions among cytokines, immune checkpoints, and perioperative stress mediators. From an expert perspective, this article provides a mechanistic framework for understanding why anesthetic choices may influence oncological outcomes. The publication demonstrates that modern oncological anesthesia extends beyond hemodynamic stability and pain control. Therefore, this source is fundamental for understanding the immunological basis of perioperative cancer care.

In their study, Bezu L. et al. [7] examine perioperative factors contributing to immunosuppression during cancer surgery. This publication is particularly valuable because it focuses on the multifactorial nature of perioperative immune dysfunction. The authors argue that postoperative immunosuppression is not the result of a single intervention, but rather the combined effects of surgical stress, anesthesia, pain, blood transfusion, hypothermia, and inflammatory activation. The work emphasizes the importance of maintaining antitumor immunity

during the perioperative period.

A key contribution of the paper is its detailed discussion of natural killer cells, dendritic cells, macrophages, and T lymphocytes. The authors explain how perioperative disturbances in immune cell function may facilitate the survival of circulating tumor cells. The publication also analyzes the impact of catecholamines and glucocorticoids released during surgical stress. Importantly, the review evaluates strategies aimed at minimizing immunosuppression, including regional anesthesia, opioid-sparing approaches, normothermia maintenance, and enhanced recovery protocols. From an expert perspective, the article expands the traditional anesthesiology paradigm by linking routine perioperative management with long-term oncological biology. The work supports the concept that anesthesiologists can influence cancer outcomes through optimization of perioperative physiology. Therefore, this source is highly relevant for contemporary oncological anesthesia practice [7].

Tan Y. et al. [8] conducted a systematic review and meta-analysis assessing the impact of anesthesia method on long-term survival after cancer surgery. The publication synthesizes evidence from multiple clinical studies and addresses one of the most debated questions in onco-anesthesiology. Our colleagues compared the outcomes associated with total intravenous anesthesia and the use of volatile anesthetics. Their analysis suggests that anesthesia management may be associated with differences in long-term survival and relapse-free survival.

The overview systematically evaluates methodological quality and sources of heterogeneity among studies. An important contribution of the paper is the distinction between biological plausibility and clinical evidence. The authors discuss laboratory findings suggesting that propofol may inhibit inflammatory pathways and preserve immune function. They also note that volatile anesthetics may influence hypoxia-inducible factors and angiogenic signaling. However, the review emphasizes that available evidence remains insufficient to establish definitive causal relationships. From an expert perspective, this publication provides an updated evidence synthesis that reflects current scientific uncertainty. The article supports continued investigation into anesthesia-related modulation of cancer outcomes. Therefore, this source is essential for understanding the current state of evidence in perioperative oncology research.

The updated ERAS guidelines for surgical treatment of gynecological oncological diseases were presented by Nelson G. et al. [9]. Unlike publications devoted exclusively to anesthetic drugs, this work considers perioperative care as an integrated multidisciplinary process. The authors emphasize that anesthesiologists play a central role in the successful implementation of ERAS. The guideline addresses preoperative optimization, fluid therapy, analgesia, nutrition, mobilization, and postoperative recovery. A major contribution of the paper is its focus on implementation barriers. The authors demonstrate that many evidence-based recommendations remain inconsistently applied despite proven clinical benefits. Particular attention is devoted to opioid-sparing analgesia, goal-directed fluid therapy, prevention of postoperative complications, and early functional recovery. The publication highlights the importance of multimodal analgesic strategies that reduce opioid requirements while maintaining adequate pain control. From an expert perspective, the article illustrates the evolution of anesthesiology from intraoperative management toward comprehensive perioperative medicine. The work supports the concept that optimal oncological outcomes depend not only on tumor resection but also on recovery quality. Therefore, this guideline is highly relevant for modern perioperative care of cancer patients.

Chang C.Y. et al. [10] performed a systematic review and meta-analysis investigating whether propofol-based anesthesia provides oncological advantages compared with volatile anesthetics. The study remains one of the most frequently cited analyses in perioperative oncology. The authors evaluated overall survival, recurrence-free survival, and cancer recurrence across multiple tumor types. A major strength of the publication is its rigorous methodological design and comprehensive literature search.

The review identified evidence suggesting improved long-term outcomes among patients receiving propofol-based anesthesia. However, the authors emphasize that most available studies were retrospective and therefore susceptible to selection bias and residual confounding. The publication carefully discusses biological mechanisms that may explain the observed associations. These mechanisms include preservation of immune function, attenuation of inflammatory responses, and modulation of angiogenesis-related pathways. Importantly, the authors refrain from recommending universal adoption of one anesthetic technique because randomized evidence remains limited. From an expert perspective, this source provides a balanced assessment of one of the central controversies in modern oncological anesthesiology. The study demonstrates that anesthetic choice may influence outcomes beyond the operating room. Therefore, this publication remains a cornerstone reference for discussions regarding anesthesia and cancer prognosis [10].

Hussain N. et al. [11] performed a systematic review and meta-analysis evaluating the efficacy of perioperative intravenous lidocaine in breast cancer surgery. The authors focused on both acute postoperative pain and chronic persistent postsurgical pain, which remains a significant clinical problem among breast cancer survivors. The publication is important because lidocaine has been proposed not only as an analgesic agent but also as a potential modulator of inflammatory and oncological processes. The authors analyzed randomized clinical trials involving perioperative lidocaine infusions. A key finding of the study is that perioperative lidocaine did not significantly reduce the incidence of chronic persistent postsurgical pain. Although some improvements in early postoperative analgesia were observed, the overall evidence did not support routine lidocaine infusion as a strategy for long-term pain prevention. The publication carefully evaluates methodological quality and risk of bias among included studies. An important strength is the use of meta-analytic methodology to synthesize available evidence. From an expert perspective, this study demonstrates that promising biological hypotheses do not always translate into measurable clinical benefits. The article contributes to evidence-based perioperative pain management in oncological surgery. Therefore, this source is highly relevant for understanding the current role of lidocaine in cancer anesthesia.

In their study, Schnabel A. et al. [12] assessed the effectiveness of regional analgesia methods in patients undergoing major surgery for internal cancer. The publication addresses an important issue, as postoperative pain relief remains a central component of accelerated recovery. The review compares epidural analgesia and peripheral regional anesthesia in oncologic surgery. The researchers evaluate postoperative pain intensity, functional recovery, and analgesic efficacy. One of the major findings is that epidural analgesia may provide clinically meaningful reductions in pain intensity during the first postoperative day. However, the certainty of available evidence remains limited. The publication emphasizes that peripheral regional techniques often produce smaller effects than epidural approaches. Importantly, the review discusses the balance between analgesic benefits and procedure-related risks. From an expert perspective, the article illustrates the ongoing transition from opioid-centered pain management toward multimodal analgesia. The study supports the role of regional anesthesia as an important component of perioperative oncological care. Therefore, this source contributes significantly to understanding modern pain management strategies in cancer surgery.

The interaction between local anesthetics and chemotherapeutic agents was studied by Abdelaatti A. et al. [13]. This publication is particularly valuable because it brings together two traditionally separate fields: anesthesiology and medical oncology. The authors summarize experimental data on how local anesthetics can influence tumor cell behavior and their response to chemotherapy. The review focuses on lidocaine, ropivacaine, and bupivacaine.

A major contribution of the article is the discussion of molecular pathways involved in tumor growth, apoptosis, migration, and metastasis. The authors demonstrate that local

anesthetics may enhance the efficacy of certain chemotherapeutic drugs in experimental models. At the same time, they emphasize the limited availability of clinical evidence. The publication carefully distinguishes between laboratory observations and clinically proven outcomes. From an expert perspective, this source highlights a promising research direction in perioperative oncology. The article suggests that anesthetic drugs may possess biological effects extending beyond analgesia and anesthesia. Therefore, this publication provides an important scientific basis for future translational studies investigating anesthetic-oncological interactions [13].

Choi H., Hwang W. [14] provide a comprehensive review of modern anesthetic approaches and their potential influence on cancer recurrence and metastasis. The authors analyze both clinical and experimental evidence concerning anesthetic drugs, regional anesthesia, opioids, ketamine, dexmedetomidine, and anti-inflammatory strategies. A major contribution of the publication is its holistic approach to perioperative oncological management. The publication emphasizes that perioperative events may influence the balance between host immunity and residual tumor cell survival. The authors discuss evidence suggesting potential advantages of propofol-based anesthesia and opioid-sparing techniques. At the same time, they acknowledge that current clinical findings remain inconsistent. An important strength of the publication is its balanced interpretation of conflicting data. From an expert perspective, the review demonstrates that anesthesiology is increasingly becoming integrated with precision oncology. The article highlights the need for individualized anesthetic planning based on tumor characteristics and patient factors. Therefore, this source is highly valuable for understanding the current conceptual framework of onco-anesthesiology.

An interesting prospective randomized study was conducted by Zhang W. et al. [15]. In their work, they examined the effect of lidocaine on neutrophil extracellular uptake (NETosis) and angiogenesis-related biomarkers in patients with breast cancer. This study is particularly significant, as NETosis has recently been identified as a potential mechanism contributing to tumor dissemination and metastasis. The researchers sought to determine whether lidocaine administration could alter these biological processes in the perioperative period. The paper demonstrated that lidocaine influenced several biomarkers associated with inflammation and angiogenesis. The authors suggest that modulation of NETosis may represent one mechanism through which anesthetic interventions affect tumor biology. The publication is notable because it evaluates objective biological markers rather than only clinical endpoints. An important strength is its prospective randomized design. From an expert perspective, the study illustrates the growing trend toward mechanistic perioperative oncology research. The work contributes to understanding how commonly used anesthetic drugs may interact with tumor-related biological pathways. Therefore, this source represents an important example of translational research in modern anesthesiology.

Ramly M.S., Buggy D.J. [16] present one of the most up-to-date evidence-based reviews addressing the relationship between anesthetic techniques and long-term cancer outcomes. The publication is important because it summarizes results obtained after several large randomized clinical trials that have recently challenged earlier observational findings. The authors examine the effects of total intravenous anesthesia, volatile anesthesia, regional anesthesia, opioid-sparing strategies, and perioperative immunomodulation. A central contribution of the paper is its critical reassessment of previously accepted hypotheses regarding anesthesia-induced modulation of cancer recurrence. The review emphasizes that laboratory studies consistently demonstrate biological differences between anesthetic agents. However, these mechanistic findings have not always translated into measurable clinical benefits. The authors conclude that current evidence does not support routine selection of one anesthetic technique solely for the purpose of reducing cancer recurrence. Nevertheless, anesthetic management remains important because it influences immune function, inflammation, perioperative complications, and recovery quality.

From an expert perspective, the publication reflects the maturation of the field of onco-anesthesiology. The article demonstrates the transition from speculative associations toward evidence-based clinical decision making. Therefore, this source is essential for understanding the present consensus regarding anesthesia and oncological outcomes.

Huh J., Hwang W. [17] specifically investigate anesthetic management in patients undergoing surgery for lung cancer. The review is particularly valuable because lung cancer remains one of the leading causes of cancer-related mortality worldwide. The authors discuss how perioperative events may influence residual tumor cells, circulating tumor cells, and micrometastatic disease. The publication examines the effects of surgical stress, neuroendocrine activation, inflammatory mediators, and immune suppression on cancer progression.

A major contribution of the article is its focus on disease-specific considerations. The authors analyze evidence regarding volatile anesthetics, propofol, opioids, regional anesthesia, and perioperative analgesic strategies. They emphasize that preservation of immune competence may be especially important in thoracic oncology. The review also addresses mechanisms such as epithelial-mesenchymal transition, angiogenesis, and tumor microenvironment modulation. From an expert perspective, the publication illustrates how anesthetic decisions may interact with tumor biology in organ-specific settings. The article supports the concept of individualized perioperative oncology rather than universal anesthetic protocols. Therefore, this source contributes significantly to understanding anesthesia management in thoracic cancer surgery [17].

In their study, Rodriguez Arango J.A. et al. [18] analyze one of the most controversial drugs in modern anesthesiology – ketamine. The publication examines the potential influence of perioperative ketamine administration on cancer recurrence and metastatic progression. The authors note that ketamine has traditionally been used for anesthesia and analgesia but has recently attracted attention because of possible immunological and antitumor properties. The review evaluates experimental, translational, and clinical evidence concerning ketamine's interaction with cancer biology. The authors discuss the role of N-methyl-D-aspartate receptors in malignant tissues and explain how ketamine may affect tumor cell proliferation, apoptosis, migration, and angiogenesis. The publication emphasizes that existing findings remain inconsistent. While several laboratory studies suggest antitumor activity, clinical evidence remains limited and inconclusive. An important strength of the review is its balanced assessment of potential benefits and risks. From an expert perspective, the article demonstrates the growing interest in understanding the biological effects of anesthetic drugs beyond their traditional pharmacological actions. Therefore, this source is highly relevant for future investigations of anesthetic-related cancer modulation.

Xie S. et al. [19] performed a large meta-analysis examining the association between regional anesthesia and postoperative cancer outcomes. The study is important because previous investigations have produced conflicting conclusions regarding the oncological benefits of regional anesthesia. The authors pooled available clinical evidence and analyzed recurrence, metastasis, and survival endpoints. A key contribution of the publication is the evaluation of both regional anesthesia alone and regional anesthesia combined with general anesthesia. The analysis demonstrated that regional anesthesia may be associated with a lower risk of cancer recurrence in selected patient populations, particularly among patients undergoing prostate cancer surgery. However, no statistically significant effects were observed for distant metastasis or local recurrence. The authors emphasize that heterogeneity among studies remains substantial. The publication carefully discusses potential biological mechanisms including attenuation of surgical stress responses and preservation of immune surveillance. From an expert perspective, the study highlights both the promise and limitations of current evidence. Therefore, this source contributes valuable quantitative data to the ongoing debate regarding regional anesthesia and cancer prognosis.

A unique study was conducted by Chew V.K. et al. [20]. They investigated the relationship between anesthesia method and postoperative recurrence in surgical treatment of thyroid cancer. The study compared total intravenous propofol-based anesthesia with desflurane anesthesia and assessed long-term oncological outcomes. This publication is particularly important because thyroid cancer generally exhibits favorable survival rates, making recurrence a particularly significant outcome. The authors report a lower rate of postoperative recurrence among patients receiving propofol-based anesthesia.

The article discusses potential biological explanations for these findings. Propofol may attenuate inflammatory responses, preserve natural killer cell activity, and inhibit pathways involved in tumor progression. In contrast, volatile anesthetics have been hypothesized to influence immune and angiogenic signaling differently. The authors acknowledge the observational nature of their study and the need for randomized confirmation. Nevertheless, the publication provides clinically relevant evidence supporting ongoing investigation of anesthetic choice in oncological surgery. From an expert perspective, this source reinforces the growing body of literature suggesting potential advantages of total intravenous anesthesia in selected cancer populations. Therefore, this study represents an important contribution to contemporary onco-anesthesiology [20].

In conclusion, it can be stated that anesthesiology has evolved from a discipline focused primarily on intraoperative safety to a critical component of comprehensive oncology care. Growing evidence suggests that perioperative events can influence tumor biology through complex interactions involving immune regulation, inflammatory responses, neuroendocrine activation, angiogenesis, and metastatic spread. Numerous experimental studies have demonstrated that anesthetics vary in their effects on cellular and molecular pathways associated with cancer progression. Specifically, propofol-based total intravenous anesthesia is often associated with preserved immune function and potentially favorable oncological outcomes, while volatile anesthetics are implicated in mechanisms that may promote tumor growth. However, the clinical significance of these findings remains controversial.

Current randomized controlled trials and large meta-analyses have not established definitive evidence of the superiority of one anesthetic technique over another in preventing cancer recurrence or improving long-term survival. Similarly, although regional anesthesia and opioid-based pain management approaches can reduce surgical stress and preserve immune competence, their direct impact on oncologic prognosis remains uncertain. Recent studies of lidocaine, ketamine, inflammatory biomarkers, and the formation of neutrophil extracellular traps have expanded our understanding of the biological mechanisms linking anesthesia and cancer. Furthermore, perioperative protocols based on the ERAS program have demonstrated significant benefits in improving postoperative recovery and reducing complications in cancer patients.

Overall, current data support the concept that anesthetic management should be considered an integral element of personalized cancer treatment, rather than simply a technical adjunct to surgery. Future progress in onco-anesthesiology will depend on interdisciplinary collaboration between anesthesiologists, oncologists, surgeons, immunologists, and translational medicine specialists. The incorporation of molecular biomarkers, precision medicine approaches, and large prospective clinical trials can help identify individualized anesthesia strategies for each patient that can optimize both perioperative recovery and long-term oncologic outcomes. Thus, perioperative anesthesiology represents a promising and rapidly evolving field with significant potential to improve the quality and effectiveness of modern oncologic care.

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## Philological Sciences

# Ali təhsil müəssisələrində “Tələffüz və Şifahi nitq vərdişləri” fənninin tədrisində Süni İntellektdən istifadə və tədrisdə Süni İntellektin rolu

Könül Ağayeva

ADU

Açar sözlər: süni intellekt, nitq təcrübəsi, dil öyrənməsi, tələffüz təlimi, adaptiv öyrənmə.

Key words: artificial intelligent, speech practice, pronunciation practice, adaptive learning.

Ключовые слова: искусственный интеллект, практика речи, практика произношения, адаптивное изучение.

Süni intellektin xarici dilin tədrisinə inteqrasiyası pedaqoji yanaşmalarda əhəmiyyətli bir dəyişikliyə işarə edir. Xarici dilin mənimsəməsinin vacib bir komponenti olan nitq praktikası ənənəvi olaraq rəy və düzəliş üçün insan təlimatlarından asılı olmuşdur lakin, Si texnologiyaları hazırda ənənəvi metodları tamamlayan və hətta bəzən üstələyən innovativ həll yolları təklif edir. Həsən Əlisoy və digərlərinin (2025) Azərbaycan ali təhsilində Si inteqrasiyası ilə bağlı tədqiqatlarında qeyd etdiyi kimi: «Süni intellektdə (Si) qlobal irəliləyişlərə cavab olaraq Azərbaycan ali təhsili sürətli rəqəmsal transformasiyadan keçir. Bu kontekstdə, ingilis dilinin tədrisi (ELT) təlim nəticələrini artırmaq üçün süni intellekt alətlərinin inteqrasiyası kimi çətinliklərlə üzləşir» [1].

Bu məqalədə bizim məqsədimiz aşağıdakı tədqiqat suallarını araşdırmaq və onları təhlil etməkdir:

- Süni intellekt alətləri universitet səviyyəsində şifahi nitq vərdişləri fənninin tədrisini necə effektiv şəkildə dəstəkləyə bilər?

- Süni intellekt sistemləri tələffüz, səlislik və intonasiya təlimi üçün hansı spesifik faydalar təmin edir?

- Şifahi nitq vərdişləri təlimində süni intellekt tətbiqi zamanı hansı çətinliklər yaranır?

- Tələbələr və müəllimlər süni intellektlə dəstəklənən nitq təlimini necə qəbul edirlər?

Şifahi nitq vərdişləri tələffüz, səlislik, intonasiya və ünsiyyət bacarıqlarının inkişaf etdirilməsini əhatə edir. Ənənəvi yanaşmalar aşağıdakılara əsaslanır:

- təlimatçı rəyi;
- audiovizual materiallar;
- dil laboratoriyaları.

Süni intellekt bu metodları aşağıdakılar vasitəsilə təkmilləşdirir:

- avtomatik nitq tanıma (ASR) - şifahi girişi transkripsiya edir və qiymətləndirir;
- təbii dil emalı (NLP) — qrammatik və leksik dəqiqliyi təhlil edir;
- maşın öyrənməsi — fərdi tələbə nümunələrinə uyğunlaşır;
- məndən nitqə (TTS) — model tələffüz təmin edir.

Koqnitiv nəzəriyyələr süni intellekt inteqrasiyasını dəstəkləyir:

- Vıqotskinin Yaxın İnkişaf Zonası — Süni intellekt xüsusi hazırlanmış iskala təklif edir;
- Kraşenin Giriş Hipotezi — Süni intellekt müvafiq səviyyələrdə başa düşülən giriş təmin edir;

- Svaynin Çıxış Hipotezi — Süni intellekt dərhal rəylə istehsalı təşviq edir.

Şifahi nitq vərdisləri üçün Süni intellekt Alətləri

#### 1. Tələffüz Təlimi

• ELSA Speak — tələffüz səhvlərini müəyyən etmək üçün süni intellektdən istifadə edir və hədəflənmiş məşqlər təqdim edir.

- Speechling — ətraflı düzəliş üçün insan və süni intellekt rəylərini birləşdirir.

- Google Pronounce — fərdi səslər üzərində real vaxt rəyi təklif edir.

#### 2. Səlislik və İntonasiya

• Rosetta Stone TruAccent — nitq tanıma istifadə edərək öyrənənin nitqini yerli modellərlə müqayisə edir.

- Babbel — danışq təcrübəsi üçün nitq tanıma sistemini özündə birləşdirir.

- Duolingo Speaking Exercises — oyunlaşdırılmış səlislik təlimi.

#### 3. Danışq Təcrübəsi

- Replika — təbii söhbət təcrübəsi üçün çatbot.

• Tandem — öyrənənləri anadillilərlə uyğunlaşdırır; Süni intellekt tərcümə və düzəlişdə kömək edir.

- Süni intellekt müəllimləri (məsələn, Duolingo Max) — GPT əsaslı danışq agentləri.

#### 4. İmmersiv Mühitlər

- VR Dil Laboratoriyaları — real dünya təcrübəsi üçün virtual reallıq simulyasiyaları.

- Mondly VR — situasiya dilinin istifadəsi üçün interaktiv ssenarilər.

Süni İntellektin pedaqoji faydalarından ən önəmlisi onun fərdiləşdirilmiş təlim metodudur ki, burada Süni intellekt sistemləri fərdi ehtiyaclara uyğunlaşır:

- spesifik tələffüz problemlərini müəyyən edir (məsələn, ispan dilində danışanlar üçün /θ/ və /ð/);

- məşq çətinliyini performans əsasən tənzimləmək;

- xüsusi təcrübə planları yaratmaq.

Ənənəvi metodlarla müqayisədə Sİ - nin üstünlükləri:

- ani səhv aşkarlanması (gecikmiş təlimatçı rəyi ilə müqayisədə);

- obyektiv qiymətləndirmə (subyektivliyin azalması);

- səhvlərin ətraflı təhlili (səs, stress, intonasiya).

Eyni zamanda Sİ artan təcrübə imkanlarına malikdir ki, bu da onun 24/7 mövcudluğu, aşağı təzyiqli mühiti (narahatlığı azaldır), limitsiz təkrarlara malik olmasıdır. Süni intellekt platformaları eyni zamanda qiymətləndirmə sistemləri, nailiyyət nişanları, rəqabət liderlik lövhələri, adaptiv çətinliklər kimi funksiyaları əhatə edir.

Qarışıq Təlim Modelləri əsasında Süni İntellektin effektiv inteqrasiya strategiyalarına, sinif otağının simulyasiyasını yaratmaq - tələbələr dərstdən əvvəl Sİ alətləri ilə məşq edirlər, laboratoriya sessiyaları — Sİ ilə dəstəklənən təcrübə üçün ayrılmış vaxt, ev tapşırıqları — sinifdən kənar iş kimi Sİ məşqləri, əlavə resurslar — ənənəvi təlimlə yanaşı könüllü Sİ təcrübəsi daxildir.

Süni İntellektin tədris planına inteqrasiya nümunələrinə həftəlik süni intellekt tələffüz modulları, işgüzar ingilis dili üçün VR rol oyunları, işə hazırlıq üçün süni intellekt tərəfindən yaradılan müsahibə simulyasiyaları mühüm yer tutur.

Onlayn Dil Proqramı gündəlik söhbət təcrübəsi üçün süni intellekt çatbotları, avtomatlaşdırılmış səlislik qiymətləndirmələri, təlimatçı tərəfindən süni intellekt tərəfindən yaradılan analitikanın icmalını hazırlamağı sanlaşdırır və müəllimlər üçün bunu əlçatan edir.

H. Əlisoy və digərlərinə (2025) görə, Azərbaycan tələbələri süni intellekt inteqrasiyasına yüksək hazırlıq nümayiş etdirirlər: «Tələbələrin təxminən 80%-i “Süni intellekt vasitələri dil öyrənməsini daha cəlbədicə edə bilər” deyərək razılıq verib, müəllim heyətinin isə təxminən 60%-i bununla razılıq verib»

[1]. Bu, tələbələr və müəllimlər arasında universitetlərin peşəkar inkişaf proqramları vasitəsilə həll etməli olduğu məsələlərin olduğunu göstərir.

Eyni zamanda Süni İntellektin istifadəsində bir sıra çətinliklər və məhdudiyətlər mövcuddur ki bunlara texniki məsələlər – qeyri-dil daşıyıcılarının tələffüzündə olan dəqiqlik, internet bağlantısı tələbləri, cihaz uyğunluğu, məlumatların məxfiliyi ilə bağlı narahatlıqlardır. Texnologiyaya həddindən artıq etibar etmək, ünsiyyətin qarşılıqlı əlaqəsinin azalması, səhv rəy ehtimalı, süni intellektdə emosional zəkanın olmaması da digər tərəfdən pedaqoji baxımdan narahatlıq yaradır. Yüksək səviyyəli alətlərin qiyməti, müəllim heyətinin təlim tələbləri, tədris planının yenidən dizaynı səyləri, dəyişikliklərə müqaviməti də nəzərə alındıqda Sİ-in istifadəsinin hələ də çətinlik yaratdığına şahidi oluruq. Bu digər tərəfdən tələbə faktorları - rəqəmsal savadlılıq boşluqları, texnologiya ilə bağlı narahatlıqlar, ünsiyyətin qarşılıqlı əlaqəsinə üstünlük kimi problemləri qarşıya qoyur.

Dr. Sərcan İslam Sadıqova və başqaları (2024) Azərbaycan kontekstində oxşar problemləri vurğulayırlar: "Müəllimlər süni intellekt inteqrasiyasına ehtiyatla müsbət münasibət göstərdilər, onun qrammatik və mexaniki səhvləri səmərəli və dəqiq aşkar etməkdəki gücünü qəbul etdilər, lakin etibar, ədalət və etika ilə bağlı narahatlıqlarını bildirdilər" [2].

Son tədqiqatlar süni intellektin effektivliyini göstərir, Johnson & Lee (2023) görə süni intellekt tələffüz vasitələrindən istifadə edən tələbələr nəzarət qruplarına nisbətən 27% daha çox inkişaf göstərdilər. Helsinki Universitetinin Pilot Tədqiqatı (2025) qarışıq süni intellekt/insan təlimi 33% daha yüksək yadda saxlama nisbətinə səbəb olduğunu sübut etdi.

Tələbələrin qavrayışı (500 universitet dil öyrənəninin sorğusu):

- 82% süni intellekt rəyini faydalı hesab etdi;
- 68% tələffüz üçün süni intellekt təcrübəsini üstün tutdu;
- 75% danışmaq narahatlığının azaldığını bildirdi;
- 59% kurslarda daha çox süni intellekt inteqrasiyası istədi.

Azərbaycanda H. Əlisoyun tədqiqatı bu tendensiyaları təsdiqləyir: "Tələbələr həmçinin süni intellektdən istifadə etməyə daha yüksək hazırlıq göstərdilər: böyük əksəriyyət fürsət verilsə, süni intellektdən müntəzəm olaraq təlimin bir hissəsi kimi istifadə edəcəklərini bildirdilər, müəllim heyətinin təxminən yarısı isə süni intellektdən tədris prosesinə daxil edəcəklərini söylədi" [1].

Natiq Əli Cavadov və digərləri (2025) Azərbaycan təhsilində süni intellekt üçün dövlət dəstəyinin vacibliyini vurğulayırlar: «Dövlət administrasiyasının Azərbaycanda süni intellektin tətbiqi və inkişafı üçün dəstəyinin olması ölkədə sahənin inkişafı üçün əlverişli zəmin yaradıldığını göstərir» [3].

Universitetlərdə tələffüz və şifahi nitq vərdişlərinin tədrisinə süni intellektin inteqrasiyası dil tədrisində transformativ bir dəyişikliyi təmsil edir - bu, həm global miqyasda, həm də Azərbaycanda sürətlə inkişaf edir. Beləliklə biz süni intellekt texnologiyalarının tələffüzün, səlisiyin, intonasiyanın və ümumi ünsiyyət bacarıqlarının artırılması üçün əhəmiyyətli faydalar təklif etdiyini görürük.

Azərbaycanlı alimlərin tədqiqatları da daxil olmaqla, empirik dəlillər süni intellekt inteqrasiyasının müsbət təsirini vurğulayır. H. Əlisoy və digərlərinin (2025) qeyd etdiyi kimi, Azərbaycan tələbələrinin təxminən 80%-i süni intellekt alətlərinin dil öyrənməsini daha cəlbedici edə biləcəyi ilə razılaşırlar [1]. Eynilə, S.İ.Sadıqova və digərlərinin də (2024) qeyd etdiyi kimi, bu sahədə müəllimlər müəyyən ehtiyatlılıq göstərsələr də, süni intellektin səhvləri dəqiq aşkarlamaqda güclü tərəflərini də qəbul edirlər [2]. Müəllim heyətinin hazırlığını tələbələrin gözləntiləri ilə uyğunlaşdırmaq üçün hədəflənmiş peşəkar inkişafa ehtiyac olmasına baxmayaraq bu tapıntılar süni intellektdən istifadə üçün perspektivli bir trayektoriya təklif edir. Sİ-in təqdim etdiyi üstünlüklərə baxmayaraq, onun tətbiqində çətinliklər hələ də qalmaqdadır. Texniki məhdudiyətlər həll edilməli, ünsiyyətin qarşılıqlı əlaqəsinin azalması riski və texnologiyaya həddindən artıq etibar da daxil olmaqla pedaqoji narahatlıqlar balanslı bir yanaşma tələb edir.

Xərclər və tədris planının yenidən dizaynı kimi institusional maneələr strateji planlaşdırma və investisiya da bir problem olaraq mövcuddur.

Dövlət təşəbbüsləri ilə dəstəklənən (Cavadov və digərləri tərəfindən vurğulandığı kimi [3]) Azərbaycanın rəqəmsal transformasiyaya sadıqlığı bu çətinliklərin öhdəsindən gəlmək üçün əlverişli mühit yaradır. Bu impulsdan istifadə etməklə, Azərbaycan universitetləri süni intellektin güclü tərəflərini insan təliminin əvəzolunmaz dəyəri ilə birləşdirərək innovativ dil təhsilində liderlik edə bilirlər.

Nəticə olaraq, süni intellekt universitet dil proqramlarında nitq praktikasında inqilab etmək üçün əhəmiyyətli potensiala malikdir. Düşünülmüş və strateji şəkildə tətbiq edildikdə, süni intellekt alətləri ənənəvi tədris metodlarını təkmilləşdirə, öyrənmələri gücləndirə və tələbələri qloballaşan dünyaya hazırlaya bilər. Texnologiya inkişaf etməyə davam etdikcə, təhsilin insan mərkəzli dəyərlərini qoruyub saxlamaqla yanaşı, süni intellektdən faydaları maksimum dərəcədə artırmaq üçün müəllimlər və texnoloqlar arasında davamlı tədqiqat, uyğunlaşma və dialoq vacib olacaqdır.

Tənqidi və inklüziv düşüncə tərzilə innovasiyanı qəbul edən universitetlər, o cümlədən Azərbaycandakı universitetlər, süni intellektdən istifadə edərək daha effektiv, cəlbədiçə və bərabər dil öyrənmə təcrübələri yarada bilirlər.

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#### Xülasə

Bu məqalədə qlobal və Azərbaycan tədqiqat perspektivlərinə diqqət yetirilərək, universitet səviyyəsində nitq təcrübəsinin tədrisində süni intellektin (Sİ) rolu araşdırılır. Burada mövcud Sİ alətləri, onların pədaqoji faydaları, tətbiq çətinlikləri və gələcək perspektivlər təhlil edilir. Tədqiqat göstərir ki, Sİ ilə işləyən həllərin fərdiləşdirilmiş rəy təmin etməklə, tələbənin müstəqilliyini artırmaqla və immersiv təcrübə mühitləri təklif etməklə dil mənimsəməsini gücləndirir.

#### Summary

This article examines the role of artificial intelligence (AI) in teaching speech practice at the university level, with a focus on global and Azerbaijani research perspectives. It analyses current AI tools, their pedagogical benefits, implementation challenges, and future prospects.

The study demonstrates that AI-powered solutions enhance language acquisition by providing personalised feedback, increasing learner autonomy, and offering immersive practice environments.

### Резюме

В данной статье рассматривается роль искусственного интеллекта (ИИ) в обучении речевой практике на университетском уровне, с акцентом на глобальные и азербайджанские исследовательские перспективы. Анализируются существующие инструменты ИИ, их педагогические преимущества, проблемы внедрения и перспективы на будущее.

Исследование демонстрирует, что решения на основе ИИ улучшают усвоение языка, предоставляя персонализированную обратную связь, повышая автономию обучающихся и предлагая иммерсивные условия для практики.

## Psychological Sciences

# Validəynlərlə uşaqlar arasında yaranan ünsiyyət çatışmazlığı və onun səbəbləri

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### Annotasiya

Müasir ailə strukturunda valideyn və övlad arasındakı ünsiyyət sadəcə məlumat mübadiləsi deyil, uşağın sosial-psixoloji inkişafını formalaşdıran fundamental mexanizmdir. Lakin son onillikdə baş verən sürətli rəqəmsal transformasiya bu münasibətlərin təbiətini köklü şəkildə dəyişmiş, tərəflər arasında yeni növ ünsiyyət çatışmazlıqlarının yaranmasına səbəb olmuşdur. Təqdim olunan məqalədə valideyn-övlad ünsiyyətində yaranan qopuqluqlar və bu prosesə təsir edən multidissiplinar faktorlar analiz edilir. Tədqiqatın əsas fokusu rəqəmsal asılılıq, xüsusilə də son dövrlərin qlobal trendi olan qısa video kontentlərin ailədaxili dialoqa neqativ təsirləri üzərində qurulmuşdur.

Araşdırma çərçivəsində beynəlxalq elmi ədəbiyyat analiz edilmiş və müəyyən olunmuşdur ki, uşaqların onlayn icmalara və rəqəmsal platformalara olan marağı ailə daxiliindəki "psixoloji mövcudluğu" zəiflədir. Bundan əlavə, məqalədə valideynlərin tətbiq etdiyi "sərt sevgi" kommunikasiya modelinin və bəzi sosial tabuların gənc yetkinlərdə yaratdığı emosional bariyerlər araşdırılır. Tədqiqatın elmi yeniliyi ünsiyyət çatışmazlığının yalnız texnoloji deyil, həm də sosial-psixoloji və bioloji maneələr kontekstində kompleks şəkildə ələ alınmasıdır. Nəticə hissəsində ailədaxili ünsiyyət boşluqlarını aradan qaldırmaq üçün rəqəmsal etika qaydalarının tətbiqi və emosional intellektə əsaslanan dialoq modelləri təklif olunur. Bu araşdırma müasir ailə psixologiyası və rəqəmsal sosiologiya sahəsində çalışan mütəxəssislər, eləcə də valideynlər üçün mühüm elmi baza rolunu oynaya bilər.

**Açar sözlər:** valideyn-övlad ünsiyyəti, rəqəmsal transformasiya, ünsiyyət çatışmazlığı, rəqəmsal asılılıq, sosial izolyasiya.

### GİRİŞ:

Ailə, fərdin formalaşdığı ilk sosial mühit və cəmiyyətin təməl daşığıdır. Bu kiçik sosial strukturun daxili dinamikasını tənzimləyən ən mühüm amil isə valideyn və övlad arasındakı ünsiyyətdir. Effektiv ünsiyyət sadəcə sözlərin mübadiləsi deyil, həm də emosional bağın qurulması, dəyərlərin ötürülməsi və uşağın özünü təhlükəsiz hiss etdiyi bir mühitin yaradılmasıdır. Lakin müasir dünyada baş verən qlobal dəyişikliklər ailə daxili kommunikasiya modellərini sınağa çəkir. Xüsusilə son onillikdə müşahidə olunan rəqəmsal transformasiya valideyn-övlad münasibətlərində əvvəllər rast gəlinməyən "kommunikasiya qopuqluqları" və ya "virtual divarlar" yaratmışdır.

Müasir elmi araşdırmalar göstərir ki, ünsiyyət çatışmazlığı tək tərəfli deyil, çoxfaktorlu bir problemdir. Texnoloji tərəqqi ailə üzvlərinin eyni fiziki məkanda olmasına baxmayaraq, fərqli rəqəmsal dünyalarda yaşamasına gətirib çıxarır. Məsələn, son illərin ən böyük rəqəmsal trendi olan qısa video kontentləri və bu platformalara yaranan asılılıq valideyn-övlad dialoqunu minimuma endirir (Bai X., 2025). Bu cür asılılıqlar uşaqlarda "psixoloji geriçəkilmə" yaradaraq, onların real həyatdakı ünsiyyət ehtiyacını virtual platformalarda axtarmasına səbəb olur (Jang J. Y. və Kim Y. C., 2012).

Problemin digər tərəfi isə valideynlərin tətbiq etdiyi ünsiyyət üslubları ilə bağlıdır. Bir çox hallarda valideynlər övladları üzərində nəzarəti qorumaq üçün "sərt sevgi" kimi tanınan avtoritar kommunikasiya modelinə müraciət edirlər (Faw M. H. və b., 2019). Bu isə övladın valideynə qarşı emosional qapanmasına və nəticədə ailə daxilində ciddi ünsiyyət boşluqlarının yaranmasına yol açır. Bundan əlavə, sosial-mədəni tabular və müəyyən həssas mövzularda açıq danışmaqdan çəkinmə tendensiyası da valideyn-övlad arasındakı məsafəni daha da artırır (Wamoyi J. və b., 2010).

Bu tədqiqatın məqsədi qeyd olunan faktorları analiz edərək, valideynlərlə uşaqlar arasında yaranan ünsiyyət çatışmazlığının kökündə duran əsas səbəbləri üzə çıxarmaq və müasir şəraitdə bu problemlərin elmi əsaslı həll yollarını təklif etməkdir. Ünsiyyət boşluqlarının vaxtında müəyyən edilməməsi uşaqlarda gələcəkdə "sosial geriçəkilmə" kimi ciddi psixoloji problemlərin yaranma riskini artırır (Hamasaki Y. və b., 2022). Bu baxımdan, mövzunun araşdırılması həm akademik psixologiya, həm də praktiki pedaqogika üçün yüksək aktualıq kəsb edir.

## **ƏSAS HİSSƏ:**

### **Ünsiyyət çatışmazlığının rəqəmsal səbəbləri.**

Müasir dövrdə rəqəmsal texnologiyalar ailənin gündəlik həyatına o qədər dərindən nüfuz etmişdir ki, artıq valideyn-övlad münasibətlərini bu amildən kənarında təsəvvür etmək qeyri-mümkündür. Əgər əvvəlki nəsillər üçün ünsiyyət çatışmazlığı əsasən coğrafi məsafələr və ya zaman darlığı ilə izah olunurdusa, hazırda problem "rəqəmsal kölgə" fenomeninə çevrilmişdir. Eyni damın altında yaşayan ailə üzvləri arasında fiziki yaxınlığın olmasına baxmayaraq, hər bir fərdin öz rəqəmsal cihazına qapanması, ailədaxili emosional və intellektual mübadiləni arxa plana keçirir.

Rəqəmsal transformasiyanın gətirdiyi bu yeni realıq, xüsusilə gənc nəslin ünsiyyət vərdişlərini kökündən dəyişdirmişdir. Aparılan tədqiqatlar göstərir ki, texnoloji vasitələr tərəflər arasında sadəcə bir əyləncə vasitəsi deyil, həm də ciddi bir "ünsiyyət baryeri" funksiyasını yerinə yetirir (Bai X., 2025). Bu fəsilə biz rəqəmsal dünyanın yaratdığı asılılıqların, onlayn icmaların uşaq psixologiyasına təsirinin və valideynlərin texnoloji proseslərə adaptasiya dərəcəsinin ailə ünsiyyətində necə qopuqluqlar yaratdığını elmi baxımdan analiz edəcəyik. Xüsusilə vurğulanmalıdır ki, bu qopuqluqlar təsadüfi deyil; onlar çox vaxt uşaqların ailə mühitində tapmadıqları sosial özünə-effektivlik hissini virtual dünyada axtarmalarının bir nəticəsidir (Jang J. Y. və Kim Y. C., 2012). Beləliklə, rəqəmsal faktorları təhlil edərkən onları sadəcə texniki cihazların istifadəsi kimi deyil, ailə daxilindəki emosional boşluqların bir simptomu kimi qiymətləndirmək zəruridir.

Son illərdə TikTok, Instagram Reels və YouTube Shorts kimi platformaların sürətli yüksəlişi, gənclərin informasiya qəbulu vərdişlərini köklü şəkildə transformasiyaya uğratmışdır. Bu platformaların təqdim etdiyi "qısa video" formatı, istifadəçini minimum zaman kəsiyində maksimum emosional stimulla təmin etmək üzərində qurulmuşdur. Lakin bu rəqəmsal yenilik ailə daxili ünsiyyət mexanizmləri üçün ciddi bir təhdidə çevrilmişdir.

Aparılan son tədqiqatlar göstərir ki, qısa video asılılığı ilə valideyn-övlad ünsiyyəti arasında tərs mütənəsiblik mövcuddur (Bai X., 2025). Bu asılılıq "dopamin dövrü" adlanan neyropsixoloji bir prosesi tətikləyir: uşaq hər yeni videoda sürətli həzz alır və bu, real həyatdakı yavaş, ardıcıl və emosional dərinlik tələb edən söhbətləri darıxdırıcı hala gətirir. Nəticədə, valideynin övladı ilə qurmağa çalışdığı dialoq çox vaxt uşağın diqqətini smartfondan ayıra bilməməsi səbəbindən uğursuzluqla nəticələnir. Bai (2025) qeyd edir ki, normal video istifadəsi ünsiyyətə birbaşa mənfə təsir göstərməsə də, bu vərdiş asılılıq səviyyəsinə çatdıqda valideynlərlə aparılan qarşılıqlı interaksiyanın keyfiyyəti kəskin şəkildə aşağı düşür.

Problem təkcə zaman itkisi ilə bitmir; burada "diqqətin parçalanması" faktoru da mühüm rol oynayır. Qısa videoların yaratdığı yüksək stimulyasiya fonunda uşaqlar valideynlərinin nəsihətlərini və ya gündəlik suallarını "fon səs-küyü" kimi qəbul etməyə başlayırlar. Bu vəziyyət valideynlərdə anlaşılamamaq və kənarlaşdırılma hissi yaradır, uşaqlarda isə rəqəmsal dünyaya "emosional qaçış"

ehtiyacını artırır. Beləliklə, qısa video asılılığı ailə üzvləri arasında sadəcə texniki bir maneə deyil, həm də keçilməsi çətin olan psixoloji bir uçurum yaradır. Bu asılılıq uşağın özünüifadə ehtiyacını ailə mühitindən tamamilə virtual mühitə transfer etməsinə şərait yaradır ki, bu da gələcəkdə ailə bağlarının tamamilə qırılması riskini daşıyır.

Rəqəmsal dünyanın ailə daxili ünsiyyətə təsiri təkcə texniki asılılıqla məhdudlaşmır; bu proses həm də dərin psixoloji ehtiyacların virtual məkana transfer olunması ilə xarakterizə olunur. Bir çox hallarda uşaqlar və yeniyetmələr valideynləri ilə qura bilmədikləri emosional bağı və tapa bilmədikləri "anlaşıma" hissini onlayn icmalarda axtarırlar. Bu vəziyyət elmi ədəbiyyatda internetin bir "virtual sığınacaq" funksiyası daşması kimi qiymətləndirilir.

Aparılan tədqiqatlar göstərir ki, valideyn-övlad ünsiyyətinin keyfiyyəti uşağın onlayn icmalardakı davranış modelinə birbaşa təsir edir (Jang J. Y. və Kim Y. C., 2012). Əgər ailə daxilində ünsiyyət birtərəfli, avtoritar və ya emosional cəhətdən soyuqdursa, uşaq öz "sosial özünə-effektivlik" hissini internet üzərindəki anonim və ya yarı-anonim qruplarda bərpa etməyə çalışır. Yəni, real həyatda özünü ifadə etməkdə çətinlik çəkən, valideyni tərəfindən dinlənilmədiyini hiss edən fərd, onlayn platformalarda daha aktiv, daha cəsarətli və daha interaktiv olur. Lakin bu "virtual cəsarət" ailə daxilindəki ünsiyyət boşluğunu daha da dərinləşdirir; çünki uşaq artıq öz problemlərini və sevincini ailəsi ilə deyil, rəqəmsal dünyadakı "yadlarla" bölüşməyə üstünlük verir.

Bundan əlavə, internet üzərində qurulan interaktiv kommunikasiya uşaqda ailədən müstəqil bir "alternativ şəxsiyyət" formalaşdırır. Bu alternativ dünya valideynlər üçün tamamilə qapalı qaldıqda, tərəflər arasında "məlumat asimetriyası" yaranır. Valideyn övladının daxili dünyasından, maraqlarından və narahatlıqlarından xəbərsiz qalır ki, bu da bir müddət sonra uşağın ailə mühitindən tamamilə emosional təcrid olunmasına və yalnız onlayn mühitdə özünü "evdəki kimi" hiss etməsinə gətirib çıxarır. Beləliklə, onlayn icmalar sadəcə bir ünsiyyət vasitəsi deyil, ailə daxilindəki ünsiyyət qıtlığını kompensasiya edən, lakin eyni zamanda ailə bağlarını zəiflədən rəqəmsal bir maneəyə çevrilir.

Rəqəmsal texnologiyalar ailə daxilinə daxil olduqca, valideynlərin bu vasitələrdən istifadə bacarığı və yanaşma tərzii ünsiyyətin keyfiyyətini müəyyən edən əsas amillərdən birinə çevrilir. Problem ondadır ki, əksər hallarda uşaqlar "rəqəmsal yerli" olduqları halda, valideynlər bu dünyaya sonradan daxil olan "rəqəmsal mühacirlər" rolundadırlar. Bu fərq tərəflər arasında həm texniki, həm də emosional bir uçurum yaradır.

Aparılan tədqiqatlar göstərir ki, valideynlərin İKT (İnformasiya-Kommunikasiya Texnologiyaları) vasitələrindən istifadə forması uşağın yaşına görə ciddi şəkildə dəyişir (Rudi J. və b., 2015). Məsələn, kiçik yaşlı uşaqların valideynləri texnologiyadan daha çox öyrədici və ya birgə əyləncə vasitəsi kimi istifadə etdikləri halda (Tarasuik J. və Kaufman J., 2017), uşaq böyüdükcə bu vasitələr nəzarət və ya sadəcə qısa məlumat mübadiləsi (məsələn, "hardasan?", "nə vaxt gəlirsən?") alətinə çevrilir. Bu keçid ailə daxili emosional dialoqun "texniki mesajlaşma" ilə əvəzlənməsinə səbəb olur ki, bu da uşaqda valideynin onun daxili dünyası ilə deyil, yalnız zahiri hərəkətləri ilə maraqlandığı təəssüratını yaradır.

Bundan başqa, valideynlərin texnoloji savadlılığının aşağı olması və ya uşağın onlayn fəaliyyətlərinə "boş vaxt itkisi" kimi baxması ciddi bir "anlaşılmazlıq baryeri" formalaşdırır. Valideyn övladının rəqəmsal maraqlarını ciddiyyə almadıqda, uşaq özünü dəyərsiz hiss edir və emosional qapanma yaşayır. Bu disbalans tərəflər arasında ortağ mövzuların tükənməsinə və nəticədə ünsiyyətin yalnız zəruri məişət məsələləri ilə məhdudlaşmasına gətirib çıxarır. Beləliklə, valideynlərin rəqəmsal dünyaya adaptasiya ola bilməməsi, onları övladlarının reallığından uzaqlaşdıran əsas faktorlardan biri kimi çıxış edir.

### **Ünsiyyət çatışmazlığının psixoloji və davranışsal bariyerləri.**

Valideyn-övlad münasibətlərində ünsiyyət qopuqluğu sadəcə texnoloji vasitələrin müdaxiləsi ilə bitmir; bu problemin kökündə həm də dərin psixoloji konstruktlar və nəsillər arası davranış fərqlilikləri dayanır. Əgər rəqəmsal faktorlar ünsiyyəti "zahiri" tərəfdən məhdudlaşdırırsa,

psixoloji baryerlər bu ünsiyyətin "daxili" keyfiyyətini və emosional dərinliyini zədələyir. Ailə daxili iyerarxiya, valideynlik üslubları və fərdlərin emosional ehtiyaclarının qarşılammaması tərəflər arasında "psixoloji məsafə" yaradır ki, bu da çox vaxt rəqəmsal asılılıqdan daha ağır nəticələrə yol açır.

Bu fəsilə biz ünsiyyət çatışmazlığını tetikleyen fundamental psixoloji faktorları analiz edəcəyik. Tədqiqatlar göstərir ki, valideynlərin övladları ilə qurduğu kommunikasiyanın tonu və forması uşağın özünüifadə cəsarətinə birbaşa təsir edir. Xüsusilə "sərt sevgi" kimi tanınan, intizamı emosional dəstəkdən üstün tutan yanaşmalar övladlarda valideynə qarşı "emosional qapanma" yaradır (Faw M. H. və b., 2019). Bundan əlavə, ailə daxilində bəzi mövzuların tabulaşdırılması və ya "ayıb" hesab edilərək müzakirədən kənar tutulması, uşaqları öz daxili dünyalarını gizlətməyə sövq edir (Wamoyi J. və b., 2010).

Psixoloji baryerlərin ən ekstremal nəticələrindən biri də fərdin cəmiyyətdən və ailədən tamamilə təcrid olunması — "hikikomori" fenomenidir. Ailə daxilində effektiv kommunikasiya kanallarının bağlanması uşağda "anlaşılmama" qorxusunu xroniki hala gətirir və onu öz virtual sığınacağına həbs edir (Hamasaki Y. və b., 2022). Beləliklə, bu fəsil çərçivəsində valideynlik modellərinin, sosial-mədəni tabuların və emosional baryerlərin ünsiyyət boşluqlarını necə qidalandırdığını elmi prizmadan təhlil edərək, problemin psixoloji arxitekturasını ortaya qoyacağıq.

Valideyn-övlad ünsiyyətində ən böyük psixoloji bariyerlərdən biri ailə daxili intizamın qurulma formasıdır. Bir çox valideynlər övladlarını gələcək həyatın çətinliklərinə hazırlamaq, onlarda məsuliyyət hissini artırmaq məqsədilə "sərt sevgi" adlanan kommunikasiya modelinə üstünlük verirlər. Bu model daxilində valideyn emosional yaxınlıqdan daha çox qaydalara, sərt intizama və uşağın nailiyyətlərinə fokuslanır. Lakin elmi araşdırmalar göstərir ki, bu cür yanaşma əksər hallarda gözlənilən müsbət nəticəni vermir, əksinə, tərəflər arasında "emosional sarsıntı" və ünsiyyət qopuqluğu yaradır.

Aparılan tədqiqatlar (Faw M. H. və b., 2019) sübut edir ki, valideyn tərəfindən tətbiq olunan həddindən artıq sərt və nəzarətedici ünsiyyət tərzii uşağın valideynə qarşı olan güvən hissini zədələyir. Uşaq öz səhvlərini, uğursuzluqlarını və ya daxili narahatlıqlarını valideyni ilə bölüşmək əvəzinə, "tənqid olunmaqdan" və ya "mühakimə edilməkdən" qorxaraq susmağa üstünlük verir. Bu "məcburi sükut" zaman keçdikcə xroniki xarakter alır və ailə daxilində dialoqun yerini sadəcə əmrlər və hesabatlar tutur. Valideyn elə düşünür ki, o, övladına düzgün yol göstərir, lakin uşaq bu prosesi "başla düşülməmək" və "emosional rədd edilmə" kimi qəbul edir.

Bundan əlavə, avtoritar valideynlik modelində ünsiyyət birtərəfli xarakter daşıyır – yuxarıdan aşağıya doğru. Belə bir mühitdə böyüyən uşaqlar öz fikirlərini müdafiə etmək və ya hissələrini ifadə etmək bacarığından məhrum olurlar. Faw (2019) qeyd edir ki, "sərt sevgi" tətbiq edən valideynlərin övladları gələcəkdə həm ailə daxilində, həm də cəmiyyətdə ünsiyyət qurmaqda çətinlik çəkir, emosional ehtiyaclarını gizlətməyə meyilli olurlar. Beləliklə, intizam naminə qurban verilən emosional yaxınlıq, valideyn və övlad arasında keçilməsi qeyri-mümkün olan bir "psixoloji məsafə" yaradır ki, bu da rəqəmsal asılılıqdan daha dərin və bərpası çətin olan fəsadlara yol açır.

Ailədaxili ünsiyyətin qarşısını alan maneələr tək-cə fərdi psixoloji faktorlarla deyil, həm də cəmiyyətin diktə etdiyi sosial-mədəni normalarla bağlıdır. Bir çox mədəniyyətlərdə, o cümlədən bizim cəmiyyətdə valideyn-övlad dialoqunda müəyyən mövzular "tabu" hesab edilir və bu mövzuların müzakirəsi həm valideyn, həm də övlad üçün bir növ narahatlıq yaradır. Bu vəziyyət elmi dildə "kommunikasiya çətinlikləri" adlandırılrsa da, əslində bu, ailə daxilində "susmaq" mədəniyyətinin kök salmasına səbəb olur.

Tədqiqatlar göstərir ki, xüsusilə gənc yetkinlər və yeniyetmələr öz şəxsi sağlamlıqları, emosional sarsıntıları və ya cinsi inkişaf prosesləri barədə valideynləri ilə danışmaqdan çəkinirlər (Wamoyi J. və b., 2010). Bu çəkinmənin kökündə "ayıb" hesab edilmək, valideyn tərəfindən mühakimə olunmaq və ya tərəflər arasındakı "hörmət" çərçivəsini pozmaq qorxusu dayanır. Wamoyi (2010) qeyd edir ki, valideynlər çox vaxt övladları ilə bu həssas mövzularda necə danışacaqlarını bilmirlər

və ya bu mövzuları "məlumat boşluğu" şəklində saxlamağa üstünlük verirlər. Nəticədə uşaq öz suallarına cavabı ailəsindən deyil, rəqəmsal dünyadan və ya həmyaşıdlarından axtarmalı olur ki, bu da çox vaxt yanlış və zərərli informasiya qəbuluna yol açır.

Bu tabular ailədaxili etibar mühitini zəiflədən əsas amildir. Ünsiyyətdəki "qapalı zonalar" artdıqca, tərəflər arasındakı ümumi dialoq da rəsmi və səthi xarakter almağa başlayır. Uşaq mühüm bir problemi olduqda valideyninə müraciət etmək yerinə, susmağı və ya bu problemi virtual sığınacaqlarda bölüşməyi daha təhlükəsiz hesab edir. Beləliklə, sosial tabular valideyn-övlad arasında sadəcə bir mövzu ətrafında deyil, bütövlükdə emosional yaxınlıq səviyyəsində ciddi çatışmazlıq yaradır. Bu baryerlərin qırılması üçün ailə daxilində açıq kommunikasiya modelinin və qarşılıqlı empatiyanın inkişaf etdirilməsi vacibdir.

Ünsiyyət çatışmazlığının və psixoloji bariyerlərin ən ekstremal və patoloji nəticəsi fərdin həm ailədən, həm də cəmiyyətdən tamamilə təcrid olunmasıdır. Müasir elmi ədəbiyyatda bu fenomen "hikikomori" olaraq adlandırılır. Əvvəllər yalnız müəyyən coğrafiyalar üçün xarakterik hesab edilən bu vəziyyət, artıq rəqəmsal transformasiyanın təsiri ilə qlobal bir problemə çevrilmişdir. Ailə daxilində effektiv kommunikasiya kanallarının tamamilə qapanması uşaqda "anlaşılmama" və "sosial uğursuzluq" qorxusunu xroniki hala gətirərək onu öz fiziki və virtual sığınacağına həbs edir.

Aparılan tədqiqatlar göstərir ki, sosial geriçəkilmə birdən-birə baş vermir; bu, uzunmüddətli ailədaxili yabançılaşmanın kulminasiya nöqtəsidir (Hamasaki Y. və b., 2022). Valideynləri ilə emosional bağları qırılmış, evdə özünü "yad" kimi hiss edən gənclər üçün öz otaqları və rəqəmsal cihazları yeganə təhlükəsiz zona hesab olunur. Bu vəziyyətdə ünsiyyət çatışmazlığı artıq bir "susqunluq" mərhələsindən çıxaraq, tam bir "fiziki və emosional yoxluq" mərhələsinə keçir. Hamasaki (2022) qeyd edir ki, ailə üzvlərinin uşağın bu vəziyyətini "tənbəllik" və ya "sadəcə oyun marağı" kimi qiymətləndirməsi problemi daha da dərinləşdirir və fərdin geri dönüş yollarını bağlayır.

Ailədaxili yabançılaşma prosesində tərəflər bir-birinin həyatından o qədər uzaqlaşırırlar ki, eyni məkanda yaşasalar da, bir-birinin emosional vəziyyətindən xəbərsiz olurlar. Bu, uşağın özünü ailə strukturunun bir hissəsi kimi deyil, sadəcə o evdə yaşayan "kirayənişin" kimi hiss etməsinə gətirib çıxarır. Belə bir mühitdə böyüyən və ya yaşayan fərd üçün virtual dünya real dünyadan daha "gerçək" və daha "mənalı" görünməyə başlayır. Nəticədə, ünsiyyət qopmuşluğu sadəcə bir dialoq problemi olmaqdan çıxıb, fərdin şəxsiyyət bütövlüyünü və sosial həyatını təhdid edən ciddi bir psixoloji böhrana çevrilir.

## NƏTİCƏ:

Ailədaxili ünsiyyət mexanizmlərinin təhlili göstərir ki, biz hazırda bəşəriyyət tarixində misli görünməmiş bir "kommunikasiya paradoksu" dövrünü yaşayırıq. Bir tərəfdən texnoloji vasitələr bizə saniyələr içində dünyanın istənilən nöqtəsi ilə əlaqə qurmaq imkanı verir, digər tərəfdən isə eyni evin içində yaşayan valideyn və övlad arasında keçilməsi çətin olan "sükut divarları" ucaldır. Bu tədqiqatın gedişatında aydın olmuşdur ki, valideyn-övlad ünsiyyətindəki qopmuşluqlar sadəcə texnikanın gətirdiyi bir fəsad deyil, həm də illərdir yığılıb qalan emosional boşluqların rəqəmsal dünyada təzahürüdür.

Rəqəmsal transformasiyanın, xüsusilə də qısa video kontentlərinin (Bai X., 2025) yaratdığı "sürətli həzz" mədəniyyəti, ailə daxilindəki "yavaş və dərin" söhbətləri rəqabətdən kənar qoymuşdur. Uşaqların onlayn icmalara sığınaraq orada özlərinə "virtual ailə" və "alternativ şəxsiyyət" axtarmaları (Jang J. Y. və Kim Y. C., 2012) əslində real həyatdakı emosional aclığın bir göstəricisidir. Lakin problemin kökü təkəcə texnologiyada deyil, həm də valideynlik modellərinin müasir dövrün tələbləri ilə toqquşmasındadır. "Sərt sevgi" yanaşması və sosial-mədəni tabular (Wamoyi J. və b., 2010; Faw M. H. və b., 2019) ünsiyyəti rəsmiləşdirir, övladın daxili dünyasını valideyn üçün "qapalı zonaya" çevirir.

Tədqiqatın ən sarsıdıcı qənaəti budur ki, ünsiyyətsizlik fərdi təcridən "hikikomori" vəziyyətinə və ailə daxilində "kirayənişin" statusuna sürükləyir (Hamasaki Y. və b., 2022). Bu isə sadəcə bir ailənin problemi deyil, gələcəkdə emosional intellekti aşağı olan, sosial təcriddən əziyyət çəkən bir nəslin formalaşması deməkdir.

Bütün bunları nəzərə alaraq, problemin həlli üçün sadəcə texnoloji məhdudiyyətlər kifayət deyil. Əsl həll — valideynlərin "rəqəmsal savadlılığı" ilə yanaşı, "emosional savadlılığının" artırılmasından, ailə daxilində hər bir fərdin özünü dəyərli və anlaşılmış hiss etdiyi "açıq dialoq platformasının" qurulmasından keçir. Ailə daxilində rəqəmsal etika qaydalarının tətbiqi və demokratik ünsiyyət modelinə keçid bu qopuqluqları aradan qaldıran ən effektiv körpüdür. Yekun olaraq vurğulanmalıdır ki, texnologiya bir alətdir, lakin ünsiyyət bir ruhdur; ruhun qorunmadığı yerdə alətlər sadəcə baryerə çevrilir.

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# The role of the excessive social media use in emotional intelligence in adolescents

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**Abstract:** The concept of emotional intelligence is a highly complex phenomenon, and scientists have extensively studied it, developing various approaches, but have yet to reach a consensus (Altunbaş, 2018). Emotional development begins at birth, accelerates particularly in early childhood, and continues throughout a person's life. Emotional intelligence, defined as the ability to understand oneself and also expressed as the ability to understand others (Atkinson RL., Atkinson RC., and Hilgard, 1995), consists of four sub-dimensions. Subjective well-being is defined as an individual's satisfaction with their life, awareness of their potential, recognition of their strengths, and ability to look at life positively. Self-control is defined as an individual's ability to control their emotional states, make decisions in the face of situations encountered in life, and change their decisions when necessary. Emotionality is defined as an individual's ability to distinguish between the emotions and feelings they experience, to show their emotions towards the people around them, and to establish good relationships with them. Sociability refers to the ability to interact with people around you, influence their emotions, defend yourself, and take a stance in conflicts and disputes. It is known that emotions and emotional intelligence are quite important for individuals, and that they are extremely important, especially during adolescence and for developmental characteristics. During this period, adolescents experience physical and emotional development. Along with these changes, they go through a significant process of maturing both sexually and psychosocially, gaining autonomy, identity awareness, and becoming socially productive. Furthermore, for adolescents, this period is a time when, in addition to cognitive development, they develop identity characteristics, demonstrate psychological and social development, and become ready for adulthood (Derman, 2008). Adolescents prefer to act independently and be alone rather than spending time with their families. It is thought that adolescents who distance themselves from their families increase their communication and interaction with their friends, peers, and social environment. It has been observed that adolescents use technological tools and devices for interaction with their social environment and peers. The intensive use of technological tools by adolescents for communication has also brought about a number of uncontrolled use problems. These tools, used uncontrollably by adolescents, have led to problems such as addiction over time. For adolescents who aim to create a new identity and self-image in social media and the virtual world by distancing themselves from their families, self-esteem and emotional intelligence characteristics are influential (Bayraktutan, 2005). In this respect, the study revealed the relationship between internet addiction in adolescents and self-esteem and emotional intelligence.

**Keywords:** social media, emotional intelligence, mental health, youth, awareness

**Introduction:** Individuals experience one of the most challenging and complex periods of their lives during adolescence, and during this time they exhibit many different changes in gender, religion, physical and psychological needs, and consequently, many behavioral characteristics (Çelikkaleli, Gökçalan, and Çapri, 2005). In addition to these behavioral changes, individuals experience developmental problems and a stressful and turbulent period during this time (Dinçel, 2006), after which they integrate into society as adults. Considering this period, which has been

called the individual's second birth, it is emphasized that this period is extremely important in terms of acquiring the necessary developmental needs (Parman, 1998). On the other hand, self-esteem, a two-dimensional element consisting of 'self-love', which is expressed as the individual's ability to define himself subjectively, to see himself as a social being, to value and approve of himself, and 'self-efficacy', which is expressed as the individual's evaluation of himself as active, competent and in control, is also quite important (Taforodi and Swann, 1995).

Following the rapid development in communication technologies, technology has begun to occupy an important place in our daily lives. This situation and the era we are in have come to be called the age of technology. Today, the use of the internet and smartphones, computers and information systems have become indispensable parts of our lives. Technology, which aims to provide people with quick and secure access to information, facilitates communication, and allows them to spend time in entertainment, has reached every individual and every home unpredictably, leading to various problems and pathological issues. Among these problems, technology addiction, internet addiction, and smartphone addiction are prominent, and these problems can cause very serious psychological and sociological problems in individuals (Küçükvardar and Tingöy, 2018).

For this purpose, a study has been conducted to determine the relationship between emotional intelligence, self-esteem, and internet addiction.

With the development and widespread use of technology, societal changes have begun to occur. These societal developments are, of course, related to changes in the family structure. Widespread technology and internet use lead to estrangement among family members and also cause problems in their physiological and psychological development (Bayraktutan, 2005).

**Research question:** Is there any relationship between emotional intelligence and social media and internet addiction?

**Emotional Intelligence:** Defined as the sum of abilities an individual should possess in order to be aware of their own emotions and the emotions of others around them, and to control their emotions by motivating themselves (Goleman, 2000).

**Self-esteem:** Positive and negative perceptions of oneself, and the belief that one is adequate, important, and valuable (Coopersmith, 1967).

**Internet addiction:** Can be defined as the inability to control the urge to overuse the internet, the increasing need for more time spent on the internet, the loss of importance of time spent without the internet, the emergence of extreme irritability, tension, and restlessness when deprived, and the gradual deterioration of the individual's work, social, and family life (Young, 2004).

In modern world, the number of people who spend most of their time in front of computers, cannot sleep without their mobile phones, and experience problems and become ill due to these habits is increasing. The situation these individuals are exposed to is gaming, mobile phone, and internet addiction (Balci, 2012). The following reasons may also contribute to individuals becoming so addicted to technology:

- Uncontrolled and excessive use of technological devices;
- Failure to understand or know the importance of the consequences of the behavior exhibited regarding technology addiction;
- Inability to control curiosity towards technology;
- Being in an environment where addiction is prevalent;
- Boredom resulting from not having much to do;
- Accepting every request from their social environment out of fear of exclusion;
- Turning to Internet Addiction instead of finding solutions to the problems an individual faces or making an effort to solve them;
- Not being aware of one's own potential and not knowing oneself well enough;
- Lack of self-confidence and feeling inadequate in communicating socially;
- Trying to correct failures in daily life through the virtual environment;

- Inability of the individual to control their own impulses;
- Anxiety about being excluded from their social environment or not being liked by them;
- Lack of vision or having a pessimistic personality (Balci, 2012).

Many people cannot find what they are looking for in their daily interpersonal relationships and try to fulfill this need through the internet (Kraut et al., 1998). It is stated that individuals who want to satisfy these unmet needs through the internet and those who cannot achieve the desired satisfaction may experience a severe withdrawal situation (Esen, 2010). When internet addiction is considered from a psychological perspective, individuals exposed to this situation develop an uncontrollable desire to connect to the internet, view the time spent without the internet as unimportant, tend to show anger and irritability when deprived of the internet, and continue excessive internet use despite a progressively worsening of their social life (Ülgen, 2014). Withdrawal symptoms such as irritability, loss of willpower or a tendency to overuse willpower, easy anger, isolation from life, and resorting to quick lies can be observed in individuals addicted to any substance (Alaçam, 2012).

Emotional intelligence is the ability of an individual to perceive, recognize, direct, and manage their own emotions and the emotions of others around them (Acar, 2001).

From an individual perspective, emotional intelligence is a type of intelligence that mediates in individuals achieving their desired goals, obtaining life satisfaction, developing problem-solving skills, managing their mental and physical potential, managing reciprocal social relationships, having a vision, making conscious choices, and reflecting their life energy constructively and positively into their lives (Erdoğan, 2008). Furthermore, it is observed that the internet, which has encompassed every aspect of our lives, has facilitated, diversified, and improved our lives. However, excessive internet use has been evaluated as an addiction based on diagnostic criteria such as causing constant mental preoccupation in the individual, inability to make plans according to the time available, and, when usage continues at an increasing level, the individual cannot control it, experiences withdrawal symptoms, their effectiveness is impaired, and they may see it as a place where they can escape from the problems they face or may face (Young and Rodgers, 1998).

In the study, the relationships between adolescents' self-esteem, emotional intelligence and its sub-dimensions, and internet addiction was examined. It was found that adolescents' self-esteem has a significant positive correlation with emotional intelligence and all its sub-dimensions, and a significant negative correlation with internet addiction. Based on this, it can be mentioned that as adolescents' self-esteem increases, their levels of emotional intelligence and its sub-dimensions—well-being, self-control, emotionality, sociability, and internet addiction—will also increase; however, as adolescents' internet addiction increases, their self-esteem, emotional intelligence, and its sub-dimensions—self-control, emotionality, sociability, and well-being—will decrease. It is believed that this situation stems from the increase in adolescents' self-esteem, their ability to understand life better, their better understanding of themselves and their surroundings, and their ability to put themselves in the place of others, thus increasing their emotional intelligence. Otherwise, internet addiction can lead to an inability to better understand themselves and the people around them, and consequently, the level of internet addiction among adolescents may increase.

**Recommendation:** In order for emotional intelligence to be integrated into education, educators also need to be trained. It is considered beneficial for teachers and administrators to also undergo this training. It is thought that providing necessary guidance to students in the risk group, especially adolescents, through preventive measures within the triangle of individual, school, and family would be beneficial. While technology and internet use bring convenience to people's lives, they can also lead to isolation, especially for children and adolescents in their developmental stages, as they prepare them for social life. For this reason, it is considered beneficial to hold

conferences by expert psychologists and scientists, including student parents, to raise awareness of the negative consequences that the internet can bring.

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## **Sociological Sciences**

# SOCIOLOGY OF DISNEY , AND SOCIOLOGY OF GENDER : NEW MODELS OF YOUNG FEMININITIES , AND YOUNG MASCULINITIES IN DISNEY MOVIES, IN RELATION TO ANIMATED DISNEY ANIMALS

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### Abstract

"Contemporary research on girlhood has shown that there are different ways of being a girl. There are multiple ways of living femininity and identifying with femininity" (Kehily 2007: 35). Postfeminist masculinities, accordingly, are developing inside the feminist idea of gender roles division, and become a progressive, and new Disney model of masculinities( Macaluso 2018:1-4). Young Femininity in Disney animated movies, are influenced by waves of feminism, there are differences between the roles of Disney's female characters, from the 1937s onwards, compared to its contemporary heroines (Merida, Mulan, Moana). The idea of femininity as Disney's transfixion into feminism, in the era of post-feminism, influences gender equality to become representative in the media. Sociology of Disney, as one of the new sub disciplines in sociology, with Sociology of Disney animated movies, Sociology of Disney parks, with the Disneyization of Sociology, is useful strategy of analysis the gender role, and the socialisation, with the Animal Sociology analysis of animated Disney animals, for the Sociology of gender classes.

Key terms: Sociology of Disney, Sociology of Gender, Animal Sociology, Disney's models of masculinities, Disney Princesses, Disney Animalities/Disney Animated Animals, Femina Cartoonica

### INTRODUCTION

Young femininities and masculinity :Disneyfication, as a sociological concept, investigates the influence of Walt Disney Company products, on the environment, and identities. Developing the professional Disney princesses, and heroines, and princes/heroes, influenced celebration of their brand, in the Disney Parks, worldwide. Sociology of Food( Mušić, 2025) and the food production, from the multicultural standpoint , in opening the restaurants, in the Disney parks, that offer the multinational food variety, that Disney animated characters eat, influenced the advancement of the interdisciplinary of research in the field. Postfeminist masculinities, accordingly, are developing inside the feminist idea of gender roles division, and become a progressive, and new Disney model of masculinities( Macaluso 2018:1-4), and

"Contemporary research on girlhood has shown that there are different ways of being a girl. There are multiple ways of living femininity and identifying with femininity" (Kehily 2007: 35).

Sociology of Animals/Animal Sociology (Mušić, 2025) as a sub discipline of sociology, has been founded in 1970-ties. Disney imaginary involves plurality of nationality, and variety of animal species found all over the world. Early and new animated Disney princess involve appearances of animalities, or transformation human-animal, ranging from crocodiles, dragons, lions, sharks, to small, and domestic animals. Animals are especially celebrated animation inside the songs, in the Disney animated movies. Dragons, and crocodiles are present inside the animated Disney movies, in all of the evolution of the princesses periods, from Maleficent, Tarzan and Jane, Frog princess, to Mulan, and Raja.

### EMPIRICAL RESEARCH

Empirical Research on Disney new masculinity and femininities vs. an old ones, was conducted during the May, 2025, Summer Semester, at Faculty of Political Sciences, inside the Sociology of Gender I classes, at the Department of Sociology, at Sarajevo University, Faculty of Political Sciences Sarajevo, with the discussion of the questions.

Question 1. Feminism, and Disney

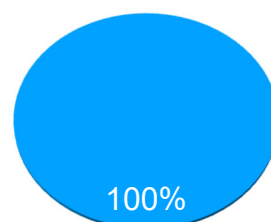
Do Disney's animated young femininity promote an emancipated feminist model of femininity?  
YES NO

All of the students, 100%, responded positively, Disney's animated young femininity promote an emancipated feminist model of femininity.

Question 2. Masculinities and Disney: new masculinities

Do Disney's animated young masculinity promote an emancipated masculine model?  
A) YES B) NO

**Do Disney's animated young masculinity promote an emancipated masculine model?**



Graph 1. Do Disney's animated young masculinity promote an emancipated masculine model?

Question 3. Disney and Animality

On the questions about the depiction of the animality inside the new Disney princesses, and the reappearance of the same animality, the students did not show more interest, than onto the young femininities, and masculinities. Students of both genders, showed the highest interest into

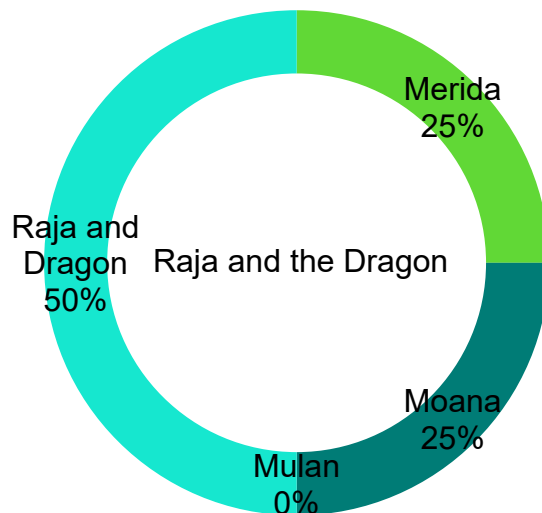
answering the questions, exclusively about young Disney animated princesses. ( Photo 1. Disney, Zootropola, <https://share.google/7ecNNq2hgoAL9Cbr0>)



Question 4. Which Disney young femininity, in your opinion, best portrays young femininity of the modern era?

Graph 2. The best portrayal of the new young femininities

The best portrayal of the new young femininities, for the 50% of the students, is formed in the Raja.



### CONCLUSION

The research results, on the theme of new/old animated Disney, displayed that there is extremely higher interest in the animated princesses, characters occupations and roles, than in the Disney animated masculinities. The opinions on the importance of the new Disney animated princess is that 100% of students confirmed that Disney's animated young femininities, and Disney animated masculinities, do promote an emancipated feminist model of femininity, and emancipated model of masculinities. Feminism, Femina Cartoonica(2021, 2024) and empowering of the women, and girls, with the emphasis on the evolution, of gender role of women, in creating new Disney young femininities, with the new professional occupation, and breaking the obstacles of discrimination, inside the occupation, traditional, entitled as male only occupations.

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# Бизнес-коучинг как эффективный инструмент развития сотрудников в компаниях Казахстана: сравнительный анализ, доверие и институциональная динамика

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## Аннотация

В условиях макроэкономической турбулентности и перехода к экономике знаний человеческий капитал становится ключевым фактором конкурентоспособности компаний. В статье на основе теоретического обзора и вторичного анализа международных данных рассматривается бизнес-коучинг как стратегический инструмент управления персоналом на предприятиях Республики Казахстан. Методология включает наукометрический анализ публикационной активности по базе Scopus (сравнение глобальной и казахстанской исследовательских повесток), систематизацию международных отчётов о возврате инвестиций в коучинг (International Coaching Federation, McGovern et al., MetrixGlobal) и анализ институциональной специфики казахстанского рынка. Сформулирована и операционализирована концепция «гибридного доверия», объединяющая институциональный и межличностный уровни. Показано, что прямое заимствование западных коучинговых моделей в условиях постсоветской «презумпции недоверия» неэффективно, а успешная имплементация требует развития внутренних менеджеров-коучей, микро-форматов взаимодействия и интеграции цифровых HR-инструментов. Статья носит обзорно-аналитический характер и закладывает теоретическую рамку для последующих эмпирических исследований казахстанского рынка.

**Ключевые слова:** бизнес-коучинг, управление персоналом, сравнительный анализ, гибридное доверие, ROI коучинга, soft skills, малый и средний бизнес, Республика Казахстан, цифровизация HR, BANI-среда.

## 1. Введение и макроэкономический контекст

Современная глобальная экономика характеризуется беспрецедентной нестабильностью и турбулентностью, описываемой концепцией BANI-мира (Brittle, Anxious, Non-linear, Incomprehensible), пришедшей на смену модели VUCA (Cascio, 2020). Эта среда требует от компаний быстрой адаптации и стратегической гибкости. Традиционные директивные методы управления, основанные на жёстком контроле, приводят к снижению вовлечённости работников, ограничению их креативности и инициативности, что негативно влияет на общую конкурентоспособность бизнеса (Whitmore, 2017). Сегодня на первый план выходят «мягкие» навыки (soft skills) — критическое мышление, эмоциональный интеллект (EQ), способность к самонаправленному обучению и адаптации (World Economic Forum, 2023).

Для Республики Казахстан эти глобальные тенденции накладываются на процессы экономической трансформации и последствия пандемии COVID-19. По данным Всемирного

банка, в 2020 году реальный ВВП страны сократился на 2,5% — это самое глубокое падение со времён мирового финансового кризиса 2008–2009 годов (World Bank, 2020). Кризис привёл к высвобождению рабочей силы и пересмотру стратегий управления персоналом. Для преодоления его последствий государство сделало стратегическую ставку на малый и средний бизнес (МСБ): по данным Бюро национальной статистики, на сферу МСП приходится 43,6% экономически активного населения страны, а доля МСП в ВВП по итогам 2022 года составила 36,5% (Бюро национальной статистики АСПР РК, 2023). Реализуются государственные программы поддержки предпринимательства («Дорожная карта бизнеса», «Енбек», «Экономика простых вещей»).

В этих условиях бизнес-коучинг становится стратегическим демпфером: он позволяет компаниям раскрывать внутренний потенциал сотрудников, снижать стресс и формировать адаптивную корпоративную культуру без значительных инвестиций в традиционные формы обучения (International Coaching Federation, 2025).

## 2. Обзор литературы и теоретическая база коучинга

### 2.1. Эволюция концепции

Истоки современного бизнес-коучинга восходят к работам Т. Голви, опубликовавшего в 1974 году книгу *The Inner Game of Tennis*, в которой главным препятствием для достижения высоких результатов был назван «внутренний соперник» в сознании человека (Gallwey, 1974). С середины 1970-х годов методология начала применяться в корпоративном контексте, а её формализация в управленческую парадигму связана с трудами Дж. Уитмора, разработавшего модель GROW в книге *Coaching for Performance* (1992), и М. Дауни, развивавшего философию партнёрского взаимодействия (Whitmore, 2017; Downey, 2003).

В академической литературе проводится чёткая демаркация коучинга от смежных дисциплин. В отличие от наставничества, где более опытный сотрудник передаёт готовые знания, коучинг направлен на самостоятельный поиск решений работником и не требует от коуча экспертности в профессиональной области клиента (International Coaching Federation, 2021). Теоретически эффективный коучинг опирается на три уникальных компонента: синергию (формирование партнёрской команды между коучем и клиентом, фокусирующейся на целях клиента); структуру (обеспечение масштабирования целей и принятия ответственности сотрудником); профессионализм и экспертность (применение специальных техник для достижения максимума продуктивности).

### 2.2. Доверие как фундамент коучинговой среды: концепция «гибридного доверия»

Категория доверия выступает фундаментальной основой коучинговой среды. Западная управленческая традиция, опирающаяся на работы Mayer, Davis и Schoorman (1995), рассматривает доверие через призму уязвимости, риска и калькулятивного расчёта: доверитель сознательно принимает риск исходя из оценки благожелательности, компетентности и добросовестности другой стороны. В отечественной научной школе (Купрейченко, 2008; Шихирев, 2003) доверие концептуализируется иначе — как проактивная ценностно-ориентированная установка, предполагающая оптимистичный сценарий взаимодействия.

Для целей настоящего исследования предлагается синтетическая концепция гибридного доверия, объединяющая два уровня. Институциональный уровень — это доверие сотрудника к организации как системе: к процедурам найма и оценки, к политикам конфиденциальности, к декларируемым ценностям; он операционализируется через индикаторы организационной справедливости (procedural и distributive justice), уровень текучести кадров и индекс eNPS. Межличностный уровень — это доверие к непосредственному руководителю и коучу; он операционализируется через индикаторы психологической безопасности команды (Edmondson, 1999), готовность сотрудника поднимать «трудные» темы и частоту запросов на обратную связь.

Гибридный характер доверия означает, что разрушение одного уровня не компенсируется устойчивостью другого: даже при высоком доверии к коучу программа окажется неэффективной, если сотрудник не доверяет институциональным гарантиям конфиденциальности. И наоборот — формальные процедуры без межличностной безопасности воспринимаются как бюрократический ритуал. Таким образом, доверие выступает «клеем», связывающим стратегический и операционный уровни управления.

### 2.3. Этические основы безопасной коучинговой среды

Поддержание гибридного доверия требует соблюдения чётких этических норм. В Таблице 1 систематизированы базовые критерии, выводимые из Этического кодекса Международной федерации коучинга и применимые к корпоративному контексту (International Coaching Federation, 2021).

Таблица 1 — Базовые этические критерии формирования безопасной коучинговой среды

Критерий	Характеристика	Пример практического применения
Конфиденциальность	Обеспечение полной приватности информации, обсуждаемой в ходе сессий	Коуч не разглашает детали обсуждений руководству без прямого письменного разрешения клиента; используется обезличенная агрегированная отчётность
Уважение к личности	Признание индивидуальных ценностей, убеждений и личностных качеств клиента	Отсутствие навязывания коучем собственных директивных взглядов и готовых решений; безоценочность восприятия
Информированное согласие	Прозрачность целей, методов и границ программы для всех сторон	Письменное соглашение, фиксирующее формат сессий, объём отчётности перед организацией и условия выхода из программы
Профессиональные границы	Чёткое разделение коучинга, психотерапии, менторинга и линейного управления	Коуч не выполняет функции непосредственного руководителя клиента и не оценивает его работу для целей KPI
Отсутствие конфликта интересов	Прозрачность всех ролей и обязательств коуча перед организацией и клиентом	Раскрытие финансовых, родственных или иерархических связей до начала программы
Ответственность за результат	Совместная ответственность коуча и клиента за процесс при сохранении автономии клиента в выборе решений	Регулярный пересмотр целей и формата работы; возможность прекращения программы по инициативе любой стороны

Примечание. Составлено автором на основе ICF Code of Ethics (International Coaching Federation, 2021).

### 3. Сравнительный анализ: глобальный опыт vs. локальные реалии

#### 3.1. Методология наукометрического анализа

Для понимания специфики научного дискурса о коучинге в Казахстане проведён сравнительный наукометрический анализ. Источник данных — реферативная база Scopus. Поиск: *TITLE-ABS-KEY ("business coaching" OR "executive coaching" OR "managerial coaching") AND SUBJAREA ("BUSI" OR "ECON" OR "SOCI")*, временной охват — 2015–2024 гг. Глобальная выборка включает 1 247 публикаций; казахстанская выборка (фильтр *AFFILCOUNTRY: Kazakhstan*) — 84 публикации. Классификация по целям исследования и методам проведена в соответствии с типологией Tranfield, Denyer и Smart (2003); кодирование выполнено двумя независимыми экспертами с последующим согласованием расхождений. Результаты представлены в Таблицах 2 и 3. Следует подчеркнуть ограниченность выборки по Казахстану (N = 84), что не позволяет делать строгих статистических обобщений, однако обозначает устойчивые тренды.

Таблица 2 — Сравнительный анализ целей экономических исследований

Цель исследования	Глобальные исследования, %	Исследования в Казахстане, %
Анализ потенциала определённой сферы / отрасли	95	84
Анализ экономического потенциала страны (макроуровень)	2	15
Анализ конкретного экономического показателя	3	1

Примечание. Расчёты автора по данным Scopus (выборка 2015–2024 гг.).

Как видно из Таблицы 2, в Казахстане значительно выше фокус на решении макроэкономических локальных задач (15% против 2% в мире). Это отражает повестку догоняющего развития, в которой исследователи стремятся обосновать макроэффекты управленческих практик для государственных программ.

Таблица 3 — Сравнительный анализ методов, применяемых в бизнес-исследованиях

Метод исследования	Глобальные исследования, %	Исследования в Казахстане, %
Синтез исследований (research synthesis)	33	12
Статистическое моделирование	20	15
Опросы (survey)	14	14
Описательная статистика	1	23
Комбинация описательной статистики и моделирования	1	11
Метод кейс-стади	8	10
Библиометрический анализ	7	1

Примечание. Расчёты автора по данным Scopus (выборка 2015–2024 гг.).

#### 3.2. Интерпретация

Данные Таблицы 3 свидетельствуют о том, что казахстанская исследовательская среда находится на этапе локализации знаний: преобладает описательная статистика (23% против 1% в глобальной выборке), при заметном отставании по синтезу исследований и библиометрии. Это означает, что отечественные компании нуждаются не в прямом

копировании абстрактных западных коучинговых моделей, а в их социокультурной адаптации под специфику локального рынка. Одновременно это указывает и на исследовательский разрыв: концептуальные и методологические рамки коучинга в Казахстане формируются преимущественно на эмпирическом, а не на теоретическом уровне.

#### **4. Эмпирические свидетельства эффективности и институциональные барьеры**

##### *4.1. Глобальные данные об эффективности коучинга*

Экономическая эффективность коучинга на международном уровне подтверждена несколькими ключевыми исследованиями. Согласно ICF Global Coaching Client Study, 86% организаций, отслеживавших возврат инвестиций, отчитались о как минимум полном возмещении вложений, а медианный ROI составил 7-кратное превышение затрат (International Coaching Federation & PricewaterhouseCoopers, 2009). Кейс-стади MetrixGlobal LLC показало 788% ROI программы коучинга в компании из Fortune 500 за счёт роста производительности и удовлетворённости сотрудников (Anderson, 2001). В исследовании McGovern et al. (2001), охватившем 100 руководителей из 56 организаций, консервативный ROI составил 5,7-кратное превышение вложений.

Передовые корпорации сделали коучинг частью бизнес-модели. В Google действует программа равноправного коучинга G2G (Googler-to-Googler), охватывающая более 6 000 внутренних коучей; по данным внутреннего опроса, 99% участников отметили рост уверенности после одной сессии, а 96% коучей сообщили о развитии собственных лидерских навыков (Google re:Work, 2021). В Microsoft при Сатье Наделле организационная культура была переориентирована с фиксированного мышления на growth mindset, а коучинговый стиль управления стал ключевым элементом программы развития менеджеров (Goldsmith & Reiter, 2020). General Electric исторически использовала коучинг как часть программ executive development в рамках Crotonville Leadership Institute.

В Таблице 4 систематизированы количественные эффекты коучинга на тангибельные и интангибельные показатели по данным исследования McGovern et al. (2001) — одного из наиболее цитируемых эмпирических источников в этой области.

Таблица 4 — Эффекты коучинга на организационные показатели (доля участников, сообщивших об эффекте)

Показатель	Доля участников, %	Характеристика эффекта
Производительность труда	53	Тангибельный: рост отдачи от рабочего времени
Качество продукта / услуги	48	Тангибельный: улучшение результата на выходе
Организационная устойчивость	48	Тангибельный: способность команды справляться с нагрузкой
Качество клиентского сервиса	39	Тангибельный: рост удовлетворённости клиентов
Снижение жалоб клиентов	34	Тангибельный
Прибыль (bottom-line profitability)	22	Тангибельный: прямой финансовый результат
Отношения с подчинёнными	77	Интангибельный: партнёрский стиль управления
Отношения со стейкхолдерами	71	Интангибельный: улучшение вертикальной коммуникации
Командная работа	67	Интангибельный
Отношения с коллегами	63	Интангибельный: горизонтальная коммуникация
Удовлетворённость работой	61	Интангибельный
Снижение конфликтности	52	Интангибельный

Примечание. Адаптировано из McGovern et al. (2001).

Следует подчеркнуть, что приведённые показатели — это частота возникновения эффекта среди участников выборки, а не средний прирост соответствующего показателя. Такая дистинкция критична для корректной интерпретации: широко цитируемая в HR-литературе формулировка «коучинг повышает производительность на 53%» является некорректной редукцией исходных данных.

#### 4.2. Институциональные барьеры в Казахстане

Несмотря на доказанную мировую эффективность, системная интеграция коучинга в Казахстане сталкивается со специфическими барьерами. Постсоветская «презумпция недоверия» означает, что деловые отношения в значительной части постсоветского пространства строятся на ожидании оппортунистического поведения контрагента (Гудков, 2012): без формирования психологической безопасности коучинг воспринимается как скрытая форма надзора со стороны руководства. Переход на гибридные форматы работы и обезличивание сторон в цифровой коммуникации дополнительно снижают качество межличностного доверия — особенно в малом и среднем бизнесе, где отсутствуют формализованные HR-процессы. На казахстанском рынке преобладают внешние коучи-фрилансеры, а программы развития внутренних менеджеров-коучей в МСБ практически отсутствуют. Наконец, стоимостный барьер: цена международных программ executive coaching несоразмерна бюджетам казахстанских МСБ, что требует разработки бюджетных гибридных и цифровых форматов.

## 5. Практическая реализация: модели и цифровизация коучинга

### 5.1. Архитектура управленческого коучинга

Для преодоления выявленных барьеров казахстанским предприятиям предлагается использовать комплексную пятиэтапную архитектуру управленческого коучинга: (1) установление целей и ожидаемых результатов; (2) анализ текущей ситуации; (3) разработка плана действий и определение ресурсов; (4) поддержка и обратная связь; (5) анализ результатов, обучение и коррекция. На каждом этапе применяются специализированные модели, краткое описание которых приведено далее.

Модель *GROW* (Goal — Reality — Options — Will) — базовая модель структурирования коучинговой сессии, разработанная Дж. Уитмором (Whitmore, 2017). Применяется на этапах 1–3. Сильная сторона — простота и универсальность; ограничение — линейность и слабая работа с глубинными убеждениями. Формат *SMART* (Specific, Measurable, Achievable, Relevant, Time-bound) используется для постановки целей (Doran, 1981) и дополняет *GROW* на первом этапе. Модель *FUEL* (Frame — Understand — Explore — Layout), разработанная Zenger и Stinnett (2010), в отличие от *GROW* фокусируется на поведенческих изменениях и переосмыслении убеждений; применима на этапах 2–3. Модель *CLEAR* (Contract — Listen — Explore — Action — Review) П. Хокинса (середина 1980-х) включает явные этапы контрактации и финального ревью (Hawkins, 2012) и подходит для долгосрочных программ — этапы 1, 4, 5. Техника *SBI* (Situation — Behavior — Impact), разработанная Center for Creative Leadership (Weitzel, 2000), применяется на этапе 4 для предоставления конкретной, безоценочной обратной связи.

Матрица выбора: для разовых сессий и быстрой постановки целей — *GROW + SMART*; для работы с поведенческими паттернами — *FUEL*; для долгосрочных executive-программ — *CLEAR*; для оперативной обратной связи — *SBI*.

### 5.2. Цифровизация и «коучинг в моменте»

Стратегическим вектором оптимизации расходов является интеграция цифровых технологий. Искусственный интеллект используется для выявления поведенческих паттернов и микро-обратной связи, а виртуальные ассистенты и Telegram-боты помогают закреплять инсайты между сессиями и удерживать фокус на целях. Эмпирически показано, что цифровые форматы коучинга по эффективности сопоставимы с очными для большинства задач развития менеджеров среднего звена (Passmore & Tee, 2023).

Для линейного персонала особенно подходит метод «коучинга в моменте» (coaching in the moment), концептуально оформленный в работе М. Бунгая Станье *The Coaching Habit* (Bungay Stanier, 2016). Метод предполагает короткие (1–3 минуты) интервенции руководителя, в которых вместо готового решения задаётся открытый вопрос, стимулирующий размышление сотрудника: «Что для тебя сейчас главный вызов?», «А что ещё?», «Что ты пробовал?». Метод не требует специальной сертификации, легко встраивается в операционные ритуалы (one-to-one, daily, ретроспективы) и снижает порог входа в коучинговую культуру для МСБ.

## 6. Заключение

Бизнес-коучинг представляет собой высокоэффективную парадигму управления, трансформирующую человеческий капитал в экономическое преимущество. Анализ международной эмпирической базы показал, что медианный ROI коучинговых программ составляет 5–7-кратное превышение вложений (International Coaching Federation & PricewaterhouseCoopers, 2009), а интангибельные эффекты — улучшение отношений с подчинёнными (77%) и снижение конфликтности (52%) — фиксируются у большинства участников программ (McGovern et al., 2001).

Сравнительный наукометрический анализ выявил, что казахстанский научный и практический дискурс находится на этапе локализации: преобладает описательная

статистика и макроэкономический фокус, тогда как методологическая зрелость синтеза и библиометрии существенно отстаёт от глобальной. Это означает, что простое заимствование западных моделей неэффективно — требуется их адаптация к социокультурной специфике.

Ключевым теоретическим вкладом настоящей работы является концепция гибридного доверия, объединяющая институциональный и межличностный уровни и объясняющая, почему в постсоветской «презумпции недоверия» программы коучинга часто не достигают декларируемых эффектов. Практические рекомендации для казахстанских компаний включают: развитие института внутренних менеджеров-коучей (по модели Google G2G), что снижает стоимостный барьер и одновременно укрепляет институциональный уровень доверия; внедрение микро-форматов — «коучинга в моменте» и коротких цифровых сессий — для линейного персонала; интеграцию ИИ-инструментов и мессенджер-ботов для поддержания фокуса между сессиями; документирование этических процедур (конфиденциальность, информированное согласие) как условия формирования институционального доверия.

*Ограничения исследования.* Работа носит обзорно-аналитический характер и опирается на вторичные данные. Для верификации концепции гибридного доверия и оценки специфики казахстанского рынка необходимо последующее эмпирическое исследование — экспертные интервью с HR-директорами МСБ и пилотные программы внутреннего коучинга с измерением эффектов до/после.

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## Historical Sciences

# Teaching Turkic Peoples' History in the Post-Soviet Era: An Analytical Examination of Transformations from the 1990s to the Present

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**Annotation:** The dissolution of the Soviet Union in 1991 marked a series of significant developments in the history of the Turkic peoples. The restoration of state independence led to profound transformations in many spheres of public and political life, including the field of education. One of the most notable changes was the introduction of “History of the Turkic Peoples” as an academic discipline. In this regard, 1991 may be regarded not only as the year of the restoration of state independence but also as the starting point for the reconstruction of the historical memory of the Turkic peoples.

Although the initial years of teaching the History of the Turkic Peoples were accompanied by a number of challenges, instructors of the subject, in cooperation with scholars and researchers in the field, succeeded in carrying out important initiatives aimed at its development. Nevertheless, despite the progress achieved, a number of shortcomings and unresolved issues continue to persist even today.

Against this background, the present article examines the current state of teaching the History of the Turkic Peoples through the framework of SWOT analysis. It analyzes the strengths, weaknesses, opportunities, and threats associated with the discipline, while also exploring the underlying causes of existing challenges and future prospects from a scholarly and pedagogical perspective. It should be particularly noted that the authors were direct participants in the processes discussed and possess extensive experience in the field of teaching Turkic history. This enables them to provide not merely a theoretical assessment but also a comprehensive and practice-oriented analysis of the issues under consideration.

The findings of the study may contribute to the improvement of curriculum design, teaching methodologies, and educational policy related to the teaching of the History of the Turkic Peoples in higher education institutions.

**Keywords:** Teaching of the History of the Turkic Peoples; Common Turkic History; Intra-Turkic Integration; Turkic World; International Turkic Academy; Baku State University.

**Introduction.** The contemporary education system is undergoing a rapid transformation from the classical paradigm of “teaching” toward a model based on the co-construction of knowledge and digital collaboration, in line with the demands of the information age. Today, the primary focus of education is no longer merely the transmission of facts; rather, it emphasizes the development of critical thinking, interdisciplinary synthesis, and lifelong learning competencies.

Digitalization, artificial intelligence, and global networking have removed many of the spatial limitations of traditional education, transforming the learning process into an interactive, flexible, and student-centered environment.

Against the backdrop of these global trends, however, the humanities and particularly the teaching of the History of the Turkic Peoples face the challenge of harmonizing national and cultural values with contemporary pedagogical methodologies. In the field of history education, the integration of digital resources and transnational approaches has become not merely an option but a strategic necessity for securing a meaningful place for the integrated Turkic world within a common scientific and educational space.

From this perspective, global educational trends necessitate the emergence of new approaches to the teaching of the History of the Turkic Peoples, characterized by a transition from ideologically driven interpretations toward academic objectivity, methodological pluralism, and technological innovation.

Following the collapse of the Soviet Union, historical scholarship and history education gradually moved beyond the constraints of Soviet ideological frameworks and began to develop on the basis of new theoretical and methodological approaches. This process created favorable conditions for reassessing long-standing historiographical stereotypes, studying the history of the Turkic peoples on the basis of greater scholarly objectivity, and systematically investigating their shared historical and cultural heritage. At the same time, it stimulated new academic and educational initiatives aimed at examining the historical past of the Turkic world within a unified conceptual framework.

Nevertheless, the transformation of the discipline has not been accompanied by a sufficient number of comprehensive scholarly assessments. Despite the achievements attained in this field, comprehensive studies evaluating the content, methodology, teaching resources, and institutional development of the History of the Turkic Peoples remain limited.

Accordingly, this article aims to evaluate the current state of teaching the History of the Turkic Peoples from the 1990s to the present, identifying its strengths, weaknesses, opportunities, and threats through a SWOT analytical framework.

***Issues and Challenges in Teaching the History of the Turkic Peoples during the Early Years of Independence.*** The policies of glasnost (openness), democratization, and later perestroika (restructuring), initiated by Mikhail Gorbachev following his rise to power in the Soviet Union in 1985, stimulated significant changes in the fields of history and education, as well as in other spheres of public life. One of the outcomes of these reforms was the strengthening of national self-awareness among the peoples of the Soviet Union, including the Turkic peoples. Following the dissolution of the Soviet Union in 1991 and the emergence of independent states, this process gained further momentum.

One of the principal tasks facing the Turkic peoples that regained their state independence was the education of a generation connected to its historical roots, cultural heritage, and national identity. In this regard, education became one of the key instruments for achieving this objective.

In Azerbaijan, Baku State University was among the first higher education institutions to introduce the course History of the Turkic Peoples. In May 1992, the Department of History of the Turkic Peoples was established within the Faculty of History and, over time, became one of the leading centers for the teaching and study of Turkic history in Azerbaijan. During the early years of Baku State University, a Department of the History of the Turkic Peoples (referred to in some sources as the Department of the History of Turkic-Tatar Peoples) was established within the Faculty of History in 1922. However, its activities were subsequently discontinued under the influence of the political and ideological environment that emerged during the Soviet period [1, p.20; 3, pp.73–74].

Prior to this development, in Azerbaijan as well as in the Soviet republics of Kazakhstan, Kyrgyzstan, Uzbekistan, and Turkmenistan, the history of the Turkic peoples had generally been taught within the broader framework of the subject History of the USSR, where it received only limited attention. Furthermore, Turkic peoples were typically presented through separate ethnic designations such as Azerbaijani, Kazakh, Kyrgyz, Uzbek, Turkmen, Tatar, and others rather than as components of a broader Turkic historical and cultural community.

It should also be noted that a number of scholars have associated the continued prevalence of the term “Turkic-speaking peoples” in place of “Turkic peoples” with identity policies pursued during the Soviet period, which emphasized linguistic classification over broader historical and cultural commonality among Turkic communities [2, p.18].

In fact, the emergence of the History of the Turkic Peoples as an independent academic discipline represented not merely a curricular reform but also one of the manifestations of a broader transformation in post-Soviet historiography. This transformation created new opportunities for examining national histories within wider regional and civilizational contexts.

However, despite the favorable conditions created by this transformation, the institutionalization of the discipline and its effective teaching were accompanied by numerous challenges.

One of the authors of the present article, S.Ruintan, has been directly involved in the teaching of the History of the Turkic Peoples since the early stages of its institutional development. In papers presented at the First International Symposium on History Education, organized by Atatürk University in Erzurum, Türkiye, in 2010, and at the Sixth International Symposium on History Education, jointly organized by Bolu Abant İzzet Baysal University and the Atatürk Research Center in Bolu, Türkiye, in 2019, she identified a number of challenges in the teaching of the History of the Turkic Peoples. These included the limited availability of academic sources, inadequate material and technical resources, insufficient opportunities for academic exchange, and students’ inadequate linguistic competencies, among other issues. In addition, she proposed several measures aimed at addressing these challenges [4, p.277; 5, pp.6-7]. The proposed measures included:

1. promoting the exchange of academic resources among universities of the Turkic states;
2. organizing interactive joint classes between universities in different Turkic countries;
3. introducing co-supervision arrangements for undergraduate and graduate research projects;
4. establishing joint grant programs among universities from different countries;
5. encouraging active participation in international conferences and symposiums, including the delivery of lectures to students within the framework of such events;
6. preparing a common History of the Turkic Peoples textbook;
7. jointly developing educational and multimedia resources, including maps and digital learning materials, to support the teaching of the History of the Turkic Peoples, and providing their translation into Turkish and Russian to ensure broader dissemination and accessibility (the inclusion of Russian was proposed in recognition of its widespread use among a significant proportion of Turkic communities at the time - S.R., F.A.);
8. facilitating short-term academic mobility programs for instructors at leading universities [5, pp.6-8].

Although certain institutional and methodological advances have been achieved since these recommendations were first proposed, a review of the current state of teaching the History of the Turkic Peoples reveals that, even after approximately sixteen years, many of the identified issues remain unresolved or only partially addressed. The persistence of these challenges over such a long period demonstrates their systemic nature and underscores the continuing need for

coordinated academic, institutional, and educational initiatives aimed at strengthening the teaching of the History of the Turkic Peoples.

***The Current State of Teaching the History of the Turkic Peoples.*** At present, the teaching of the History of the Turkic Peoples is undergoing a transition from ideologically driven paradigms toward greater academic objectivity, methodological pluralism, and digitalization. Among the most significant trends are the increasing adoption of interdisciplinary approaches - integrating archaeology, genetics, linguistics, and other related disciplines - as well as the growing role of the Organization of Turkic States in promoting common educational initiatives. Against this background, a SWOT analysis reveals the following picture:

#### Strengths

*Interdisciplinary Approach:* Increasing use of archaeological, numismatic, paleogenetic, and ethnolinguistic evidence contributes to a more evidence-based and comprehensive understanding of Turkic history;

*De-ideologization:* A gradual departure from Soviet-era and Eurocentric interpretative frameworks has facilitated a more objective examination of issues such as ethnogenesis, statehood traditions, and cultural development among the Turkic peoples;

*Institutionalization:* The establishment and expansion of specialized university departments (e.g., at Baku State University and Al-Farabi Kazakh National University) and academic institutions, including the International Turkic Academy, have strengthened the institutional foundations of the field.

#### Weaknesses

*Regional Fragmentation:* The predominance of nationally oriented historical narratives often limits the development of a broader Common Turkic History perspective;

*Shortage of Qualified Academic Personnel:* Challenges and gaps remain in the transition from classical, outdated teaching methods to modern educational approaches. Existing shortcomings in academic administration, as well as the tendency to prioritize the search for “more prestigious researchers or instructors,” hinder the effective utilization of the potential of young and promising researchers and educators, and in some cases even make such utilization impossible;

*Information and Resource Gaps:* High-quality scholarly works and teaching materials translated into local languages remain insufficient or inaccessible in some educational contexts;

*Terminological Inconsistencies:* The lack of a unified historical terminology leads to differing interpretations of the same historical events across countries. For instance, in studies of the statehood traditions of Turkic peoples, terms such as “khanate” “beylik” and “empire” are not always defined or applied in accordance with their historical and scholarly meanings, resulting in conceptual inconsistencies;

*Formalism in Academic Cooperation:* Academic collaboration is frequently guided by protocol considerations and the prominence of individuals rather than by the quality and impact of scholarly outcomes, thereby limiting the development of a results-oriented academic environment.

#### Opportunities

*Digitalization of Education:* The development of interactive maps, 3D reconstructions of ancient Turkic settlements, and multimedia educational platforms offers significant opportunities for innovation in teaching;

*Academic Mobility:* Strengthening inter-university partnerships through exchange programs, joint research projects, and grant initiatives can contribute to capacity building and knowledge transfer;

*Development of Common Textbooks:* The preparation of shared educational materials on the history of the Turkic peoples may contribute to the formation of a common cultural and historical understanding;

*Improved Access to Archival Sources:* To bridge existing gaps, improving access to archival materials on Turkic history held in different countries, together with other supportive initiatives, may provide a stronger foundation for enhancing the teaching and study of the History of Turkic Peoples.

#### Threats

*Politicization of History:* The history of Turkic peoples is at times employed for narrow political purposes. For instance, topics related to the Enlightenment movements among Turkic peoples in the nineteenth and twentieth centuries, as well as their broader statehood traditions, are often presented differently in the textbooks of various countries, occasionally in contradictory ways and sometimes through predominantly nationalist interpretations;

*Nationalist Disputes:* The risk of intensifying disputes over historical heritage. For example, disagreements may arise regarding which nation or state can be regarded as the direct successor of a particular historical state that existed in the past;

*Academic Conservatism:* Resistance among certain segments of the academic community to the implementation of new educational standards and innovative teaching methods.;

*Historical Misinformation (Pseudo History):* The growing dissemination of pseudo-historical narratives and unverified historical claims through digital media presents a significant challenge to evidence-based history education.

The SWOT analysis demonstrates that, despite significant progress in the institutionalization and modernization of the teaching of the History of the Turkic Peoples, a number of structural and methodological challenges continue to limit its development. At the same time, the opportunities created by digital technologies, academic mobility, and increasing cooperation among Turkic states provide a favorable environment for addressing these challenges. The future development of the discipline will largely depend on the extent to which educational institutions, research centers, and relevant state and international organizations are able to coordinate their efforts in establishing a common academic and educational framework [6, pp.219-220].

In this regard, the teaching of the History of the Turkic Peoples should be viewed not only as an educational undertaking but also as an important instrument for strengthening scholarly cooperation, cultural dialogue, and intellectual integration across the Turkic world.

***Initiative and Institutional Leadership: The Case of Baku State University.*** The case of Baku State University demonstrates that the advancement of the teaching of the History of the Turkic Peoples depends not only on interstate agreements and institutional frameworks but also on the agency of universities, academic departments, and individual scholars. In this regard, teacher leadership and grassroots academic initiatives may play a crucial role in fostering educational innovation and strengthening scholarly cooperation within the Turkic world.

Referring to this issue, Professor Asmad Mukhtarova, Head of the Department of History of the Turkic Peoples at Baku State University, notes that since the restoration of the department's activities in 1992, significant efforts have been undertaken in the fields of research, promotion, and teaching of Turkic history. As a result, the department has become one of the leading centers for the study and teaching of Turkic history in Azerbaijan. Among its achievements were the preparation of the first post-Soviet textbook on the ancient and medieval history of the Turkic peoples, the publication of curricula, methodological guides, textbooks, and monographs on various periods and issues of Turkic history, the establishment of a specialized teaching laboratory, the creation of the online library "Our Library", the training of young specialists, and academic internships of faculty members at Turkish universities [2, pp.20-24; 3, pp.74-76].

More broadly, the experience of Baku State University demonstrates that sustainable progress in the teaching of the History of the Turkic Peoples may be achieved not only through state-level educational initiatives but also through the proactive engagement of universities, academic departments, and individual scholars. This case highlights the important role of institutional initiative and academic leadership in advancing cooperation and innovation within the field.

***Conclusion and Future Perspectives for the Teaching of the History of the Turkic Peoples.*** A retrospective assessment conducted in the thirty-fifth year following the restoration of state independence demonstrates that substantial efforts are still required to transform the teaching of the History of the Turkic Peoples into an interactive, flexible, and student-centered learning environment that transcends traditional spatial limitations. Likewise, further progress is needed to harmonize national and cultural values with contemporary pedagogical methodologies.

Although the common textbooks developed under the initiative of the International Turkic Academy - such as Common Turkic History, Common Turkic Literature, and Common Turkic Geography - represent an important step forward, the fact that these initiatives have not yet fully encompassed all Turkic states, together with the limited effectiveness of some academic exchange programs due to financial and logistical constraints, points to the continuing need for a more systematic and coordinated approach.

In addition, the prioritization of individual authority and informal academic networks over merit-based academic practices and institutional mechanisms may, in certain cases, hinder the sustainable development of the field.

More broadly, while education constituted primarily a national concern during the state-building processes of the 1990s in the newly independent Turkic states, by 2026 it has become an academic and strategic necessity for strengthening integration within the Turkic world and enhancing its position in an increasingly competitive global environment. This objective requires the enrichment of teaching practices through digital technologies and interdisciplinary methodologies, as well as the advancement of historical scholarship based on academic objectivity rather than ideological considerations.

Ultimately, the qualitative development of the teaching of the History of the Turkic Peoples will depend not only on state-level policies and institutional support but also on the initiative of educators, academic leadership, and methodological innovation. As demonstrated by the experience of Baku State University, sustainable progress is most likely to emerge through the interaction of institutional frameworks and grassroots academic initiatives.

If the primary objective of teaching the History of the Turkic Peoples at the end of the twentieth century was the restoration of historical memory, its principal mission in the second quarter of the twenty-first century should be the formation of a common scholarly space and the integration of Turkic studies into global academic discourse.

In the future, the establishment of a common digital platform integrating universities, research institutions, and academic libraries across the Turkic world could significantly contribute to the dissemination of educational resources, archival materials, and scholarly research. The integration of artificial intelligence, digital humanities, and large-scale historical databases into history education may open new avenues for both teaching and research in the field of Turkic history. The next stage of development should involve not only expanding academic cooperation but also fostering common scholarly schools based on shared methodological principles across universities of the Turkic world.

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## Geological and Mineralogical Sciences

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# ПРЯМОШУКОВА ТЕХНОЛОГІЯ ЧАСТОТНО-РЕЗОНАНСНОЇ ОБРОБКИ СУПУТНИКОВИХ ТА ФОТО ЗНІМКІВ: РЕЗУЛЬТАТИ ЗАСТОСУВАННЯ ДЛЯ ОБСТЕЖЕННЯ ЛОКАЛЬНИХ ДІЛЯНОК І КРУПНИХ БЛОКІВ В УКРАЇНІ

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### Вступ

Супер-мобільна прямопошукова технологія частотно-резонансної обробки та декодування супутникових та фото знімків надала унікальну можливість провести величезний обсяг експериментів в різних регіонах земної кулі з метою вивчення глибинної будови Землі, пошуків горючих і рудних корисних копалин, а також води. В процесі проведення експериментальних робіт отримано численні свідчення на користь глибинного (абіогенного) генезису вуглеводнів в рамках концепції водневої дегазації Землі [Шестопалов и др., 2018]. В статті описані особливості мобільних прямопошукових методів, узагальнені результати їх масштабної апробації і тестування та охарактеризовані частково результати проведених експериментальних робіт в 2022-2026 рр. на території України.

### Результати апробації технології частотно-резонансної обробки та інтерпретації супутникових знімків і фотознімків в різних регіонах світу

Основні результати проведених експериментальних робіт в різних регіонах земної кулі та опублікованих в [Якимчук и др., 2019а; 2019б; Якимчук, Корчагін, 2019а,б,в, Якимчук та ін, 2026] зводяться до наступного.

**Методи досліджень.** Мобільна прямопошукова технологія, що використовується та постійно удосконалюється, включає модифіковані методи частотно-резонансної обробки та декодування супутникових знімків і фотознімків, а також вертикального зондування (сканування) розрізу [Якимчук и др., 2019а]. Окремі методи технології базуються на принципах «речовинної» парадигми геофізичних досліджень, сутність якої полягає в пошуках

конкретної (цільової у кожному випадку) речовини – нафти, газу, газоконденсату, золота, цинку, урану тощо. В модифікованих методах частотно-резонансної обробки супутникових знімків використовуються резонансні частоти баз хімічних елементів, мінералів, порід та корисних копалин (фотографії та фотомонтажі конкретних зразків). Колекція зразків нафти включає 117 екземплярів, газоконденсату – 15 зразків. Осадкові породи включають наступні групи: 1-а – (псефіти), 2-а – (псаміти), 3-я – (аледрити, аргіліти, глини), 4-а – (аргіліти каолінітові), 5-а – (глини каолінітові), 6-а – (осадово-вулканокластичні породи), 7-а – (вапняки), 8-а – (доломіти), 9-а – (мергелі), 10 – (кременисті породи). Групи магматичних і метаморфічних порід наступні: 1-а – (граніти та ріоліти), 2-а – (гранодіорити та дацити), 3-я – (сіеніти та трахіти), 4-а – (діорити та андезити), 5-а – (лампрофіри), 6-а – (габро та базальти), 7-а – (ультрамафічні породи), 8-а – (сіеніти та фоноліти), 9-а – (габроїди та базальтоїди), 10-а – (ультрамафічні та мафічні породи), 11-а – (кімберліти та лампроїти), 12-а – (карбонатити), 13-а – (грануліти), 14-а – (гнейси), 15-а – (кристалічні сланці). Фотографії наборів зразків осадових, метаморфічних і магматичних порід, що використовуються в процесі виконання інструментальних вимірів, запозичені з електронного документа <https://karpinskyinstitute.ru/ru/info/sprav/petro/petro-mobil.pdf>. Особливості методів та методика проведення вимірювань описані більш детально в [Якимчук и др., 2019а; 2019б; Якимчук, Корчагин, 2019а,б,в].

Відзначимо також, що в технології, яка постійно удосконалюється, використовується частотно-резонансний принцип реєстрації корисних сигналів [12]. Супутникові знімки чи фотознімки об'єктів дослідження, а також фотографії зразків порід, корисних копалин і хімічних елементів – це, у принципі, пучності стоячих електричних хвиль, виявлених Ніколою Тесла в 1899 р. в глибинних горизонтах Землі [Тесла, 2009; 2010].

При проведенні інструментальних вимірювань з використанням розроблених комп'ютеризованих комплексів послідовно зіставляються супутникові або фотознімки об'єктів вивчення з фотографіями зразків порід, корисних копалин та хімічних елементів. У процесі зіставлення вимірювальним блоком реєструються електромагнітні відгуки (сигнали), які дозволяють зробити висновок про присутність (відсутність) конкретних порід, цільових корисних копалин та хімічних елементів у розрізі об'єкта вивчення. Такі особливості методів обробки та декодування супутникових знімків, що розробляються, є підставою для використання термінів «частотно-резонансна технологія» («частотно-резонансні методи»). Обробка супутникових знімків та фотознімків проводиться в лабораторних умовах, без організації та проведення польових геолого-геофізичних досліджень. Це надає можливість оперативно проводити дослідження в будь-якому регіоні земної кулі, а отже технологію, яка розробляється, можна вважати супер-мобільною.

Принципово важлива особливість прямопошукових частотно-резонансних методів полягає в тому, що на відміну від класичних геофізичних, вони надають реальну можливість наповнювати розріз, який вивчається, відповідними комплексами осадових, метаморфічних і магматичних порід, а також визначати інтервали розрізу, перспективні на виявлення горючих і рудних корисних одночасно, у процесі проведення вимірювань (реєстрації сигналів) розробленими апаратурно-вимірювальними пристроями (тобто без додаткових етапів моделювання та геологічної інтерпретації результатів геофізичних вимірювань). В даному повідомленні, а також в опублікованих матеріалах [Якимчук и др., 2019а; 2019б; Якимчук, Корчагин, 2019а,б,в] представлені та аналізуються результати інструментальних вимірювань виключно!

***Про прогнозовані глибини синтезу нафти, конденсату та газу.*** Важливе місце в прямопошуковій технології займає методика вертикального сканування (зондування) розрізу, використання якої надає можливість реєструвати відгуки (сигнали) на резонансних частотах хімічних елементів, мінералів, корисних копалин, води, а також осадових,

метаморфічних і магматичних порід в різних інтервалах глибин, аж до центру. Землі. Застосування методу зондування (сканування) на відомих родовищах ВВ, а також на ділянках реєстрації відгуків на частотах нафти, конденсату та газу призвело до встановлення існування умовної межі на глибині 57 км, вище якої фіксуються сигнали (відгуки) на резонансних частотах нафти, конденсату та газу, а нижче (глибше) – на частотах водню та вуглецю! І що характерно – ця межа фіксуються на відповідних ділянках реєстрації сигналів від ВВ на поверхні практично у всіх регіонах земної кулі!

Численні результати фіксації межі синтезу інструментальними вимірюваннями безпосередньо (не інтерпретацією результатів вимірювань) дозволяють припустити існування в цьому інтервалі глибин термодинамічних умов, сприятливих для синтезу нафти, конденсату та газу з водню і вуглецю, які мігрують знизу. Можна також говорити про наявність на цій глибині необхідних умов для формування природного реактора синтезу нафти, конденсату та газу. Можна також припустити, що в такому реакторі почнеться процес генерації вуглеводнів тільки при реалізації в цьому інтервалі серії додаткових (достатніх!) умов для запуску процесу синтезу. На даний момент для опису достатніх умов роботи «реактора» достовірна інформація відсутня.

Зазначимо також, що в процесі проведення експериментів встановлено наявність на глибинах 68(69) км ще однієї межі, в інтервалі якої відбувається синтез води. При проведенні пошукових робіт додаткові процедури для фіксації сигналів на частотах води вище глибин 68(69) км виконуються також.

**Про глибинні канали (вулкани) міграції флюїдів та мінеральних речовин.** При проведенні геофізичних досліджень в Українській морській антарктичній експедиції 2018 р. з використанням розроблених методів у Південній Атлантиці та в районі Антарктичного п-ва виявлено значну кількість глибинних каналів (вулканів) міграції флюїдів, мінеральних речовин та хімічних елементів, заповнених різними осадовими та магматичними породами, у тому числі і сіллю. Отримані матеріали дають підстави для припущення про недооцінку дослідниками впливу вулканічної діяльності на формування зовнішнього вигляду та внутрішньої будови планети Земля. Експериментальними дослідженнями у 2019-2020 рр. підтверджено наявність вулканічних споруд різного типу в різних регіонах земної кулі [Якимчук и др., 2019б; Якимчук, Корчагин, 2019а,б,в]. У зв'язку з цим, при проведенні досліджень з метою пошуків корисних копалин додатково виконуються інструментальні вимірювання, спрямовані на встановлення наявності (відсутності) глибинних каналів (вулканів) у межах крупних блоків та локальних ділянок обстеження. Результати проведених експериментальних робіт такого характеру можуть бути резюмовані наступним чином.

1. В різних регіонах світу виявлено численні глибинні канали (вулкани), заповнені осадовими породами 1-6 груп, 7, 8, 9, 10 та 11 (сіль) груп, а також магматичними породами 1 (граніти), 6 (базальти), 7 (ультрамафічні породи) та 11 (кімберліти) груп.
2. Корені вулканів, заповнених породами перелічених груп практично завжди фіксуються на глибинах 996 км, 723 км, 470 км та 195-217 км, 95-99 км. Інтервал 195-217 км можна вважати шаром рідкого (пластичного) стану порід.
3. Вулкани з коренями в інтервалі 195-217 км можна вважати "молодими" грязьовими вулканами. Активність такого типу вулканів спостерігається нині.
4. Вулканічні споруди з коренями на глибинах 996 км, 723 км та 470 км доцільно відносити до категорії «старих».
5. Наявність на ділянках обстеження вулканічних споруд з коренями на різних глибинах дозволяє припустити про процеси активізації в цих регіонах в різний час.
6. Зразки порід, що заповнюють канали вулканів з коренем на поверхні 996 км, можуть фіксуватися в інтервалі глибин 0-996 км, з коренем на глибині 723 км - в інтервалі 0-723 км,

з коренем на глибині 470 км - в інтервалі 0-470 км., з коренем 217 км – лише в інтервалі 0-217 км, а з коренем на глибині 95 км – тільки в інтервалі 0-95 км.

**Про зв'язок скупчень вуглеводнів із глибинними вулканами різного типу.** У процесі проведення досліджень на ділянках розміщення відомих родовищ нафти та газу, пошукових площах та локальних майданчиках буріння свердловин встановлено, що відгуки (сигнали) на резонансних частотах нафти, конденсату та газу реєструються лише в районах розташування каналів (вулканів), заповнених певними групами осадових та магматичних порід. На даний момент результати виконаних експериментальних робіт у різних регіонах дозволяють достатньо обґрунтовано констатувати наступне.

1. В межах глибинних каналів, заповнених осадовими породами 1-6 груп, практично завжди реєструються відгуки на резонансних частотах ВВ. В багатьох випадках в контурах таких каналів фіксуються також відгуки на частотах бурштину.

2. В вулканах, заповнених 7-ою групою осадових порід (карбонати, вапняки), сигнали на частотах нафти, конденсату і газу також реєструються дуже часто. Але відгуки від бурштину в цих вулканах не фіксуються.

3. На ділянках вулканічних структур, заповнених сіллю, також фіксуються відгуки на резонансних частотах ВВ.

4. В межах вулканічних комплексів заповнених осадовими породами 8-ї групи (доломіти), 9-ої групи (мергелі) та 10-ої групи (кременисті породи) відгуки на частотах нафти, конденсату та газу не зареєстровані жодного разу!

5. На ділянках обстеження, в яких фіксуються відгуки від ВВ, в межах (в центральних частинах, швидше за все) глибинних каналів міграції флюїдів, мінеральних речовин та хімічних елементів практично завжди фіксується межа 57 км. Нижче цієї межі реєструються відгуки на частотах водню та вуглецю, вище – нафти, конденсату, газу та бурштину (тільки у каналах певного типу) [Якимчук и др., 2019а; 2019б; Якимчук, Корчагин, 2019а,б,в].

6. В районах обстежених вулканів, заповнених гранітними породами, також отримано сигнали від вуглеводнів у гранітах, у тому числі на поверхні 57 км. Ці результати свідчать про можливий синтез вуглеводнів в деяких типах гранітних вулканів. Обстежені ділянки у районах розташування гранітних масивів поповнюють базу об'єктів (гранітних вулканів), в яких є умови для синтезу ВВ.

7. Встановлено також, що на багатьох ділянках відгуки від ВВ фіксувалися також з інтервалів знаходження ультрамафічних порід.

**Висновки.** Результати масштабної апробації мобільних прямопошукових методів можна вважати додатковими та вагомими свідченнями на користь вулканічної моделі формування зовнішнього вигляду планет та супутників Сонячної системи, а також родовищ рудних та горючих корисних копалин.

### **Результати рекогносцирувального обстеження вугільних басейнів України**

Рекогносцирувальне обстеження вугільних басейнів на території України проведено з метою оцінки перспектив виявлення покладів ВВ (нафта, газ, конденсат) в глибоких та глибинних горизонтах розрізу. Результати проведених робіт зводяться до наступного [Якимчук, Корчагин, 2025в].

**Львівсько-Волинський вугільний басейн.** В процесі частотно-резонансної обробки всього знімка з басейном на рис. 1 зареєстровані відгуки від нафти, конденсату, газу, бурштину, вугілля та води. Отримані сигнали від 2-ої (слабкий), 3-ої (слабкий), 4-ої (слабкий), 5-ої (слабкий), 6-ої (слабкий), 7-ої (інтенсивний), 8-ої, 9-ої, 10-ої, 11-ої, 12-ої груп осадових порід та 1, 2, 3, 4, 5, 6, 7, 8 і 9 груп магматичних.

Встановлено наявність глибинного каналу з коренем на глибині 723 км, заповненого 7-ою групою магматичних порід, та каналів з коренями на глибині 470 км, заповнених осадовими породами та 6-ою групою магматичних порід.

Скануванням розрізу з кроками 10 см, 50 см і 1 м сигнали на частотах вугілля отримані в інтервалі глибин 20-1130 м (простежено до 2 км).

Скануванням розрізу з поверхні з кроком 1 м відгуки від нафти зафіксовані в наступних інтервалах: 1) 260-1280 м; 2) 1500–2600 м; 3) 3430–4570 м; 4) 5950–7950 м; перехід на крок 5 м; 5) 8650-9900 м; 6) 10850-13700 м (до 15 км простежено).

Відгуки від нафти, конденсату, газу та бурштину отримані також на поверхні синтезу ВВ 56.9 км.

**Ділянка в районі м. Червоноград (Україна).** На рис. 1 представлений супутниковий знімок території Львівсько-Волинського кам'яновугільного басейну України. При обробці фрагмента цього знімка у районі м. Червоноград (позначеного на рис. 1 прямокутним контуром) зафіксовано відгуки (інтенсивні) від бурого вугілля, конденсату, газу, бурштину, газогідратів, води; сигнали на частотах нафти були відсутні.

З використанням зразків першої групи осадових порід корінь глибинного каналу осадових порід встановлено на глибині 723 км!

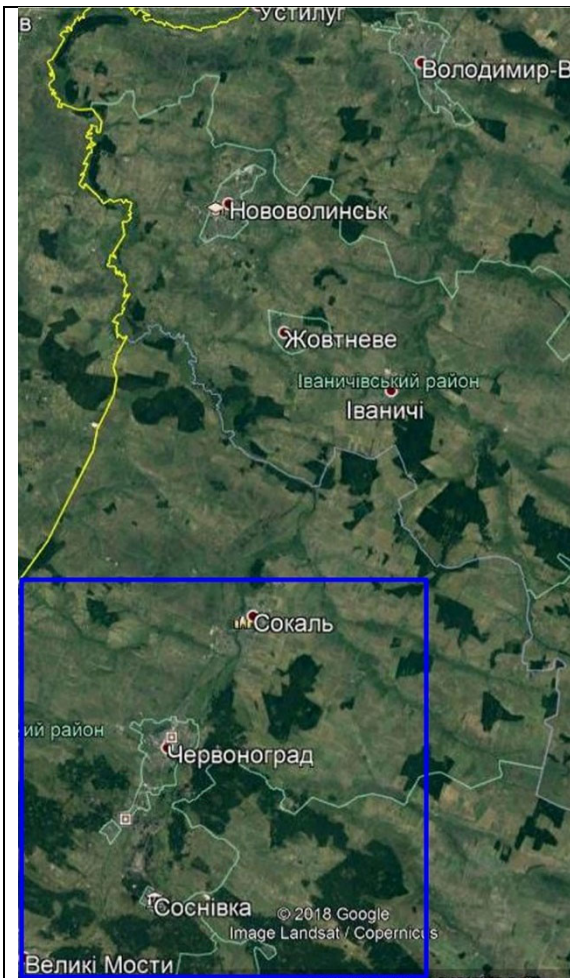
На поверхні 56.9 км зареєстровані відгуки від води, газогідратів, бурштину, газу; сигнали від нафти тут були відсутні. Відгуки від води фіксувалися на поверхні 68.9 км. Сигнали від бурого вугілля зареєстровані в інтервалі 12-215 м, а бурштину – 12-64 м.

Скануванням розрізу з поверхні з кроком 1 м встановлено такі інтервали відгуків на частотах газу: 1) 50-530 м; 2) 1200–2100 м; 3) 2620–3800 м; 4) 4480-4820 м; на 5 м з 5 км; 5) 7000-8750 м; 6) 10300–11600 м; 7) 12100–12550 м; 8) 13000-13700 м (простежено до 15 км).

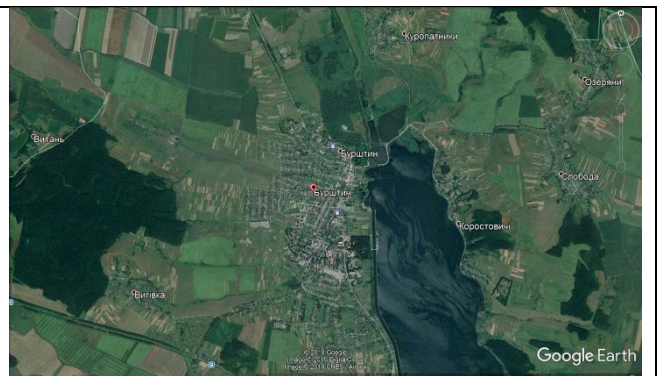
**Район м. Бурштин (Україна).** Супутниковий знімок ділянки розташування м. Бурштин наведено на рис. 2. При його обробці зафіксовано відгуки на частотах нафти, конденсату, газу (інтенсивний), а також 3-ої, 4-ої (слабкий), 5-ої, 6-ої, 7-ої (дуже інтенсивні) та 12-ої (слабкий) груп осадових порід і 7-ої групи магматичних порід.

Фіксацією відгуків від порід на різних глибинах корінь вулкану магматичних порід (7-а група) визначено на глибині 195 км, а 7-ої групи осадових (карбонатних) – на 470 км.

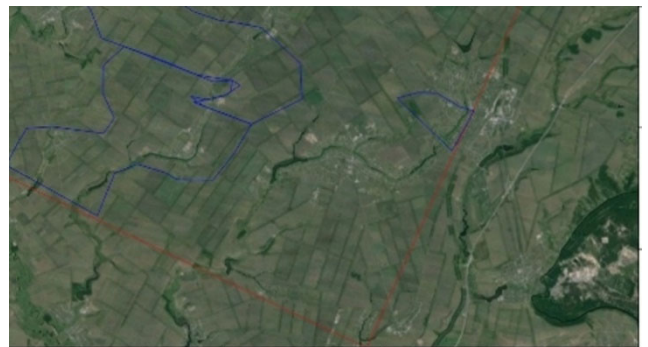
На поверхні 56.9 км зафіксовано сигнали нафти, конденсату, газу та бурштину.



**Рис. 1.** Супутниковий знімок площі Львівсько-Волинського вугільного басейну.



**Рис. 2.** Супутниковий знімок ділянки розташування населеного пункту Бурштин (Україна).



**Рис. 3.** Супутниковий знімок ділянки обстеження у районі Новомосковського вугільного родовища.

Скануванням розрізу з 0 м із кроком 1 м зафіксовано такі інтервали відгуків на резонансних частотах нафти: 1) 790-1430 м; 2) 1750-2200 м; 3) 3200-4060 м; 4) 5000-5200 м (далі не простежено).

При скануванні розрізу з 0 м із кроком 1 см сигнали (інтенсивні) на частотах бурштину зафіксовані з 1.1 м.

**Новомосковське вугільне родовище (Дніпропетровська область).** При обробці супутникового знімку площі в районі родовища (рис. 3) зафіксовано сигнали від бурого вугілля, газогідратів, бурштину (з 11 с), газу, конденсату, 1-ої та 2-ої (дуже слабкий) груп осадових порід; відгуки від нафти та магматичних порід були відсутні.

Фіксацією відгуків на різних глибинах корінь каналу осадових порід визначено на глибині 723 км.

На поверхні 56,9 км. отримані відгуки від бурштину, газогідратів, газу, конденсату; сигналів від нафти не зафіксовано

Скануванням розрізу відгуки від бурого вугілля зареєстровані в інтервалі 4-98 м (крок сканування – 10 см), а від бурштину – 170-265 м (крок сканування – 1 м).

Скануванням розрізу зі 100 м з кроком 1 м встановлено такі інтервали відгуків на частотах газу: 1) 170-580 м; 2) 950-1430 м; 3) 1630-1720 м; 4) 2490-3100 м; 5) 3450-4170 м; 6) 4360-4770 м; на крок 5 м; 7) 6950-8950 м; 8) 14260-16400 м (далі не простежено).



4. Другий етап проекту: обробка фрагмента супутникового знімка в межах якого існують умови для синтезу ВВ на поверхні 57 км в детальному режимі з метою визначення глибин залягання та товщин інтервалів розрізу з покладами ВВ (нижче вугільних пластів).

*Коментар.* Реалізація (оперативно проведена) на площі вугільного басейну запропонованого проекту дозволить виділити в його межах фрагмент (фрагменти) для проведення детальних пошукових робіт та оцінити доцільність буріння пошукових свердловин на вуглеводні.

#### **Результати рекогносцирувального обстеження Олеської площі**

В 2025 р. проведено апробацію прямопошукових методів в межах Олеської площі на заході України.

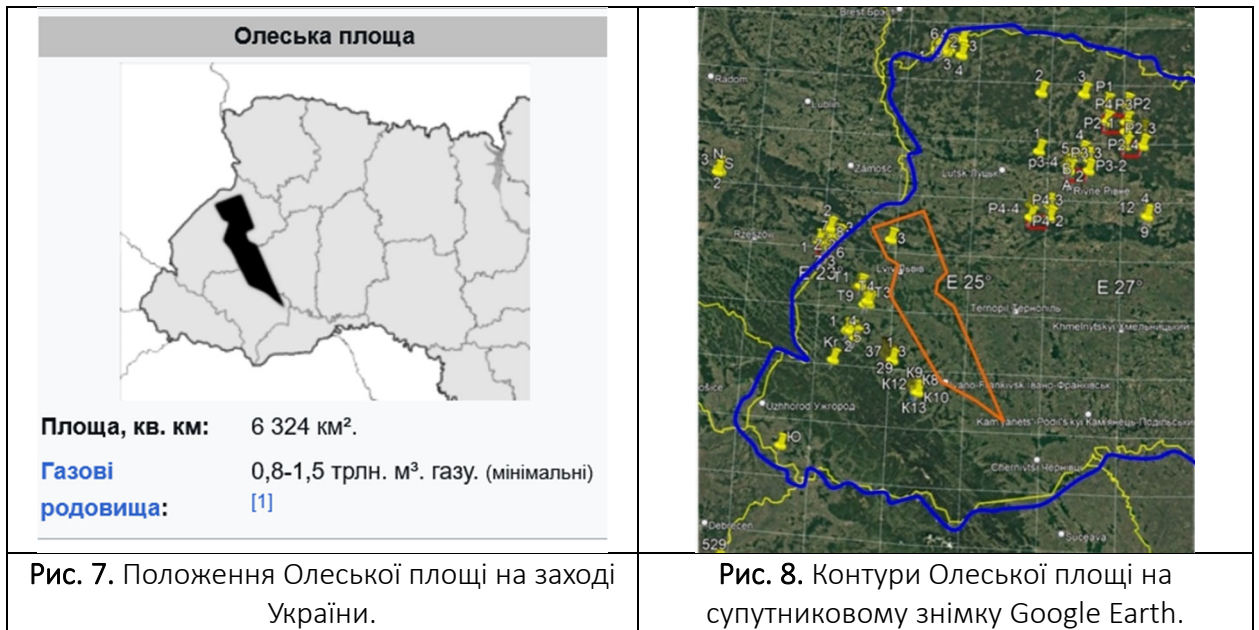
*Результати рекогносцирувальних досліджень.* На сайті [«Укрнафта»...] наведена інформація про отримання компанією «Укрнафта» спецдозволу на видобуток сланцевого газу в межах Олеської площі. В зв'язку з цим, на Олеській площі із застосуванням прямопошукової технології частотно-резонансної обробки супутникових та фото знімків проведені дослідження рекогносцирувального характеру з метою оцінки перспектив виявлення покладів вуглеводнів (ВВ) в глибинних горизонтах розрізу в традиційних (не сланцевих) колекторах [Якимчук та ін., 2025а, б].

Для проведення досліджень контури площі (рис. 7) нанесені (приблизно) на знімок Google Earth (рис. 8), який розбито на три фрагменти (рис. 9). В рекогносцирувальному режимі проведена обробка нижніх фрагментів знімків на рис. 9а, 9б, 9в.

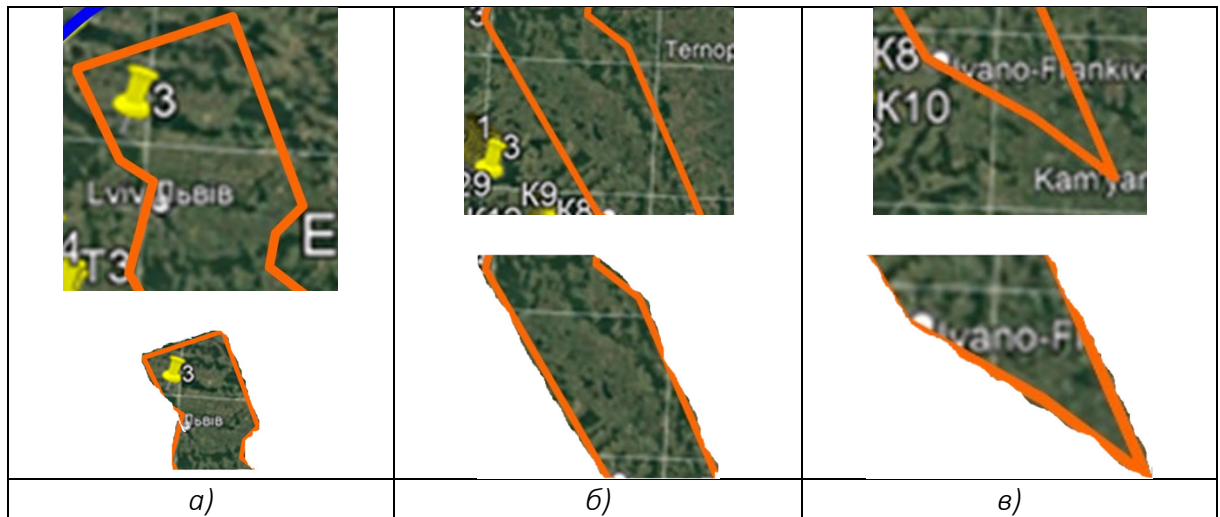
В процесі частотно-резонансної обробки супутникового знімка північної ділянки Олеської площі (рис. 9а) в рекогносцирувальному режимі з поверхні зафіксовано спільний сигнал на частотах ВВ, бактерій метаноокислючих, жовтого фосфору і 7-ої групи осадових порід (карбонати, вапняки). Інструментальними вимірами зафіксовані процеси міграції газу і жовтого фосфору в атмосферу.

Під час частотно-резонансної обробки супутникового знімка центральної ділянки Олеської площі (рис. 9б) в рекогносцирувальному режимі з поверхні зафіксовано спільний сигнал на частотах ВВ, бактерій метаноокислючих, жовтого фосфору і 7-ої групи осадових порід (карбонати, вапняки). Інструментальними вимірами зафіксовані факти (процеси) міграції газу і жовтого фосфору в атмосферу.

В межах центральної ділянки зафіксовано також сигнали вуглеводнів на глибині їх синтезу 57 км в вулканічному комплексі, заповненому 7-ою групою осадових (карбонатних) порід!



В процесі обробки знімка південної ділянки Одеської площі (рис. 9в) з поверхні зафіксовано спільний сигнал на частотах ВВ, бактерій метаноокислючих, жовтого фосфору і 7-ої групи осадових порід (карбонати, вапняки). Інструментальними вимірами зафіксовані факти (процеси) міграції газу і жовтого фосфору в атмосферу.



**Рис. 9.** Контури північної (а), центральної (б) та південної (в) частин Одеської площі на супутниковому знімку.

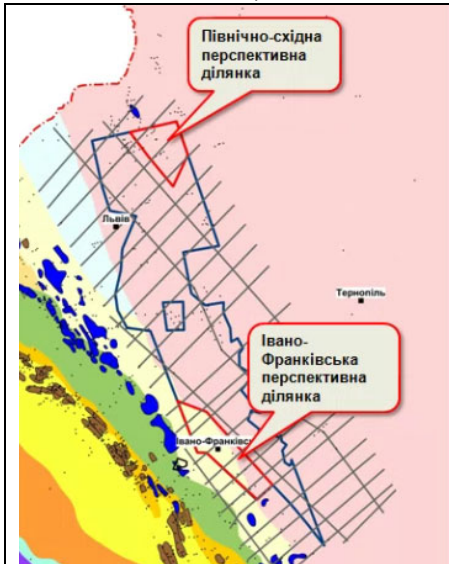
*Короткий коментар.* При проведенні обстеження Одеської площі в інтегральному режимі із реалізацією обмеженої кількості процедур інструментальних вимірів відгуки (сигнали) на частотах (спектрі частот) ВВ в межах всіх трьох ділянок зафіксовані!

На центральній ділянці площі відгуки на частотах ВВ зафіксовані на межі синтезу 57 км в вулканічному комплексі, заповненому 7-ою групою осадових (карбонатних) порід. В вулканах, заповнених вапняками, умови для синтезу ВВ на глибині 57 км існують.

В центральних частинах вулканічних структур, в яких існують умови для синтезу ВВ на глибині 57 км, продуктивні пласти можуть бути зафіксовані також в глибоких та глибинних інтервалах розрізу.

При проведенні детального обстеження Олеської площі, перспективні для буріння свердловин ділянки та площадки можуть бути локалізовані.

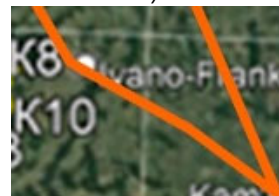
Зондуванням (скануванням) розрізу глибини залягання та товщини насичених вуглеводнями пластів можуть бути визначені. Процедура вертикального сканування розрізу дозволяє також визначити типи порід в насичених вуглеводнями пластах.



**Рис. 10.** Перспективні ділянки Олеської площі [Петровський та ін., 2025]



а)



б)

**Рис. 11.** Знімки перспективних ділянок площі



**Рис. 12.** Супутниковий знімок центральної ділянки Олеської площі

**Результати додаткових інструментальних вимірювань.** На конференції в м. Львів, в доповіді [Петровський та ін., 2025] запропоновано детальні дослідження проводити в межах Північно-східної та Івано-Франківської (рис. 10) перспективних ділянок Олеської площі. Така пропозиція сформульована за результатами аналізу даних буріння пошукових свердловин в межах площі. Заслухана доповідь спонукала авторів провести додаткові інструментальні вимірювання в межах розміщення запропонованих ділянок (зондування розрізу в першу чергу). Результати зондування розрізу в межах перспективних ділянок зводяться до наступного [Якимчук та ін., 2025б].

1. В процесі зондування інтервалу 0-7 км Північно-східної ділянки (рис. 11а), крок 25 см, відгуки (сигнали) на частотах ВВ зафіксовані в двох інтервалах глибин: **430-484 та 2387-2509 м**. А при додатковому скануванні інтервалу **2387-2509 м**, крок 1 см, – **2504.2-2507.65 м (3.45 м)**.

2. При зондуванні інтервалу 0-7 км Івано-Франківської ділянки (рис. 11б), крок 25 см, відгуки (сигнали) зафіксовані в одному інтервалі глибин: **2978-3037 м (59 м)**. А при додатковому скануванні інтервалу **2978-3037 м**, крок 1 см, – в двох інтервалах глибин: **3028.79-3030.4 м (1.51 м); 3033.7-3035.2 м (1.5 м)**. При обробці знімка ділянки (рис. 11б) з поверхні сигнали на частотах ВВ не фіксувались на протязі 150 с вимірювань.

3. При скануванні інтервалу 0-10 км центральної ділянки Олеської площі (рис. 12) з кроком 1 м відгуки на спектрі частот ВВ зафіксовані в **14 інтервалах розрізу**: 1) 246,0-343,0; 2) 450,0-505,0; 3) 676,0-749,0; 4) 980,0-1278,0; 5) 1521,0-1803,0; 6) 1996,0-2074,0; 7) 2322,0-2700,0; 8) 3111,0-3456,0; 9) 3966,0-4156,0; 10) 5021,0-5712,0; 11) 6030,0-6631,0; 12) 7298,0-7893,0; 13) 8255,0-8541,0; 14) 9054,0-9292,0.

Крок сканування 1 м – крупний. В виділених інтервалах розрізу колекторів з ВВ різних товщин може бути декілька.

*Висновки.* Результати рекогносцирувального обстеження прямопошуковими методами трьох ділянок Олеської площі дозволяють констатувати, що детальні геолого-геофізичні роботи з метою вибору майданчиків для буріння пошукових свердловин на початковому етапі досліджень доцільно проводити в межах центральної ділянки площі, на якій сигнали на частотах вуглеводнів (нафта, конденсат, газ) зафіксовані на межі їх синтезу 57 км. Локальні ділянки (площадки) для буріння свердловин в межах площі (центральної ділянки) можуть бути локалізовані під час детального обстеження ділянки прямопошуковими методами і зондування розрізу з дрібним кроком.

В процесі проведення експериментальних досліджень на Олеській ліцензійній площі отримані додаткові свідчення на користь абіогенного (глибинного) синтезу ВВ (нафта, газ, конденсат) в вулканічних комплексах, заповнених вапняками.

### **Результати застосування частотно-резонансних методів для вибору ділянки буріння свердловини на водень**

Апробацію прямопошукових методів проведено також в межах локальної ділянки на заході України в Рівненській області, обстеження якої проводилось з метою вибору площадки для буріння пошукової свердловини на природний водень. Результати проведених робіт зводяться до наступного [Якимчук, Корчагін, 2025б].

**Обстеження крупної ділянки.** На початковому етапі досліджень з метою пошуків скупчень водню в рекогносцирувальному режимі проведено частотно-резонансну обробку супутникового знімка території в районі пошуків (рис. 13а). На другому етапі робіт проводилося обстеження окремих фрагментів знімка на рис. 13а з метою локалізації ділянок скупчення водню в розрізі.

В процесі частотно-резонансної обробки всього супутникового знімка площі пошуків (рис. 13а) з поверхні зареєстровані сигнали на частотах водню, нафти, конденсату, газу, бурштину, бактерій метаноокисляючих, фосфору (червоного, жовтого), горючих сланців, газогідродатів, антрациту, бактерій водневих, живої води, мертвої води (слабкої інтенсивності, 7 с), льоду. Відгуки від глибинних базальтів і солі натрій-хлористої не отримані.

Зафіксовані сигнали від 1-6, 7-ї (вапняки), 8-ї (доломіти), 9-ї (мергелі) та 10-ї (кременисті) груп осадових порід, а також 6-ї (габро і базальти), 6А (долерити та андезити), 6Б (лампроїти) і 14-ої груп магматичних порід.

На поверхні (глибині) синтезу ВВ 57 км зареєстровано відгуки від нафти, конденсату, газу, бурштину, фосфору (жовтого), азоту, вуглецю, водню, живої води, а на глибині 59 км – від мертвої води, кисню та вуглекислого газу. На поверхнях 13 км та 48 км відгуки від мертвої води не отримані.

Відгуки від нафти з вапняків зареєстровані на глибині 57 км, а на поверхнях 11 км, 13 км та 46 км не зафіксовані. Сигнали від нафти з псамітів (друга група осадових порід) на глибині 11 км були відсутні.

Фіксацією відгуків на різних поверхнях визначено глибини коренів наступних вулканічних комплексів: 1) 1-6 групи осадових порід – 470 км; 2) вапняки – 470 км; 3) доломіти – 470 км; 4) базальти – 470 км; 5) крем'янисті породи – 723 км. З інтервалу 470-996 км зареєстровано відгуки від гранітів (старих). Відгуки від мергелів на поверхні 50 км були відсутні, що свідчить про розташування кореня вулкана з мергелями, за межами площі обстеження.

В цілому, територія рекогносцирувального обстеження на рис. 13а перспективна для пошуків прогнозованих скупчень нафти, конденсату, газу, бурштину, водню, живої (цілющої) води.

Надалі, при обробці окремих фрагментів супутникового знімка на рис. 13 проводилася фіксація відгуків лише від компоненти пошуків (водню), деяких типів порід та окремих хімічних елементів.

**Результати обстеження локальної ділянки.** Положення локальної ділянки обстеження на супутниковому знімку території пошуків скупчень водню показано на рис. 13.

В процесі обробки фрагмента знімка з вирізом на рис. 13б зареєстровані відгуки лише від 10-ої групи осадових (кременистих) порід.

Під час обробки локального фрагмента знімка ділянки на рис. 13в зареєстровані відгуки на частотах водню, фосфору червоного, азоту (слабкої інтенсивності), бактерій водневих, живої води, 8-ї (доломіти) групи осадових порід та 6-ої (базальти), 6А, 6Б груп магматичних порід. Скануванням розрізу з поверхні з кроком 1 см, верхня кромка базальтів зафіксована на глибині 9 м; відгуки від базальтів простежені скануванням з кроками 10 см і 1 м до 1 км (глибше сканування не проводилося). Корінь базальтового вулкана фіксацією відгуків на різних поверхнях визначено на глибині 470 км.

При скануванні розрізу з поверхні, крок 5 см, зафіксовані відгуки на частотах водню з базальтів, м: 21– (з 50 – на крок 10 см) – (67 – інтенсивний – 78) – (170 – інтенсивний 200)(210 – інтенсивний – (220 - дуже інтенсивний – 245)) – (269-інтенсивний – (306 дуже інтенсивний – 360)) (450 – інтенсивний –475) – (500 – інтенсивний (640 – дуже інтенсивний – 675)) – (730 – інтенсивний – 755) – (775 – інтенсивний – 798) (900 – інтенсивний – 912) (935 –інтенсивний – (965 – дуже інтенсивний – 1008)).....(далі сканування не проводилося).

На поверхні 10 м з верхньої частини розрізу отримані відгуки від водню, червоного фосфору і живої води.

На поверхні 0 м з верхньої частини розрізу зафіксовано сигнали від водню та червоного фосфору (міграція газів в атмосферу).

При скануванні розрізу з поверхні крок 1 см, відгуки від водню отримані з інтервалу 1.0-3.8 м; далі сигнали почали фіксуватися із 23 м.

В процесі сканування розрізу з поверхні, крок 1 см, отримані відгуки від живої води, м: 1-(9-10 -інтенсивний) (з 20 м, 10 см крок)- (30 - інтенсивний -(82 - дуже інтенсивний - 147)) (170 – інтенсивний, дуже інтенсивний 220) (далі сканування не проводилося).

При обробці знімка з поверхні зафіксовані сигнали від наступних зразків доломітів з колекції: 1) доломіт заміщення (131); 2) доломіт кавернозний (133).

Відгуки від доломітів заміщення фіксувалися при скануванні з кроками 1 см і 10 см з 4 м до 100 м (далі сканування не проводилося). На глибині 10 м зареєстровані інтенсивні сигнали.

При скануванні розрізу 0-10 м, крок 1 см, відгуки на частотах кавернозних доломітів отримані з інтервалу 1.40-4.40 м. Сигнали водню з доломітів заміщення в цьому інтервалі розрізу були відсутні.

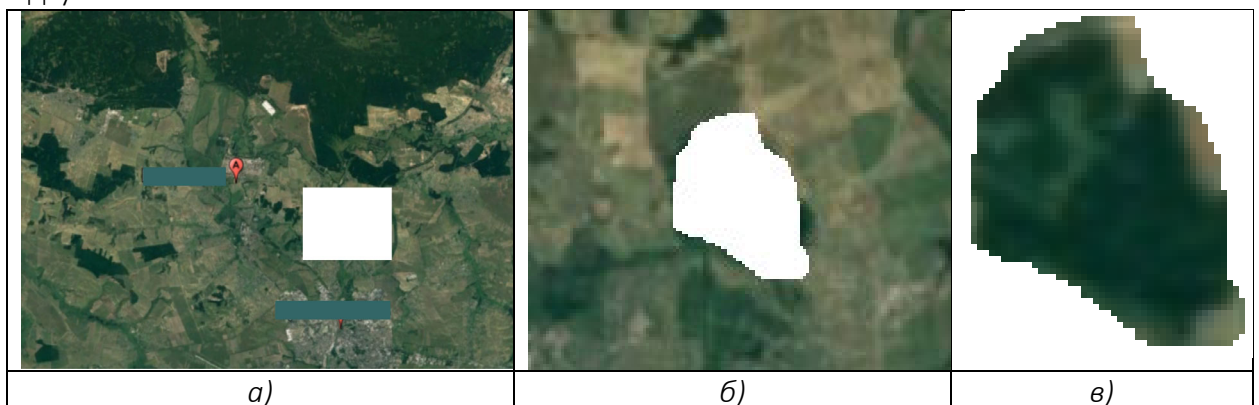


Рис. 13. Положення локальної ділянки обстеження на супутниковому знімку території пошуків скупчень водню.

На глибині 10 м відгуки від кавернозних доломітів отримані тільки з верхньої частини розрізу. З інтервалу 0-10 м не отримані відгуки від живої води з кавернозних доломітів при скануванні розрізу з кроком 1 см.

При скануванні розрізу з поверхні, крок 1 см, відгуки від живої води з доломітів заміщення отримані з інтервалу 12 см - 8.9 м. На глибині 9 м відгуки від живої води з доломітів заміщення були відсутні з нижньої частини розрізу.

З метою верифікації та уточнення отриманих даних проведено також обробку супутникового знімка локальної ділянки у більшому масштабі (рис. 14). Окремі фрагменти локальної ділянки показано на рис. 15.

Відгуки на частотах водню і червоного фосфору при обробці знімка на рис. 15а не зафіксовано.

Під час обробки знімка на рис. 14 із вирізом фрагмента на рис. 15а відгуки від водню та фосфору червоного зафіксовані, а з вирізом фрагмента на рис. 15б не отримано.



**Рис. 14.** Супутниковий знімок (Google Earth) локальної ділянки обстеження.

Сигнали від водню і червоного фосфору зафіксовані при обробці фрагмента знімка на рис. 15б. Відгуки від доломітів у межах цього фрагмента не отримані. При скануванні розрізу з поверхні, крок 1 см, відгуки від базальтів почали фіксуватися з 9.5 м. Корінь базальтового вулкана визначений на глибині 470 км. На поверхні 10 м з верхньої частини розрізу отримані відгуки від 2-ї (псаміти), 3-ї, 4-ої та 8-ої груп осадових порід.

В межах фрагмента знімка на рис. 15а отримані відгуки лише від 8-ї (доломіти) групи осадових порід. На глибині 50 км також зафіксовані сигнали тільки від цих порід. При скануванні розрізу з поверхні, крок 1 см, відгуки від доломітів заміщення (131) почали фіксуватися з 3.8 м, а від доломітів кавернозних – з 2.8 м. На поверхні 4 м з верхньої частини розрізу отримані сигнали від 2-ї (псаміти), 3-ї, 4-ї та 8-ї груп осадових порід.

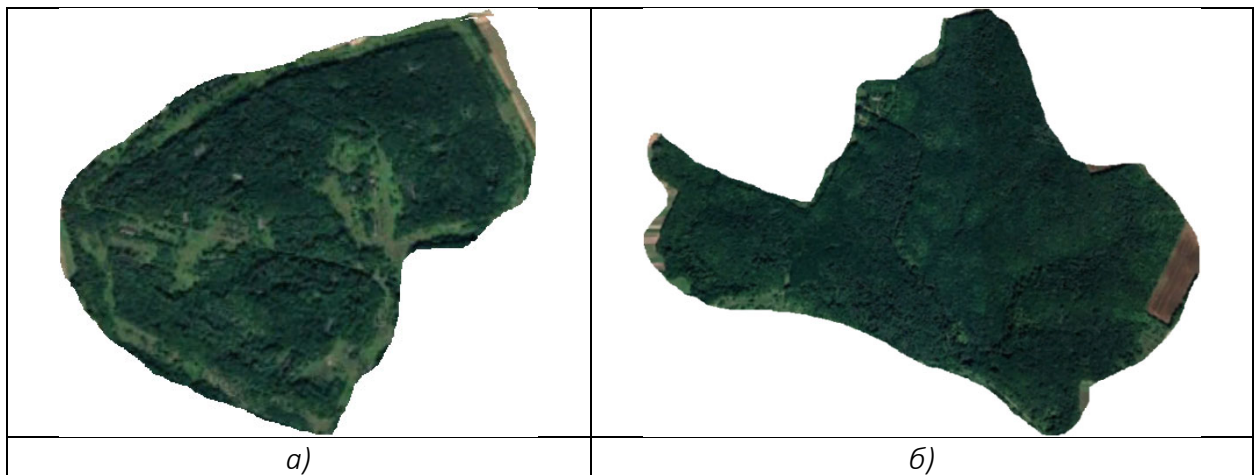


Рис. 15. Супутникові знімки (Google Earth) фрагментів локальної ділянки обстеження.

Проведено також частотно-резонансну обробку знімків двох невеликих зон (рис. 16б і 16в) в межах фрагмента обстеження на рис. 15б.

Під час обробки знімка на рис. 16б із поверхні зафіксовано відгуки від базальтів, живої води, водню, бактерій водневих, фосфору червоного. Скануванням розрізу, крок 1 см, верхня кромка базальтів зафіксована на глибині 7.9 м.

При скануванні розрізу з поверхні, крок 1 см, відгуки від водню отримані з наступних інтервалів, м: 1) 2.6-4.5 м, 2) 24.5- (з 25 м на крок 10 см) (85-інтенсивний-107)-(123-інтенсивний-(150- дуже інтенсивний -192))(214-інтенсивний -270)-(290-інтенсивний -326)-(365-інтенсивний -388)-(420-інтенсивний -430)-(445-інтенсивний -(450-дуже інтенсивний-486))...( до 500 м простежено).

В межах знімка на рис. 16в відгуки від базальтів, водню та фосфору червоного не отримані. Зафіксовано сигнали лише від солі. Верхня кромка солі зафіксована скануванням із кроком 10 см на глибині 17 м. Корінь соляного вулкану визначено на глибині 723 км.

З поверхні в контурах знімка на рис. 16в відгуки від нафти, газу та фосфору білого не отримані. Зазначимо також, що при додатковому обстеженні знімка на рис. 15б відгуки від солі слабкої інтенсивності зафіксовані (із затримкою 9 с).

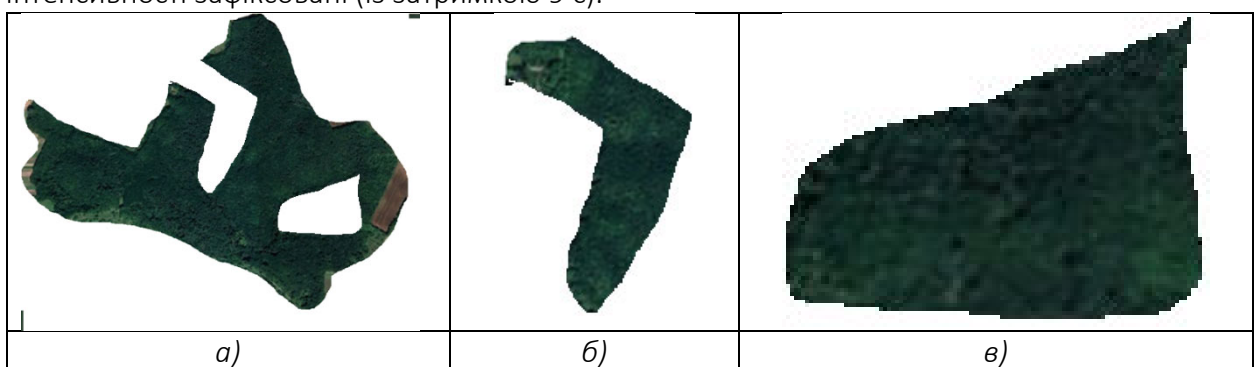


Рис. 16. Знімки (Google Earth) невеликих зон обробки та їх розміщення на фрагменті локальної ділянки обстеження

Фрагмент зображення на рис. 16б розбитий на чотири локальні зони (рис. 17), частотно-резонансна обробка яких проведена додатково.

*Зона 1 (рис. 17а).* Під час обробки знімка на рис. 17а з поверхні зафіксовано відгуки від базальтів, живої води, водню, водневих бактерій, фосфору червоного; сигнали від 6А та 6Б груп порід були відсутні. Верхня кромка базальтів визначено скануванням з кроком 1 см на глибині 2 м.

При скануванні розрізу з поверхні, крок 1 см, відгуки від водню зафіксовані з інтервалу, м: 7.5-(з 10 м на крок 10 см)-(78-дуже інтенсивний -(122-супер інтенсивний -144))-(260-інтенсивний -336-інтенсивний -410)-(470-інтенсивний -500).

*Зона 2 (рис. 17б).* В межах знімка на рис. 17б відгуки слабкої інтенсивності одержані від водню (7 с), фосфору червоного (7 с), бактерій водневих (10 с). Відгуки від солі та осадових порід були відсутні. Відгуки від базальтів отримані із затримкою, а від 6А та 6Б груп магматичних порід відразу. Скануванням розрізу, крок 10 см, верхня кромка базальтів визначена на глибині 46 м.

На глибині 46 м відгуки на частотах водню, живої води та фосфору (червоного) із нижньої частини розрізу зареєстровані без затримок; з верхньої частини розрізу сигнали цих елементів були відсутні.

На глибині 46 м з верхньої частини розрізу отримані відгуки лише від 6А та 6Б груп порід; з нижньої частини розрізу сигнали від цих порід були відсутні. При скануванні розрізу крок 1 см, відгуки від порід 6Б групи почали фіксуватися з 2.8(3.0) м, а від 6А групи - з 3 м.

При скануванні розрізу з 40 м, крок 1 см, відгуки від водню зафіксовані з інтервалу, м: 47-(50 - інтенсивний-54) (на крок 10 см) - (108 - інтенсивний -140) - (155 - інтенсивний -210)-(310-інтенсивний -320)-(425-інтенсивний -(430-дуже інтенсивний -450))-(520-дуже інтенсивний - 620))....

Відзначимо також, що відгуки від водню отримані також на глибині 41 м, але зразу ж зникли. *Зона 3 (рис. 17в).* Під час обробки знімка зони зафіксовано відгуки від базальтів, живої води, водню, бактерій водневих, фосфору червоного; сигнали від 6А та 6Б груп порід були відсутні. Верхня кромка базальтів зафіксована скануванням з кроком 10 см на глибині 29 м. Відгуки від водню з базальтів почали фіксуватися при скануванні з 31 м.

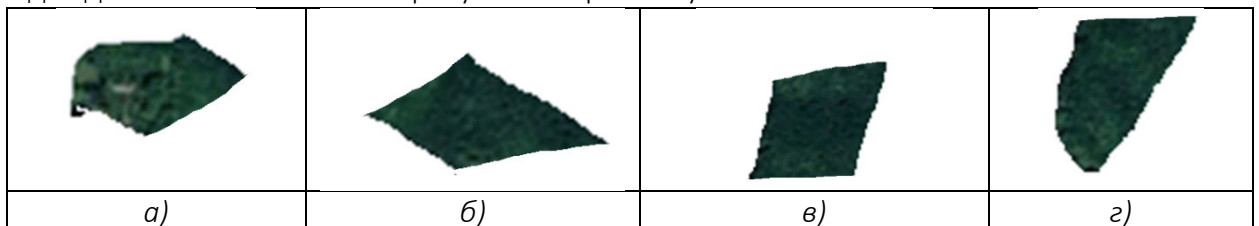


Рис. 17. Знімки (Google Earth) локальних зон обробки в межах ділянки на рис. 16б.

*Зона 4 (рис. 17г).* В межах знімка зони зафіксовано відгуки від базальтів, живої води, водню, водневих бактерій, фосфору червоного; сигнали від 6А та 6Б груп порід були відсутні. Верхня кромка базальтів зафіксована скануванням з кроком 10 см на глибині 18 м. Відгуки від водню з базальтів почали фіксуватися при скануванні з 32 м.

Локальна зона на рис. 17а є першочерговим об'єктом для буріння свердловини на водень! Площа цієї зони - приблизно 100×200 м (150×300 м).

*Висновки.* В межах території обстеження в процесі частотно-резонансної обробки супутникових знімків локальних ділянок різної площі виявлено та локалізовано зону скупчення водню та живої (цілющої) води. Такі зони майже завжди фіксуються на ділянках розташування вулканічних структур, наповнених базальтовими породами. В процесі дроблення супутникових знімків на фрагменти різної величини найперспективніші для буріння пошукових свердловин ділянки (зони) виявлено та локалізовано. Скануванням розрізу з кроками різної величини визначено потужності та глибини залягання найбільш перспективних колекторів з воднем, а також живую (цілющую) воду.

В цілому оперативно отримано значний обсяг нової (додаткової та незалежної) інформації, яка свідчить про доцільність буріння пошукових свердловин на водень і дозволяє визначити оптимальні місця їх закладення.

**Апробація прямопошукових методів на ліцензійних ділянках, проданих на аукціоні**

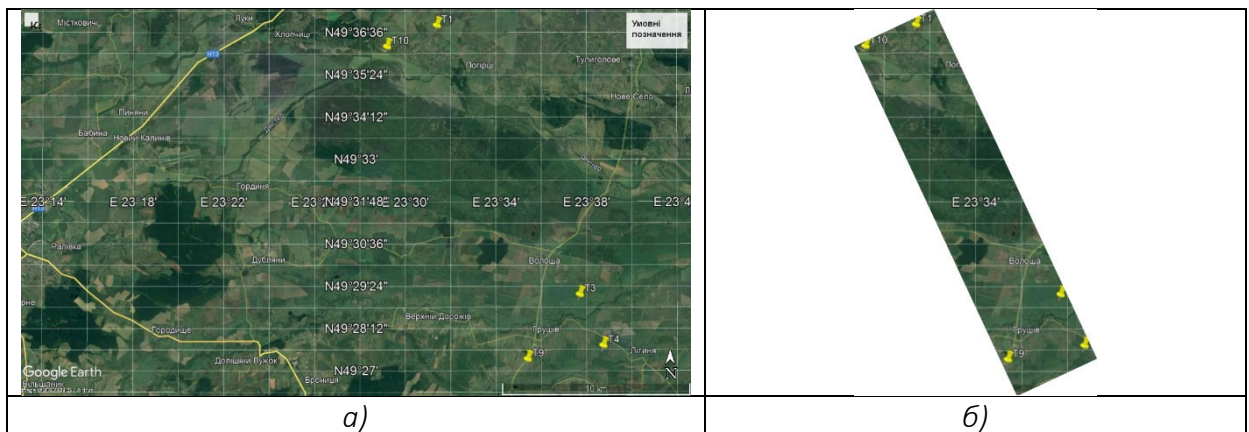
З метою демонстрації інформативності мобільних методів в інтегральному режимі проведено обстеження територій Тинівської, Решетилівської та Південно-Русанівської ділянок, проданих на аукціоні в Україні.

Інформація про Тинівське родовище, а також Решетилівську та Південно-Русанівську площі (ситуаційні плани та координати) отримана із сайтів Інтернету. З використанням координат ділянок підготовлено супутникові знімки (рис. 18-20) для частотно-резонансної обробки в демонстраційному режимі з метою додаткової оцінки перспектив виявлення нафти та газу. На рис. 18-20 положення ліцензійних ділянок показано на знімках більшої площі.

На всіх трьох ділянках обстеження виконано обмежений обсяг вимірювальних процедур.

**Тинівське газове родовище.** При обробці фрагмента знімка Тинівської площі (рис. 18б) на поверхні зареєстровані відгуки на частотах 1-6 груп осадових порід, газу, а також нафти і газоконденсату слабкої інтенсивності.

Інструментальними вимірами встановлено наявність умов для синтезу ВВ на глибині 57 км. При скануванні розрізу з кроком 10 см відгуки на частотах газу отримані з інтервалу 312-332 м. При подальшому скануванні з кроком 1 м сигнали від газу зареєстровані з двох інтервалів пошуків: 1668-(1800-2000 м дуже інтенсивний)-2070; 3550-3719 м.



**Рис. 18.** Положення Тинівської площі на супутниковому знімку (а) та фрагмент знімка частотно-резонансної обробки (б).

*Особливості результатів обробки:* а) вулкан 1-6-ої груп осадових порід; б) синтез ВВ на глибині 57 км у вулкані; в) фіксація відгуків на частотах газу із поверхні; г) реєстрація скануванням відгуків на частотах газу в трьох інтервалах розрізу.

**Решетилівська площа.** У процесі частотно-резонансної обробки знімка Решетилівської площі (рис. 19б) з поверхні зареєстровані відгуки на частотах 1-6 груп осадових порід. Корінь вулкана цих порід визначено на глибині 470 км.

При скануванні розрізу з кроком 1 м відгуки на частотах газу отримані з інтервалу пошуків 1392-1679 м.

Спільні сигнали газу та 2-ої групи осадових порід (псаміти) при скануванні з кроком 1 м зареєстровані з інтервалу пошуків 1406-1604 м. При скануванні цього інтервалу з кроком 10 см відгуки на частотах газу зареєстровані з трьох пластів: 1423-1434 м, 1470-(1490-1515-дуже інтенсивний)-1517 м, 1600-1605 м.

*Особливості результатів обробки:* а) вулканічний комплекс осадових порід 1-6 груп з коренем на глибині 470 км; б) синтез ВВ (газ, нафта) на глибині 57 км у вулкані; в) відгуки дуже слабкої інтенсивності на частотах нафти з поверхні; г) інтервал пошуків покладів газу в псамітах (піщаниках) при скануванні розрізу з великим кроком; д) три газонасні пласти в псамітах при скануванні з кроком 10 см.

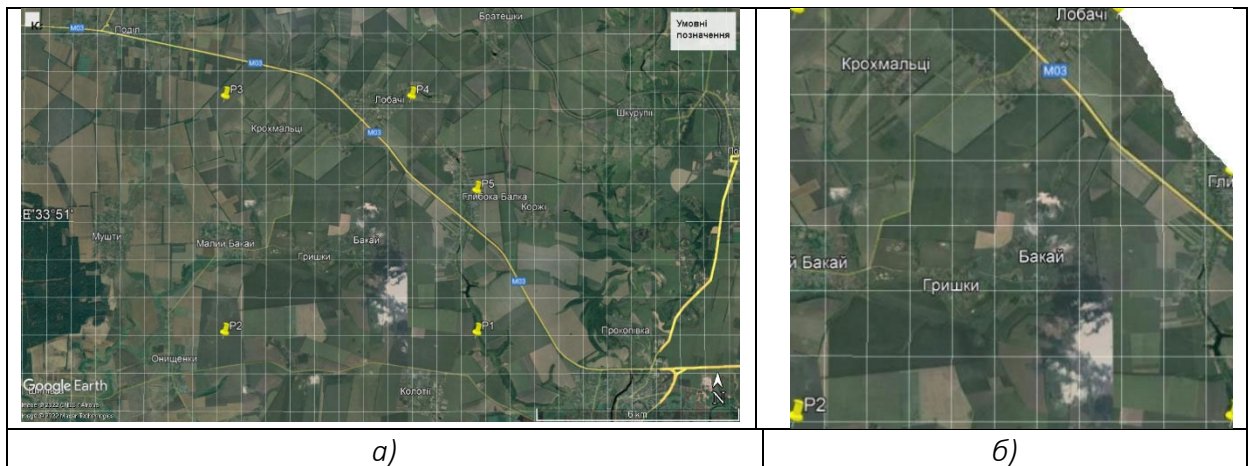


Рис. 19. Положення Решетилівської площі на супутниковому знімку (а) та фрагмент знімка частотно-резонансної обробки (б).

**Південно-Русанівська площа.** У процесі частотно-резонансної обробки знімка площі на рис. 20б з поверхні зареєстровані сигнали на частотах газу, фосфору (жовтого), а також 7-ї (вапняки) і 8-ї (доломіти) груп осадових порід. Нижня кромка вапняків зафіксована на глибині 99 км, а з інтервалу 99-723 км отримані відгуки від 10-ї (кременисті) групи осадових порід. При скануванні розрізу з великим кроком 1 м, відгуки на частотах газу з вапняків зареєстровані з наступних інтервалів пошуків газонасичених пластів: 923-999 м, 1208-(1300-1500-дуже інтенсивний)-1626) м, 3647-4014 м, а з кроком 10 см – 924-967 м, 980–997 м, 1209-1228 м, 1269-1293 м, 1315-1392 м, 1411-1514 м, 1564-1625 м, 3651-3759 м, 3926-4014 м.

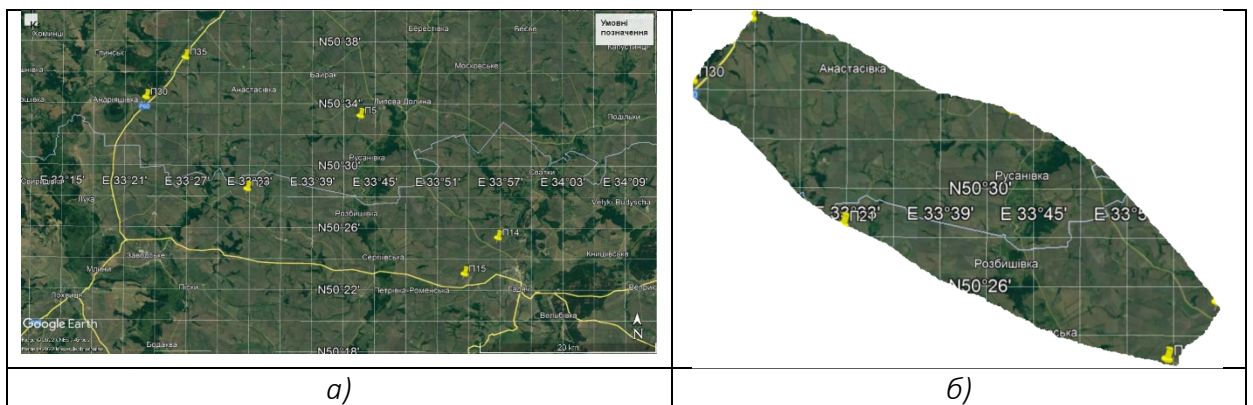


Рис. 20. Положення Південно-Русанівської площі на супутниковому знімку (а) та фрагмент знімка частотно-резонансної обробки (б).

**Особливості результатів обробки:** а) вулканічний комплекс із коренем на глибині 99 км, заповнений осадовими породами 7-ої групи (вапняки); б) синтез ВВ на глибині 57 км у вапняках; в) сигнали на частотах газу з вапняків із трьох інтервалів пошуків покладів при скануванні розрізу з великим кроком.

**Коментарі та висновок.** Експериментальні дослідження на трьох ділянках обстеження проведено без попереднього аналізу (і використання при проведенні інструментальних вимірювань) наявних геолого-геофізичних матеріалів.

Результати оперативно проведеної обробки супутникових знімків ліцензійних ділянок у демонстраційному режимі можна вважати додатковими фактами на користь доцільності проведення в їх межах додаткових робіт (довивчення) та розробки прогнозованих ресурсів

газу в структурних пастках різного типу, закартованих раніше геофізичними методами. Зазначимо, що в межах Тинівської площі розташоване Грушівське родовище газу.

З іншого боку, встановлення наявності на всіх трьох ділянках вулканічних комплексів, у межах яких створюються умови для синтезу ВВ на глибині 57 км, а також фіксація відгуків на частотах газу з поверхні та в декількох інтервалах розрізу слід вважати додатковим підтвердженням працездатності мобільних прямопошукових методів частотно-резонансної обробки супутникових знімків та фотознімків.

Обстежені ділянки поповнюють базу даних (фактів), що свідчать на користь абіогенного синтезу вуглеводнів у глибинних горизонтах Землі, вертикальної міграції флюїдів із зони синтезу до поверхні та вулканічної моделі формування скупчень (покладів) нафти, конденсату, газу у верхніх горизонтах розрізу.

На ділянках розташування запроєктованих свердловин рекомендується провести детальне сканування розрізу з метою оцінки доцільності їх буріння, а також глибин буріння. Сканування розрізу на ділянках буріння пошукових свердловин у детальному режимі надає такі можливості:

- а) з досить високою точністю визначити інтервали та потужності нафто- та газоноасичених пластів;
- б) з використанням колекцій зразків нафти та конденсату встановити тип флюїду в колекторах;
- в) визначити типи порід в колекторах з покладами та в покришках над ними.

#### **Апробація прямопошукових методів на ділянках вздовж сейсмічних профілів**

Мобільна прямопошукова частотно-резонансної обробки та декодування супутникових та фото знімків використовувалась при проведенні рекогносцирувального обстеження крупних блоків та локальних ділянок вздовж сейсмічного профілю TESZ-2021 [Starostenko at al. 2023]. Нижче наведено результати обстеження з використанням прямопошукових методів пошукової ділянки в районі міста Васильків (Київська область).

**Ділянка досліджень в районі пункту вибуху ПВ-5.** Супутниковий знімок невеликої ділянки рекогносцирувального обстеження в районі пункту вибуху ПВ-5 (координати: 50°11'02" N; 30°23'57" E) на сейсмічному профілі TESZ-2021 [Starostenko at al. 2023] наведено на рис. 21. У процесі частотно-резонансної обробки знімка з поверхні зареєстровані сигнали на частотах нафти, конденсату, газу, бурштину, вуглекислого газу, бактерій метаноокислюючих, фосфору (червоного та жовтого), горючих сланців, газогідратів, льоду, антрациту, азоту, кисню, вуглецю, водню, бактерій водневих, живої води.

Зафіксовані сигнали від 1-6 груп осадових порід, 1-ї (граніти молоді та старі), 6-ї (базальти), 6А (долерити та андезити) та 6Б (лампроїти), 14-ої груп магматичних порід. Корені вулканів, заповнених осадовими породами та базальтами, визначено на глибині 470 км. Верхній край базальтів зафіксовано скануванням з кроком 1 м на глибині 80 м, а відгуки від 1-6 груп осадових порід при скануванні з кроком 1 см почали фіксуватися із 60 см.

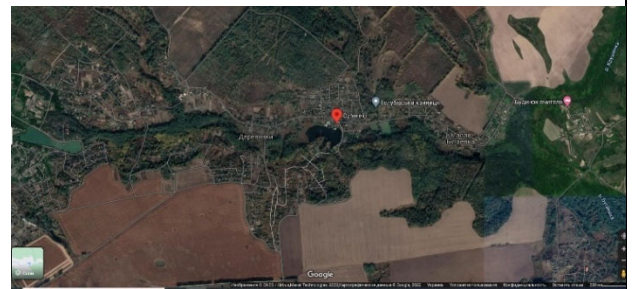
На поверхні 5 км із верхньої частини розрізу отримані відгуки лише від молодих гранітів, а з нижньої – лише від старих. На глибинах 15 км та 25 км відгуки від молодих гранітів отримані з верхньої частини розрізу; від старих гранітів сигнали зафіксовані лише на глибині 25 км. З нижньої частини розрізу відгуки від гранітів (молодих та старих) не зафіксовано.

Додатковими інструментальними вимірами з інтервалу 470-723 км отримано відгуки від 10-ої групи осадових (кременистих) порід, а з інтервалу 723-996 км – від гранітів (старих). На поверхні 723 км із верхньої частини розрізу відгуки від старих гранітів отримані із затримкою 60 с.

На поверхні 0 м із верхньої частини розрізу зафіксовано сигнали на частотах водню, фосфору (жовтого та червоного), вуглекислого газу, газу (метану), азоту, кисню (підтверджено міграцію газів в атмосферу).



**Рис. 21.** Супутниковий знімок ділянки рекогносцирувального обстеження в районі пункту вибуху ПВ-5 (жовтий маркер в центрі).



**Рис. 22.** Супутниковий знімок ділянки розташування водоносних джерел.

Скануванням розрізу з поверхні, крок 10 см, відгуки на частотах газу отримані з інтервалів: 1) 248-260 м (слабкої інтенсивності), перехід на крок 50 см, 2) 715-860 м, 3) 980-(1600-інтенсивний)-(2550-інтенсивний)-2800 м, 4) 2880-(3480-інтенсивний)... (сигнали простежені лише до 5 км). Відгуки від газу отримані з нижніх частин розрізу на глибинах 5 км, 10 км і 15 км.

На межі синтезу ВВ 57 км зареєстровані відгуки від нафти, конденсату, газу, бурштину та вуглекислого газу.

В межах площі на рис. 21 верхня кромка базальтів скануванням з кроком 10 см зафіксована на глибині 87 м. На поверхні 86 м з верхньої частини розрізу отримані відгуки від 1-6 груп осадових порід та живої води.

При скануванні з 86 м, крок 10 см, відгуки водню з базальтів почали фіксуватися зі 105 м, а сигнали від живої води при скануванні з кроком 1 см зареєстровані відразу.

При обробці фрагмента знімка в прямокутному контурі на рис. 21 на поверхні 50 км зареєстровані сигнали тільки від 6-ої (базальти) групи магматичних порід, відгуки від осадових порід не отримані. (У межах цієї ділянки розташований лише базальтовий вулкан). А у процесі обробки знімка на рис. 21 без фрагмента у прямокутнику на поверхні 50 км зафіксовані сигнали від солі, 1-6, 7-ої (вапняки), 9-ої (мергелі), 10-ої (кременисті) груп осадових порід, 1-ої (граніти старі), 6-ї (базальти), 11-ої (кімберліти) груп магматичних порід. (Під час проведення детальних інструментальних вимірювань на обстеженій території (рис. 21) можуть бути також локалізовані положення вулканічних комплексів, заповнених вапняками, мергелями, крем'янистими породами та кімберлітами).

Під час обробки знімка ділянки з водоносними джерелами на рис. 22 зареєстровані сигнали від фосфору (червоного), водню, бактерій водневих, живої води, 8-ї (доломіти) групи осадових порід, а також 6-ї (базальти), 6А і 6Б груп магматичних порід. Відгуки від нафти, конденсату, газу, бактерій метаноокислюючих та солі не отримані. Від доломітів та 6-ї, 6А, 6Б груп порід відгуки зареєстровані на поверхні 11 км з нижньої частини розрізу.

Нижня кромка доломітів визначена на глибині 99 км, базальтового вулкана – на 470 км, а з інтервалів 99-723 км і 723-996 км отримано відгуки від 10-ої групи осадових (кременистих) порід і гранітів (старих), відповідно.

Скануванням розрізу з поверхні, крок 50 см, верхня кромка базальтів визначена на глибині 730 м. На цій глибині з верхньої частини розрізу отримані відгуки від доломітів, водню, живої води та водню з доломітів (!), а з нижньої частини – від 6-ої, 6А, 6Б груп магматичних порід. Скануванням розрізу з поверхні, крок 5 см, відгуки на частотах водню з доломітів зафіксовані з інтервалів: 1) 53-97 м, 2) 118-134 м, 3) 262-(275-інтенсивний)-398 м, 4) 497-(560-інтенсивний)-(570-дуже інтенсивний)-581 м.

При скануванні, крок 1 мм, відгуки живої води фіксувалися з 30 см.

На поверхні 0 м з повітря зафіксовано відгуки від водню (з 14 с) і фосфору червоного (з 21 с), що свідчить про їх міграцію (відносно слабо) в атмосферу.

**Площа обстеження в районі м. Васильків.** В матеріалах на сайті [Тайни города...] наведено інформацію про численні водоносні джерела (у тому числі і з цілющою водою) у м. Васильків. Ці відомості зумовили доцільність додаткового обстеження більшої площі в районі м. Васильків з метою вивчення особливостей глибинної будови території. Супутниковий знімок площі додаткових інструментальних вимірювань представлено на рис. 23.

При частотно-резонансній обробці знімка на рис. 23 з поверхні зареєстровані сигнали на частотах нафти, конденсату, газу, бактерій метаноокислюючих, фосфору (червоного, коричневого, жовтого), водню, водневих бактерій, живої води, коеситу; відгуки від бурштину, золота, глибинних базальтів, солі калійно-магнієвої та натрій-хлористої не отримані.

Зафіксовані сигнали від 7-ї (вапняки), 8-ї (доломіти), 9-ї (мергелі) груп осадових порід і 1-ї (граніти старі), 6-ї (базальти), 6А, 6Б груп магматичних.

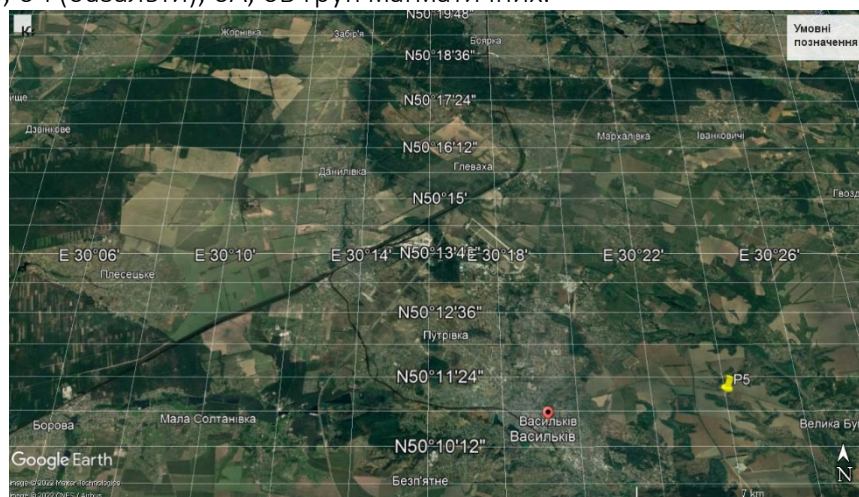


Рис. 23. Супутниковий знімок ділянки в районі м. Васильків (Київська область).

Корінь вулкана доломітів визначено на глибині 99 км, мергелів – на 218 км, вапняків та базальтів – на 470 км, гранітів (старих) – на 996 км, а з інтервалу 99-723 км отримано відгуки від 10-ої групи осадових (кременистих) порід.

На поверхні синтезу ВВ 57 км зареєстровані сигнали від нафти, конденсату, газу, фосфору (жовтого) та нафти з вапняків; відгуки від нафти з гранітів на глибинах 57 та 46 км були відсутні.

Сигнали від живої води зафіксовані на глибинах 68 км та 46 км (слабкої інтенсивності), а від мертвої – на 48 км та 59 км.

На поверхні 0 м з повітря отримані відгуки від водню (7 с), фосфору червоного (7 с) і жовтого (7 с), що свідчить про їх міграцію в атмосферу.

Скануванням розрізу з кроком 50 см верхній край базальтів визначено на глибині 730 м. На цій глибині з верхньої частини розрізу отримані відгуки від водню з доломітів.

З поверхні зареєстровані також сигнали від живої та мертвої води. При скануванні розрізу з кроком 1 мм відгуки від живої води почали фіксуватися з 35 см, а від мертвої - з 10 см.

При скануванні розрізу з поверхні до 5000 м, крок 50 см, відгуки на частотах газу отримані з інтервалу 2286-(2550-інтенсивний)-(2700-дуже інтенсивний)-(2990-дуже інтенсивний)-3125 м. Сигнали на частотах газу зареєстровані також із нижніх частин розрізу на глибинах 5 км, 10 км та 15 км.

**Основні результати та висновки.** У процесі проведення рекогносцирувального обстеження площі в районі розміщення пункту вибуху ПВ-5 (рис. 21 та 22) підтверджено наявність перспективної для пошуків покладів нафти та газу ділянки, а також додатково виявлено базальтовий вулканічний комплекс із воднем та живою (цілющою) водою. В межах базальтового вулкана прогнозовані скупчення водню в доломітах можуть бути виявлені в 4 пластах у верхній частині розрізу. Таку особливість будови розрізу на території України інструментальними вимірами зафіксовано вперше.

На відносно великій площі в районі м. Васильків (рис. 23) інструментальними вимірами підтверджено існування базальтового вулканічного комплексу з воднем та живою водою, а також виявлено заповнений вапняками вулкан, у якому існують умови для синтезу нафти, конденсату та газу на поверхні 57 км.

На ділянці в районі пункту вибуху ПВ-5 доцільно провести додаткові дослідження детального характеру (для потенційних інвесторів), в тому числі:

а) Скануванням розрізу з кроками 50 см та 1 м оцінити інтервали пошуків нафтових та газоконденсатних покладів.

б) Визначити глибини залягання та потужності нафтових, газоконденсатних та газових пластів при скануванні інтервалів пошуків нафтогазоносних покладів з кроком 1 см і дрібнішими.

в) Встановити типи порід у колекторах нафтогазоносних пластів, а також у покришках над ними.

г) З використанням наборів зразків нафти (117 екземплярів) та газоконденсату (15 екземплярів) доцільно визначити конкретні їх типи в найбільш перспективних нафтогазоносних пластах.

д) Сканування розрізу у достатній кількості точок на ділянці обстеження дозволить локалізувати положення глибинного каналу міграції нафти, конденсату та газу з межі їх синтезу у верхні горизонти розрізу.

е) На ділянці розташування базальтового вулкана скануванням розрізу з дрібними кроками доцільно визначити інтервали пошуків скупчень природного водню та живої (цілющої) води.

ж) Додатковими інструментальними вимірами можуть бути охарактеризовані цілющі властивості живої води (проти яких вірусів і паразитів жива вода буде ефективною).

**Сейсмічний розріз TESZ-2021.** В січні 2025 р. проведена додаткова апробація частотно-резонансних методів з використанням сейсмічних матеріалів вздовж профіля TESZ-2021 (рис. 24) [Starostenko et al. 2023].

В процесі проведення інструментальних вимірів з використанням рисунка із сейсмічними трасами вздовж фрагмента профіля (рис. 24) та зразків нафти, конденсату спільні сигнали (відгуки) почали реєструватися із 13 с інструментальних вимірів!

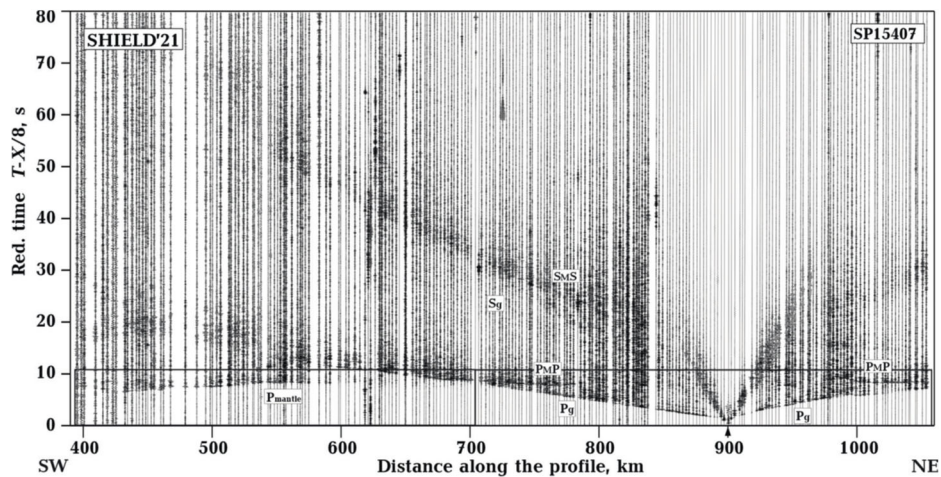


Рис. 24. Сейсмічний запис P- і S-хвиль, нормалізованих за вертикальними компонентами для сейсмічного розрізу SP15407 [Starostenko et al. 2023].

При проведенні інструментальних вимірів такого ж характеру спільні сигнали (відгуки) реєструвались також з 5-ої с вимірів від солі, осадових порід 1-6, 8-ої (доломіти), 9-ої (мергелі) груп, гранітів, гнейсів, кристалічних сланців, аспідних сланців.

Результати проведених експериментів в черговий раз засвідчили про інформативність сейсмічних записів і можливість (та доцільність) їх використання для частотно-резонансної обробки при пошуках горючих та рудних корисних копалин.

*Висновки.* Проведені експериментальні дослідження в різних регіонах світу свідчать про те, що коректно побудовані та представлені сейсмічні розрізи (у тому числі і з використанням технології STRYDE) через перспективні структури є інформативними для частотно-резонансної обробки та можуть бути використані для додаткового підтвердження результатів обробки супутникових знімків та фотознімків ділянок обстеження. Частотно-резонансна обробка сейсмічних розрізів сприятиме підвищенню інформаційної змістовності сейсмічних матеріалів (наповненню сейсмічних розрізів конкретними комплексами порід та корисними копалинами).

#### Ділянки рекогносцирувального обстеження на території України

*Липовеньківсько-Сухоташлицька ділянка ореолів золота.* Супутниковий знімок ділянки обстеження (рис. 25) підготовлено для обробки з використанням графічних матеріалів статті [Павлюк та ін., 2019].

При частотно-резонансній обробці знімка сигнали на частотах золота зафіксовані (хоч і слабкої інтенсивності).

Відгуки від нафти, конденсату, газу, графіту, водню, води, алмазів та солі не зареєстровані, від мертвої води сигнал отримано.

Зареєстровані сигнали без затримки від 1, 2 та 4 груп магматичних порід, відгуки від осадових порід відразу не отримані.

Фіксацією відгуків різних глибинах (50, 150, 450, 550, 995, 996 км), корінь каналу (вулкана) гранітних порід визначено на глибині 996 км.

На поверхні 400 км отримано відгуки від 5, 7 і 8 зразків гранітів (молодих), а на поверхні 600 км – лише з 12-19 зразків (старих). Отже, ділянка обстеження розташована в межах старого та молодого гранітних вулканів.

Скануванням розрізу з поверхні, кроки 1 см і 5 см відгуки на частотах золота отримані з інтервалу 49-(80-сильний)-99 м. Глибше сканування здійснювалося з кроком 10 см до 200 м і кроком 50 см до 500 м, проте відгуки золота у цьому інтервалі не отримані.

Відгуки від золота отримані з нижньої частини розрізу поверхнях 500 і 600 м, а на поверхні 700 м – сигнали були відсутні.

Сканування розрізу з 500 м, крок 50 см зафіксований другий інтервал відгуків від золота: 590-600-(інтенсивний)-650 м.

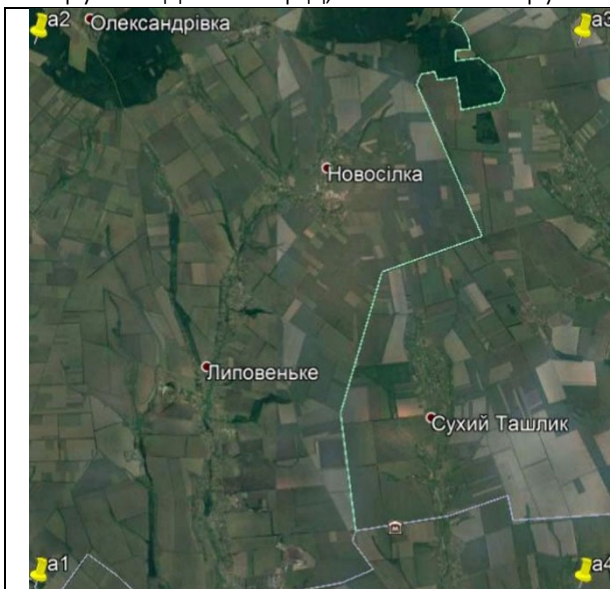
З поверхні зафіксовані сигнали від наступних хімічних елементів: цинк, галій, германій, ртуть, талій, свинець, вісмут, полоній.

**Територія Теплицького та Бершадського районів Вінницької області.** З використанням графічних ілюстрацій із статті [Ентін та ін., 2019] для проведення експериментів підготовлено супутниковий знімок ділянки обстеження – рис. 26.

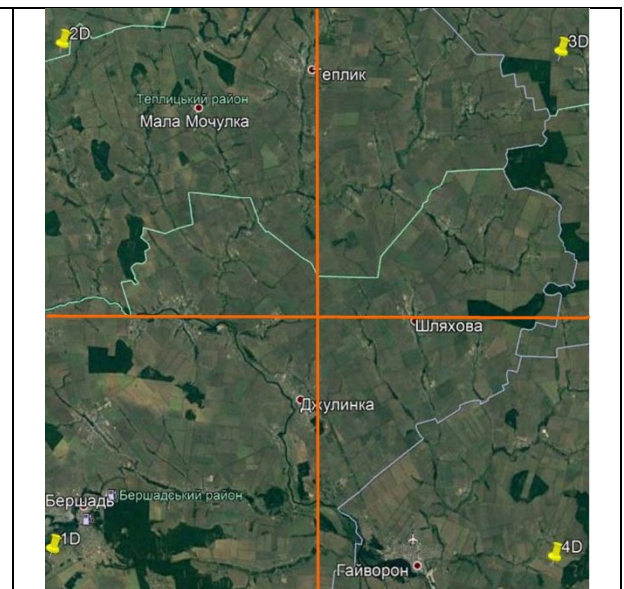
При частотно-резонансній обробці знімка ділянки (рис. 26) із поверхні відгуки на частотах золота не зафіксовано?! Не отримано сигнали від золота на поверхні 59 км! Це перша несподіванка. У статті [Ентін та ін., 2019] наводиться інформація про виявлені ореоли золота геохімічною зйомкою!

З поверхні зафіксовано сигнали від нафти, конденсату, газу, бурштину, горючого сланцю, брекчії аргілітової, газогідратів, льоду, вугілля, антрациту, води глибинної та мертвої, бурого вугілля (два типи), лонсдейліту, солі калій-магнієвої та солі. Це друга несподіванка! Такі результати свідчать про наявність цієї площі глибинного вулкана осадових порід (на УЦ!).

Подальші інструментальні вимірювання підтвердили це: з поверхні зафіксовано відгуки від 1-6 груп осадових порід, а також 1-10 груп магматичних.



**Рис. 25.** Супутниковий знімок Липовеньківсько-Сухоташлицької ділянки ореолів золота.



**Рис. 26.** Супутниковий знімок ділянки з фрагментами території Теплицького та Бершадського районів Вінницької області.

Фіксацією відгуків від різних груп порід на різних глибинах визначено глибини коренів наступних вулканів: 1) 1-6 група осадових порід – 470 км; 2) граніти – 470 км; 3) сіль – 723 км; 4) 7-а група магматичних (ультрамафічних) порід - 723 км.

Сигнали від золота з гранітів не отримані з поверхні та на глибині 59 км.

Відгуки від нафти з гранітів і солі не зафіксовані, а з другої групи осадових порід зареєстровані. Отримано також сигнали від нафти з 7-ої групи магматичних порід з поверхні, а також на глибині 57 км.

Фіксацією відгуків на різних глибинах встановлено, що верхній край ультрамафічних порід розташований в інтервалі глибин 4.7-4.8 км.

На поверхні 4.7 км із верхньої частини розрізу отримані відгуки від гранітів та солі. Верхня кромка цих порід розташована в інтервалі 300-400 м. Скануванням розрізу з 300 м, крок 5 см відгуки від солі почали фіксуватися з 347 м.

Від зразка гранітів 16 (старі) відгуки почали фіксуватися в інтервалі 16-17 км. Скануванням розрізу з 16 км, крок 50 см відгуки від 16 зразка почали фіксуватися з 16.070 км та простежені з кроками 1 м та 10 м до 22.800 км.

Скануванням розрізу з 4.7 км, крок 10 см відгуки від нафти з ультрамафічних порід отримані з наступних інтервалів: 1) 4718 - на крок 1 м -5340 м; 2) 5610-(6550-інтенсивний)-6970 м; 3) 8290-9630 м (до 10 км. простежено).

З інтервалу 6970-8290 м (відсутність нафти) отримані відгуки від гранітів.

Відгуки від нафти з осадових порід зафіксовані на поверхні 57 км.

Скануванням розрізу з 4.7 км, крок 10 см відгуки від нафти з 2-ї групи осадових порід отримані з наступних інтервалів: 1) 4715-(інтенсивний)(4770-інтенсивний)(4780-дуже інтенсивний)(4-інтенсивний)(інтенсивний) )(5000-інтенсивний)(5220-інтенсивний)-5373 м, на крок 1 м; 2) 5480-6385 м; 3) 7050-(7770-інтенсивний)-8845 м; 4) 9430-10150 м (до 10200 м простежено).

Скануванням розрізу, крок 10 см, відгуки від гранітів зафіксовані з 8 м.

Для попередньої локалізації виявлених вулканічних комплексів знімок ділянки обстеження (рис. 26) було розбито відрізками на чотири окремі фрагменти, частотно-резонансна обробка яких проведена окремо.

*Фрагмент 1 (північний захід).* З поверхні зафіксовані відгуки від алмазів, солі, осадових порід 1, 2, 3 груп, а також 1, 2, 3, 4, 5, 11 магматичних груп.

Корінь гранітного каналу зафіксовано на глибині 996 км. На поверхні 470 км отримано відгуки лише від «старих» зразків гранітів.

Сигнали від 11 групи магматичних порід (кімберліти) зафіксовані в інтервалі 11-12 км.

*Фрагмент 2 (північний схід).* З поверхні зареєстровані відгуки від нафти, конденсату, газу, бурштину, горючого сланцю, брекчії аргілітової, газогідратів, льоду, вугілля, антрациту, води глибинної (слабкий), води мертвої, солі, осадових порід 1-6 груп і магматичних порід 1-ої групи (граніти) (із затримкою).

Фіксацією відгуків різних глибинах (50, 150, 450, 550, 650, 750, 723 км) корінь соляного вулкана визначено на глибині 470 км, а 1-6 груп осадових порід – на 723 км.

*Фрагмент 3 (південний захід).* З поверхні зафіксовані відгуки від лонсдейліту, солі калій-магнієвої, осадових порід 7-9 груп та магматичних порід 1-5, 7-8 груп.

Фіксацією відгуків на різних глибинах корені вулканів 7-ї групи (вапняки) та 8-ї групи (доломіти) осадових порід встановлені на глибині 470 км, а 7-ї групи магматичних (ультрамафічних) порід – на 723 км.

З поверхні із затримкою зафіксовані сигнали на частотах нафти з вапняків, а також з 7-ї групи магматичних порід.

*Фрагмент 4 (південний схід).* При обробці фрагмента знімка з поверхні зафіксовані сигнали від водню, глибинної води, солі, осадових порід 8, 9, 10 груп і магматичних порід 1, 2, 3, 4, 5, 6 груп.

Корені вулканів 8-ої групи (доломіти) та 9-ої групи (мергелі) осадових порід визначено на глибині 470 км.

Корінь базальтового вулкана зафіксовано в інтервалі 95-96 км. Верхня кромка базальтів скануванням розрізу з поверхні крок 1 м зафіксована на глибині 240 м. Відгуки простежені до 25 км.

Сигнали від 1-6 групи магматичних порід (граніти) зафіксовані в інтервалі від поверхні до 6.275 км.

Відгуки від водню при скануванні з 240 м почали фіксуватися з 250 м.

На поверхні 240 м з верхньої частини розрізу зафіксовано відгуки від доломітів та мергелів, від води та водню відгуки з верхньої частини розрізу не отримані!

Сигнали від води при скануванні розрізу почали фіксуватися з 243 м, а відгуки від води з базальтів (у тому числі й дуже інтенсивні) – з 260 м.

Фіксацією відгуків на різних глибинах нижня кромка 10-ої групи осадових порід встановлена в інтервалі 53-54 км.

*Ділянка кар'єру.* У статті [Єнтін та ін., 2019] наводиться супутниковий знімок ділянки розташування занедбаного кар'єру в районі населеного пункту Чернятка. Під час обробки знімка цієї ділянки з поверхні зафіксовано відгуки від 1-6, 7-10 груп осадових порід, Корінь вулкана, заповненого вапняками, визначено на глибині 470 км.

На поверхні 57 км з великою затримкою отримано сигнали від нафти.

**Кар'єр каолінових глин в Житомирській області.** Під час проведення експериментів використовувався зразок каолінової глини, представлений на рис. 27. Супутниковий знімок району розташування відомого кар'єру каолінів у Житомирській області показано на рис. 28. При частотно-резонансній обробці цього знімка отримані сигнали тільки від 8-ої групи осадових порід, від магматичних порід відгуки були відсутні. З поверхні зафіксовані також відгуки на частотах зразка каолінів на рис. 27.

Фіксацією відгуків на різних глибинах (50, 150, 250, 350, 450, 470 км) корінь вулкана (каналу), заповненого 8-ою групою осадових порід (доломіти), визначено на глибині 470 км.

**Локальні ділянки обстеження у Хмельницькій області.** Основна мета робіт – підтвердження прогнозованої наявності у цьому районі області покладів графіту, урану та апатитів.

*Перша ділянка розташована* у районі населеного пункту Буртин у Полонському районі (рис. 29). З поверхні при обробці знімка (рис. 29) зафіксовано сигнали від вуглецю, радону, від урану та солі відгуків не отримано.

На ділянці зареєстровані відгуки від 1, 2 та 4 груп магматичних порід, від осадових порід сигнали не отримані.



Рис. 27. Фотографія зразка каоліну.



Рис. 28. Супутниковий знімок ділянки з кар'єром каолінових глин у Житомирській області (Україна).

Фіксацією відгуків різних глибинах (5, 10, 15, 20, 50, 150, 250, 350, 450, 550, 470 км) корінь гранітного вулкана визначено на глибині 470 км. В інтервалі гранітів зафіксовані сигнали лише від 2-9 зразків молодих гранітів, від зразків 11-19 старих гранітів відгуки не отримані. З поверхні не отримано відгуків від ВВ (нафта, конденсат, газ), водню, води, мертвої води. На частотах зразків бурого вугілля з Амурської області сигнали зафіксовані.

Від зразка графіту відгуки з нижньої частини розрізу фіксувалися на поверхнях 0, 1, 2 км, а на поверхнях 2.5 і 3 км сигнали вже були відсутні. Отже, нижня межа прогнозованих покладів графіту перебуває у інтервалі глибин 2 – 2.5 км.

На поверхні 2.5 км зареєстровані також відгуки радону, а від урану сигнали були відсутні з нижньої і верхньої частин розрізу.

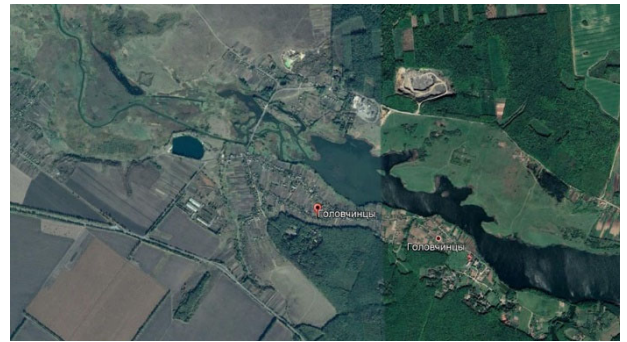
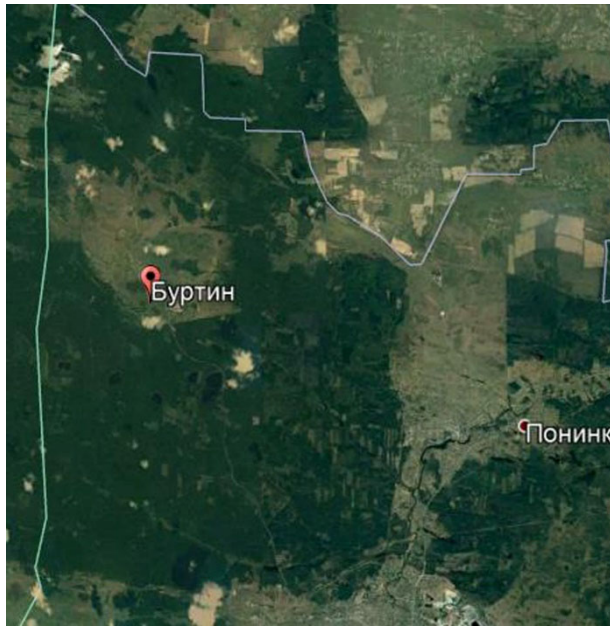


Рис. 30. Супутниковий знімок ділянки обстеження у районі н. п. Головчинці (Хмельницька область).

Рис. 29. Супутниковий знімок ділянки обстеження у районі н. п. Буртин (Хмельницька область).

Друга ділянка обстеження розташована в районі с. Головчинці у Летичівському районі (рис. 30).

Під час обробки знімка ділянки (рис. 30) на частотах зразків апатитів та фосфатів відгуки зафіксовані з поверхні. При цьому відгуки тільки зразка фосфатів були відсутні, а від апатитів отримані.

З поверхні не зафіксовано відгуків від ВВ, бурштину, вугілля, водню, води, мертвої води, солі калій-магнієвої та осадових порід. Отримано сигнали від 7, 8, 9 та 10 груп магматичних порід. Фіксацією відгуків на різних глибинах (2.5, 5, 50, 150, 250, 350, 450, 550, 450, 550, 650, 750, 722, 723 км) корінь вулкана, заповненого 7-ою групою магматичних порід, визначено на глибині 723 км.

**Іллінецький кратер.** При частотно-резонансній обробці супутникового знімка Іллінецької структури (рис. 31а) з поверхні не зафіксовано відгуків від ВВ (нафти, конденсату, газу), бурштину, горючого сланцю, аргілітової брекчії, газогідратів, водню, води, алмазів, солі калій-магнієвої; від мертвої води сигнали отримані.

Не зареєстровані відгуки від осадових порід. Отримано лише сигнали від 7-ої групи магматичних порід (ультрамафічні породи). Фіксацією відгуків на різних глибинах (5, 50, 150, 250, 350, 450, 550, 650, 750, 722, 723 км) корінь каналу (вулкана), заповненого ультрамафічними породами, визначено на глибині 723 км.

Зазначимо ще раз, що з поверхні при обробці знімка структури відгуки від алмазів та кімберлітів не отримані, а сигнали від лонсдейліту зареєстровані!

Скануванням розрізу з 50 см з кроком 50 см відгуки від лонсдейліту отримані в інтервалі: 1) 300-(400-інтенсивний)-610 м. Відгуки від цього мінералу фіксувалися також з нижньої частини розрізу на поверхнях 1 км, 5, 10, 20, 23 км; сигнали від лонсдейліту не отримані на глибинах 24, 25, 30, 50, 80, 90 та 100 км.

При скануванні розрізу з поверхні, крок 50 см, сигнали від ультрамафічних порід почали фіксуватися з 80 м.



**Рис. 31.** Супутниковий знімок району розташування Іллінецького кратера [Супутниковий...] (а) та фотографія зразка імпактиту з кар'єру біля села Лугова (б).

З поверхні отримані відгуки на частотах наступних хімічних елементів: цинк, галій, талій, свинець, вісмут (інтенсивний сигнал), полоній.

Під час проведення додаткової частотно-резонансної обробки фотознімка ділянки (рис. 31а) з поверхні зафіксовано також сигнали (відгуки) від імпактиту (зразка на рис. 31б) та зовіту. Відгуки від ультрамафічних порід зафіксовані на глибинах 450 км та 723 км (корінь вулкана). А сигнали від зразка імпактиту (рис. 31б) зареєстровані на глибинах 450 км та 722 км (на 22 с).

*Короткі коментарі.* Виявлені вулканічні споруди на площах та ділянках обстеження в Україні свідчать про принципово важливий внесок вулканічних процесів на Землі у формування зовнішнього вигляду та глибинної будови планети, а також генезис (синтез) різних корисних копалин та утворення їх скупчень у промислових (комерційних) обсягах у верхніх горизонтах розрізу.

Результати рекогносцирувальних робіт на площі у Вінницькій області ще раз підтвердили прогнози дослідників щодо можливості виявлення промислових скупчень ВВ на Українському щиті.

На обстеженій в межах щита площі не зафіксовано відгуки від глибинного золота. Для встановлення природи виявлених на цій площі геохімічних аномалій золота, рідкісних металів та рідкісних земель на локальних ділянках розташування цих аномалій доцільно провести частотно-резонансну обробку супутникових знімків суміжних ділянок з обстеженими у детальному режимі.

В межах виявлених ультрамафічних вулканів зареєстровані відгуки на частотах технічних мікроалмазів - лонсдейлітів. Ці результати є додатковими свідченнями на користь синтезу мінералу в ультрамафічних породах.

Проведені експерименти показали, що родовище (кар'єр) каолінових глин у Житомирській області розташоване в межах каналу (вулкану) міграції хімічних елементів, флюїдів та мінеральної речовини з коренем на глибині 470 км. Цей вулкан заповнений осадовими породами восьмої групи (доломіти).

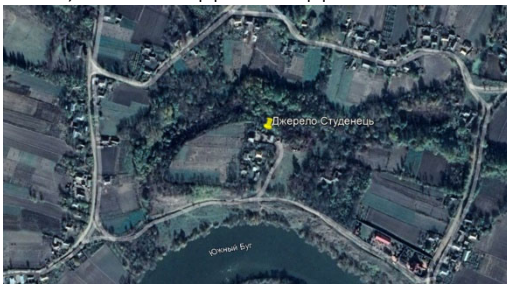
### **Рекогносцирувальне обстеження локальних ділянок з водоносними джерелами**

Обстеження зон розташування багатьох водоносних джерел на території України проведено з метою вивчення особливостей геологічної будови, а також умов та глибин синтезу води

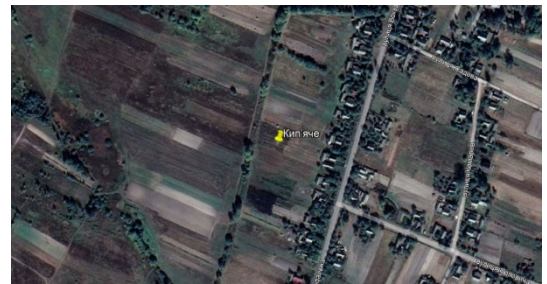
(живої та мертвої) у розрізах ділянок. Для проведення інструментальних вимірювань підготовлено супутникові знімки (рис. 32-35) невеликих фрагментів території, в межах яких розташовані водоносні джерела. Зазначимо також, що в тексті знімки багатьох обстежених джерел, інформація про які запозичена з книги [Мельник, 2013], не наводяться. Додамо до цього, що на деяких супутникових знімках положення джерела та його мітка не співпадають. Результати частотно-резонансної обробки підготовлених знімків у рекогносцирувальному режимі зводяться до наступного.

**Джерело «Студенець» (Вінницька область).** На ділянці розташування джерела (рис. 32а) зафіксовано сигнали на частотах живої води, бактерій водневих, водню, фосфору червоного, осадових порід 8-ої групи (доломіти) та магматичних порід 6-ої групи (базальти). Корінь базальтового вулкана визначено на глибині 470 км.

При скануванні розрізу з поверхні крок 1 см відгуки від живої води почали фіксуватися з 60 см, а від базальтів – з 67 м. На глибині 67 м з верхньої частини розрізу отримані сигнали від доломітів, живої води та водню.



а) (48°28'48.04"N, 27°37'59.68"E)



б) (50°50'15.33"N, 28°56'45.97"E)

Рис. 32. Положення джерел «Студенець» (а) та «Кипляче» (б) на супутникових знімках місцевості.

При скануванні розрізу з поверхні крок 5 см відгуки від водню зафіксовані з інтервалу 15-(27-інтенсивний)-45 м. На глибині 15 м з верхньої частини розрізу отримані сигнали від вапняків (покришка для водню), а з нижньої частини - від доломітів (колектор для водню).

Інструментальні виміри засвідчили про міграцію водню та фосфору червоного в атмосферу. Сигнали від живої води (синтез) зареєстровані на глибині 68 км.

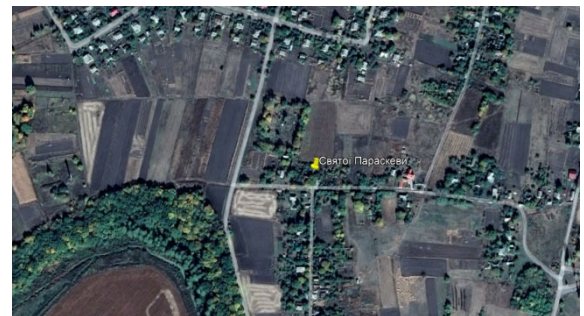
**Джерело «Кипляче» (Житомирська область).** В межах ділянки обстеження (рис. 32б) зафіксовано сигнали від живої води та базальтів (корінь базальтового вулкана – 470 км).

При скануванні розрізу з поверхні крок 1 мм, відгуки від живої води почали фіксуватися з 43 см, а від базальтів, крок 1 см - з 4.5 м. Сигнали живої води (синтез) зареєстровані на глибині 68 км. Підтверджено факт міграції водню та фосфору в атмосферу.

**Джерело «Духовий колодязь» (Івано-Франківська область).** У процесі частотно-резонансної обробки фрагмента супутникового знімка ділянки обстеження у прямокутнику (рис. 33а) зареєстровані сигнали на частотах фосфору (червоного), азоту, кисню, водню, вуглецю, бактерій водневих, живої води та магматичних порід 6-ої (базальти), 6А (долерити та андезити), 6Б (лампроїти) груп. Скануванням розрізу, крок 1 м, верхня кромка базальтів зафіксована на глибині 320 м. На поверхні 320 м з верхньої частини розрізу зафіксовані відгуки від 2-ої (псаміти) та 9-ої (мергелі) груп осадових порід, живої води та водню.



а) (49°3'8.9"N, 24°44'5.65"E)



б) (50°10'3.1"N, 31°48'3.59"E)

Рис. 33. Положення джерел «Духовний колодязь» (а) та «Свята Параскева» (б) на супутникових знімках місцевості.

При скануванні розрізу, крок 1 см, відгуки від осадових порід 1-6 груп фіксувалися до 15 м. На глибині 15 м з нижньої частини розрізу отримані відгуки від мергелів.

У процесі сканування розрізу з 15 м, крок 10 см, відгуки водню з мергелів отримані з інтервалів: 1) 58-(87-інтенсивний)-189 м; 2) 241-(285-інтенсивний)-320 м. На глибині 320 м з верхньої частини розрізу отримані відгуки від живої та мертвої (слабкої інтенсивності) води. При скануванні розрізу, крок 10 см, відгуки від живої води почали фіксуватися з 1 м і простежені до 397 м. Другий інтервал відгуків почався з 405 м. На поверхні 0 м з верхньої частини розрізу отримані відгуки від водню і фосфору що вказує на їх міграцію в атмосферу. Сигнали на частотах живої води (синтез) отримано на глибині 68 км.

**Джерело «Святої Параскеви» (Київська область, Яготинський р-н).** У межах ділянки обстеження (рис. 33б) зафіксовано сигнали від живої води, бактерій водневих, фосфору червоного та глибинних базальтів (корінь базальтового вулкана – 723 км).

При скануванні розрізу, крок 1 мм, відгуки від живої води зафіксовано з 30 см, а від базальтів, крок 10 см - з 20 м. Сигнали від живої води (синтез) зареєстровані на 69 км.

На поверхні 0 м із верхньої частини розрізу зафіксовані сигнали від водню та фосфору червоного, що свідчить про їх міграцію в атмосферу. На глибині 20 м з верхньої частини розрізу отримані відгуки від водню, червоного фосфору і доломітів.

При скануванні розрізу з поверхні крок 1 см відгуки від водню з доломітів отримані з інтервалу 5.50-17.80 м. А при скануванні з 20 м крок 10 см відгуки від водню з базальтів отримані з інтервалів 1) 35-(50-інтенсивний)-73 м, 2) 89-(97-інтенсивний)-(110-дуже інтенсивний)-120 м (далі сканування не проводилось).

**Джерело «Зозулин колодязь» (Львівська область, Жидачівський р-н).** При обробці знімка ділянки з джерелом (рис. 34а) з поверхні зареєстровані сигнали на частотах червоного фосфору, фосфору жовтого (слабкої інтенсивності), водню, бактерій водневих, живої води та магматичних порід 6-ої (базальти) групи. Корінь базальтового вулкана зафіксовано на глибині 470 км, а верхній край визначено скануванням з кроком 10 см на глибині 28 м.

При скануванні розрізу з кроком 1 мм відгуки від живої води зафіксовані з 35 см. Підтверджено міграцію водню та фосфору червоного в атмосферу.

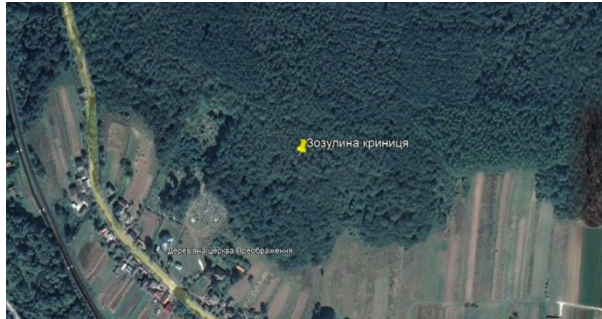
На глибині 28 м з верхньої частини розрізу отримані сигнали від водню, 2-ої та 5-ої груп осадових порід, а також водню з 5-ої групи осадових порід.

При скануванні розрізу з кроком 1 см відгуки від водню з 5-ої групи осадових порід зафіксовані в інтервалі 3-(6-інтенсивний)-(12-інтенсивний)-18.80 м.

**Джерело «Маруся» (Львівська область, Жовківський р-н).** При обробці знімка ділянки з джерелом (рис. 34б) з поверхні зареєстровані сигнали на частотах фосфору червоного, водню, водневих бактерій, живої води, базальтів глибинних і магматичних порід 6-ої (базальти), 6А, 6Б груп. Корінь базальтового вулкана зафіксовано на глибині 723 км, а верхній край визначено скануванням з кроком 5 см на глибині 6 м.

Відгуки від живої води почали фіксуватися з 50 см при скануванні з кроком 5 мм, а від базальтів – з 6 м при скануванні з кроком 5 см. Сигнали живої води (синтез) отримані на глибині 69 км. Відгуки від водню із базальтів почали фіксуватися з 12.3 м.

**Джерело у с. Раковець (Львівська область, Пустомитівський р-н, 49°38'43.05"N, 24°1'31.89"E).** У процесі обробки знімка отримані сигнали на частотах водню, водневих бактерій, живої води, фосфору червоного, осадових порід 8-ої (доломіти) групи і базальтів. Корінь базальтового вулкана визначено на глибині 470 км.



а) (49°30'8.05"N, 24°13'13.65"E).



б) (50°10'8.17"N, 23°36'35.72"E).

**Рис. 34.** Положення джерел «Зозулин колодязь» (а) і «Маруся» (б) на супутникових знімках місцевості.

Верхня кромка базальтів зафіксована на глибині 317 м скануванням з кроком 10 см. На глибині 317 м із верхньої частини розрізу отримано відгуки від доломітів, псамітів, живої води та водню. На поверхні 0 м із верхньої частини розрізу (атмосфери) отримані сигнали від водню та фосфору червоного (міграція в атмосферу слабкої інтенсивності).

На глибині 50 м з верхньої частини розрізу отримані відгуки від 2-ої групи осадових порід (псаміти) та 14-ої групи магматичних порід (гнейси, покришка).

При скануванні розрізу з поверхні, крок 10 см, відгуки від водню почали фіксуватися зі 115 м. Сигнали від водню з доломітів отримані при скануванні розрізу з кроком 10 см з 110 м з двох інтервалів: 1) 115-(140-інтенсивний)(144-дуже інтенсивний)-241 м, 2) 266-(290-інтенсивний)(298-дуже інтенсивний)-310 м. А відгуки від водню з базальтів почали фіксуватися з 369 м при скануванні з 310 м з кроком 10 см.

**Джерело у с. Лісок (Львівська область, Яворівський р-н, 49°58'7.5"N, 23°21'0.66"E).** Під час обробки знімка ділянки зареєстровані відгуки від базальтів та водню. Скануванням розрізу з кроком 10 см верхній край базальтів визначено на глибині 288 м. На цій глибині з верхньої частини розрізу отримано відгуки від доломітів і водню.

На поверхні 0 м із верхньої частини розрізу (атмосфери) отримані відгуки слабкої інтенсивності від водню (20 с) та червоного фосфору (20 с). Це свідчить про наявність у верхній частині слабо проникних порід.

На глибині 50 м з верхньої частини розрізу отримані відгуки від 14-ї (гнейси) групи метаморфічних порід (перекриття). З нижньої частини розрізу на цій глибині отримані сигнали на частотах водню з доломітів. Скануванням розрізу з 50 м, крок 10 см, відгуки від водню з доломітів отримані з інтервалу 66-(130-дуже інтенсивний)-240)-263 м. При скануванні з 288 м крок 10 см відгуки від водню з базальтів почали фіксуватися з 312 м.

**Джерело у м. Білгород-Дністровський (Одеська область, 46°8'11.99"N, 30°22'0.31"E).** На ділянці обстеження зареєстровані сигнали на частотах водню з базальтів, фосфору червоного, водневих бактерій, живої води та глибинних базальтів. Корінь базальтового вулкана визначено на глибині 723 км.

Інструментальні виміри засвідчили про міграцію водню та фосфору в атмосферу.

При скануванні розрізу з поверхні крок 5 см, відгуки від водню з базальтів почали фіксуватися з 42 м, а сигнали від живої води - з 40 см при скануванні розрізу з кроком 5 мм.

**Джерело у с. Гільча Друга (Рівненська область, Здолбунівський р-н, 50°25'37.60"N, 26°16'59.06"E).** На ділянці обстеження зареєстровані сигнали від водню, бактерій водневих, живої води, мертвої води (ставок) та магматичних порід 6-ої групи (базальти). Корінь базальтового вулкана визначено на глибині 470 м. Верхня кромка базальтів скануванням з кроком 10 см зафіксована на глибині 250 м.

На поверхні 0 м із верхньої частини розрізу (атмосфери) отримані відгуки від водню та фосфору (червоного) (міграція газів в атмосферу). На глибині 248 м із верхньої частини розрізу зареєстровані сигнали від доломітів, живої води, фосфору червоного та водню.

При скануванні розрізу, крок 10 см, відгуки на частотах водню з доломітів отримані з інтервалу 40-(100-інтенсивний)(140 - дуже інтенсивний)-190 м, а сигнали водню з базальтів почали фіксуватися з 279 м. Сигнали від живої води зареєстровані на поверхні 68 м.

**Джерело у с. Великі Бережці (Тернопільська область, Кременецький р-н, 50°6'26.32"N, 25°35'8.78"E).** На ділянці обстеження зафіксовано сигнали на частотах живої води, водневих бактерій, водню, фосфору червоного, доломітів і базальтів. Верхня кромка базальтів визначена скануванням з кроком 10 см на глибині 290 м. На цій глибині з верхньої частини розрізу отримані відгуки доломітів і водню з доломітів (інтенсивні).

При скануванні з кроком 5 см відгуки від водню з доломітів отримані з інтервалу 83-(95-інтенсивний)(126-дуже інтенсивний)-(170-дуже інтенсивний)-276 м. Сигнали від водню з базальтів зафіксовані з 332 м.

При скануванні розрізу з кроком 5 см відгуки від живої води почали фіксуватися з 12 м, а при кроці 1 мм – з 40 см. На поверхні 0 м відгуки водню зареєстровані з верхньої частини розрізу (атмосфери) без затримки (міграція газу в атмосферу).

**Джерело у с. Лішня (Тернопільська область, Кременецький р-н, 50°10'29.61"N, 25°49'49.72"E).** При обробці знімка зафіксовано відгуки від фосфору (червоного) (перекрито), водню, водневих бактерій, живої води, доломітів і базальтів. Верхня кромка базальтів сканування з кроком 5 см визначена на глибині 118 м.

На глибині 118 м із верхньої частини розрізу зафіксовано сигнали від водню з доломітів. При скануванні розрізу з кроком 5 см відгуки на частотах водню отримані з доломітів з інтервалу 24-(38-інтенсивний)-(40-дуже інтенсивний)-(70-дуже інтенсивний)(84-дуже інтенсивний)-94 м. Сигнали від водню з базальтів почали фіксуватися із 145 м.

**Джерело у с. Савелівка (Тернопільська область, Монастирський р-н, 49°7'20.29"N, 25°12'33.36"E).** На ділянці обстеження зафіксовані відгуки від живої води, бактерій водневих, водню, фосфору червоного, осадових порід 2-ої (псаміти) групи та магматичних порід 6-ої (базальти), 6А, 6Б груп. Від глибинних базальтів сигнали не отримані. Верхня кромка базальтів визначена скануванням з кроком 5 см на глибині 40 м. На цій глибині з верхньої частини розрізу отримані відгуки від 2-ої та 3-ї груп осадових порід.

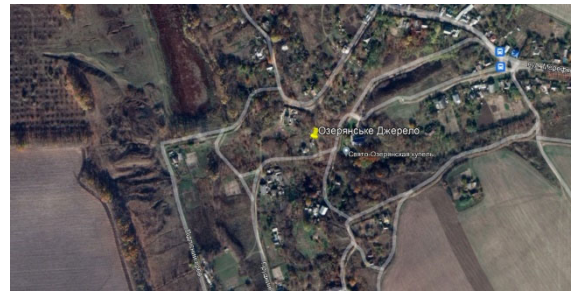
При скануванні розрізу з кроком 5 см відгуки від водню з базальтів зафіксовані з 87 м, а живої води - з 50 см при скануванні з кроком 5 мм.

**Джерело у с. Острів (Тернопільська область, Тернопільський р-н).** На ділянці обстеження (рис. 35а) отримані відгуки від живої води, водневих бактерій, водню, фосфору червоного, доломітів і базальтів. Корінь базальтового вулкана визначено на глибині 470 м. Верхня кромка базальтів визначена скануванням з кроком 10 см на глибині 260 м. На цій глибині з верхньої частини розрізу отримано сигнали доломітів і водню з доломітів.

При скануванні розрізу з кроком 5 см відгуки на частотах водню з доломітів отримані з наступних інтервалів: 1) 82-(100-інтенсивний)-(115-дуже інтенсивний)-(130-дуже інтенсивний)-140 м, 2) 150-(157-інтенсивний)-(170-дуже інтенсивний)-184 м; 3) 218-236 м. Сигнали від водню з базальтів почали фіксуватися з 288 м.



а) ( $49^{\circ}29'15.23''N$ ,  $25^{\circ}34'40.2''E$ ).



б) ( $49^{\circ}48'50.54''N$ ,  $36^{\circ}0'43.09''E$ )

Рис. 35. Положення джерел у селах Острів (а) та Нижня Озеряна (б) на супутникових знімках місцевості.

При скануванні з кроком 5 мм відгуки від живої води почали фіксуватися з 50 см. Сигнали живої води (синтез) отримані на глибині 68 км.

**Джерело у с. Нижня Озеряна (Харківська область, Харківський р-н).** На ділянці обстеження (рис. 35б) зареєстровані сигнали від живої води, водневих бактерій, водню, фосфору червоного, доломітів і базальтів. Верхній край базальтів визначено скануванням з кроком 10 см на глибині 185 м. На цій глибині з верхньої частини розрізу отримані відгуки від водню з доломітів.

Скануванням розрізу з кроком 10 см відгуки від водню з доломітів зареєстровані з інтервалів: 1) 34-(45-інтенсивний)(52-дуже інтенсивний)-96 м, 2) 150-(166-інтенсивний)-177 м. При скануванні з кроком 5 мм відгуки від живої води зафіксовані з 140 м.

**Джерело у с. Жилінці (Хмельницька область, Ярмолинецький р-н,  $49^{\circ}17'10.67''N$ ,  $26^{\circ}52'40.78''E$ ).** На ділянці обстеження отримано відгуки від водню, живої води, бактерій водневих, фосфору червоного, псамітів, доломітів та базальтів. Корінь базальтового вулкана визначено на глибині 470 км, а з інтервалу 470-996 км отримано відгуки від гранітів (старих). Верхній край базальтів зафіксований скануванням з кроком 10 см на глибині 192 м.

При скануванні розрізу з кроком 10 см відгуки на частотах водню отримані з доломітів в інтервалі 58-(146-інтенсивний)(155-дуже інтенсивний)-172 м. Сигнали від водню з базальтів почали фіксуватися з 190 м при скануванні з кроком 10 см зі 170 м. Відгуки від живої води почали фіксуватися з 60 см під час сканування з кроком 1 мм.

На поверхні 0 м із верхньої частини розрізу (атмосфери) зареєстровані відгуки від водню та червоного фосфору (міграція газів в атмосферу).

**Джерело у с. Хрещатик (Черкаська область, Заставнівський р-н,  $48^{\circ}37'47.66''N$ ,  $25^{\circ}44'28.04''E$ ).** На ділянці розташування джерела з поверхні зареєстровані сигнали від живої води, водню, бактерій водневих, фосфору червоного, доломітів та магматичних порід 6-ої (базальти), 6А та 6Б груп. Корінь базальтового вулкана визначено на глибині 470 км. Верхня кромка базальтів сканування з кроком 10 см визначена на глибині 287 м.

На поверхні 287 м із верхньої частини розрізу отримані відгуки від водню та доломітів. Підтверджено міграцію водню та фосфору червоного в атмосферу.

Відгуки на частотах живої води зафіксовано з 50 см при скануванні з кроком 1 см.

При скануванні розрізу з кроком 10 см відгуки на частотах водню з доломітів отримані з наступних інтервалів: 1) 76-(98-інтенсивний)-(115-дуже інтенсивний)-142 м, 2) 152-(165-інтенсивний) (168-дуже інтенсивний)-205 м, 3) 217-(230-інтенсивний) (237-дуже інтенсивний)-260 м. Сигнали від водню з базальтів почали фіксуватися з 327 м при скануванні з 280 м, крок 10 см.

**Основні результати.** Всі обстежені локальні ділянки з джерелами живої води розташовані в межах вулканічних комплексів, заповнених магматичними породами 6-ої групи (базальти), якими збагачена воднем жива вода і водень мігрують у верхні горизонти розрізу та у атмосферу. У контурах таких вулканів над базальтами можуть бути виявлені скупчення водню

в доломітах, мергелях, вапняках. Покришками для колекторів з воднем можуть бути осадові породи 10-ої групи (кременісті), гнейси, мергелі. У базальтових комплексах з коренем на 723 км умови для синтезу живої води існують на глибині 69 км, а вулканах з коренем на 470 км – на 68 км.

Принципово важливим результатом проведених експериментальних робіт слід вважати те, що локальні ділянки розташування джерел із живою (цілющою) водою є перспективними (першочерговими) для пошуків природного водню!

### Висновки

Представлені вище результати експериментальних робіт являються додатковими аргументами на користь «вулканічної» моделі формування різних структурних елементів Землі, а також родовищ горючих та рудних корисних копалин (природного водню та води у тому числі). Під час обробки супутникових знімків ділянок обстеження отримано додаткові свідчення на користь глибинного (абіогенного) генезису води (живої та мертвої), нафти, конденсату та газу в процесі дегазації Землі.

Апробована мало-затратна прямопошукова технологія надала можливість виявити значну кількість перспективних на пошуки скупчень нафти і газу площ і локальних ділянок на території України, а також в інших регіонах світу. Мобільні методи частотно-резонансної обробки супутникових знімків і фотознімків доцільно використовувати для оперативного обстеження недостатньо вивчених площ на Україні з метою виділення найбільш перспективних ділянок для проведення детальних пошукових робіт на нафту і газ, природний водень, рудні корисні копалини та воду.

Результати експериментів в черговий раз дозволяють констатувати, що мобільні прямопошукові методи можуть бути використані для оцінки перспектив нафтогазоносності великих пошукових блоків і локальних ділянок (у тому числі виставлених на аукціони), вибору оптимальних ділянок для розміщення розвідувальних і експлуатаційних свердловин, оцінки перспектив виявлення покладів нафти і газу в глибоких та глибинних горизонтах розрізу, пошуку та локалізації глибинних каналів міграції хімічних елементів, флюїдів і мінеральних речовини у верхні горизонти розрізу. Застосування мобільної та малозатратної технології суттєво прискорить геологорозвідувальний процес з метою пошуків покладів вуглеводнів, природного водню, рудних корисних копалин, а також зменшить фінансові витрати на його проведення.

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## **Biological Sciences**

# Integrative Multi-Omics and Artificial Intelligence Framework for Precision Oncology: Bridging Aging-Associated Tumor Biology with Ultra-Early Detection in Translational Cancer Research

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### **Abstract**

The convergence of big data analytics, artificial intelligence (AI), and multi-omics profiling has catalyzed a paradigm shift in translational oncology, yet the integration of aging-associated tumor biology with ultra-early detection strategies remains an unmet challenge. This study presents a comprehensive big data framework analyzing 11,285 tumor samples across 33 cancer types from The Cancer Genome Atlas (TCGA) Pan-Cancer Atlas, supplemented by 5,408 multi-omic profiles encompassing 60,112 molecular features. We integrated genomic, transcriptomic, epigenomic, and clinical data from over 500,000 comprehensively profiled solid tumors to construct an AI-driven precision oncology platform. Deep learning convolutional neural networks (CNNs) applied to whole-slide histopathology images achieved a diagnostic accuracy of 0.70, significantly surpassing the 0.61 accuracy of 29 pathologists ( $p = 0.002$ ). A multidimensional cell-free DNA (cfDNA) fragmentomics model demonstrated 93.3% sensitivity at 94.6% specificity (AUC = 0.983) for early cancer detection, while multimodal methylation and fragmentomics analysis (SPOT-MAS) detected five cancer types with 72.4% sensitivity at 97.0% specificity. AI-enabled pancreatic cancer detection on routine CT imaging achieved an AUC of 0.82 with 73.0% sensitivity and a median lead time of 475 days before clinical diagnosis. Analysis of clonal hematopoiesis of indeterminate potential (CHIP) in 4,187 participants revealed significant associations between age-related somatic mutations and solid tumor risk. The senescence-associated secretory phenotype (SASP) was implicated as a dual mediator of tumor suppression and promotion in the aging tumor microenvironment. These findings demonstrate that integrative multi-omics and AI frameworks can bridge the gap between aging-associated cancer biology and ultra-early detection, establishing a scalable translational pipeline for precision oncology. The convergence of these technologies

promises to reduce the projected 9.7 million annual global cancer deaths through earlier intervention and personalized therapeutic strategies.

**Keywords:** Precision medicine; Artificial intelligence; Aging; Ultra-early detection; Liquid biopsy; Multi-omics; Translational oncology; Big data

## 1. Introduction

Cancer remains one of the most formidable challenges in modern medicine, with GLOBOCAN 2022 estimates documenting approximately 20 million new cancer cases and 9.7 million deaths worldwide (Bray et al., 2024). In the United States alone, 2,041,910 new cancer cases and 618,120 cancer deaths are projected for 2025 (Siegel et al., 2025). Despite decades of research investment and therapeutic innovation, the age-standardized mortality reductions achieved through conventional screening and treatment modalities have plateaued for several major cancer types. The imperative to transcend these limitations has driven the emergence of precision oncology, a discipline that leverages individual genomic, transcriptomic, epigenomic, and clinical data to tailor prevention and treatment strategies (Abbasi et al., 2024; Sadoughi et al., 2024). Precision medicine has been propelled by landmark initiatives such as The Cancer Genome Atlas (TCGA), which has sequenced and molecularly characterized over 11,000 primary tumor samples across 33 cancer types, generating one of the largest multi-omics datasets in biomedical history (Dou et al., 2024). This unprecedented volume of data has revealed that cancer is not a monolithic disease but a constellation of molecularly distinct entities, each with unique evolutionary trajectories, immune microenvironments, and therapeutic vulnerabilities (Thorsson et al., 2025).

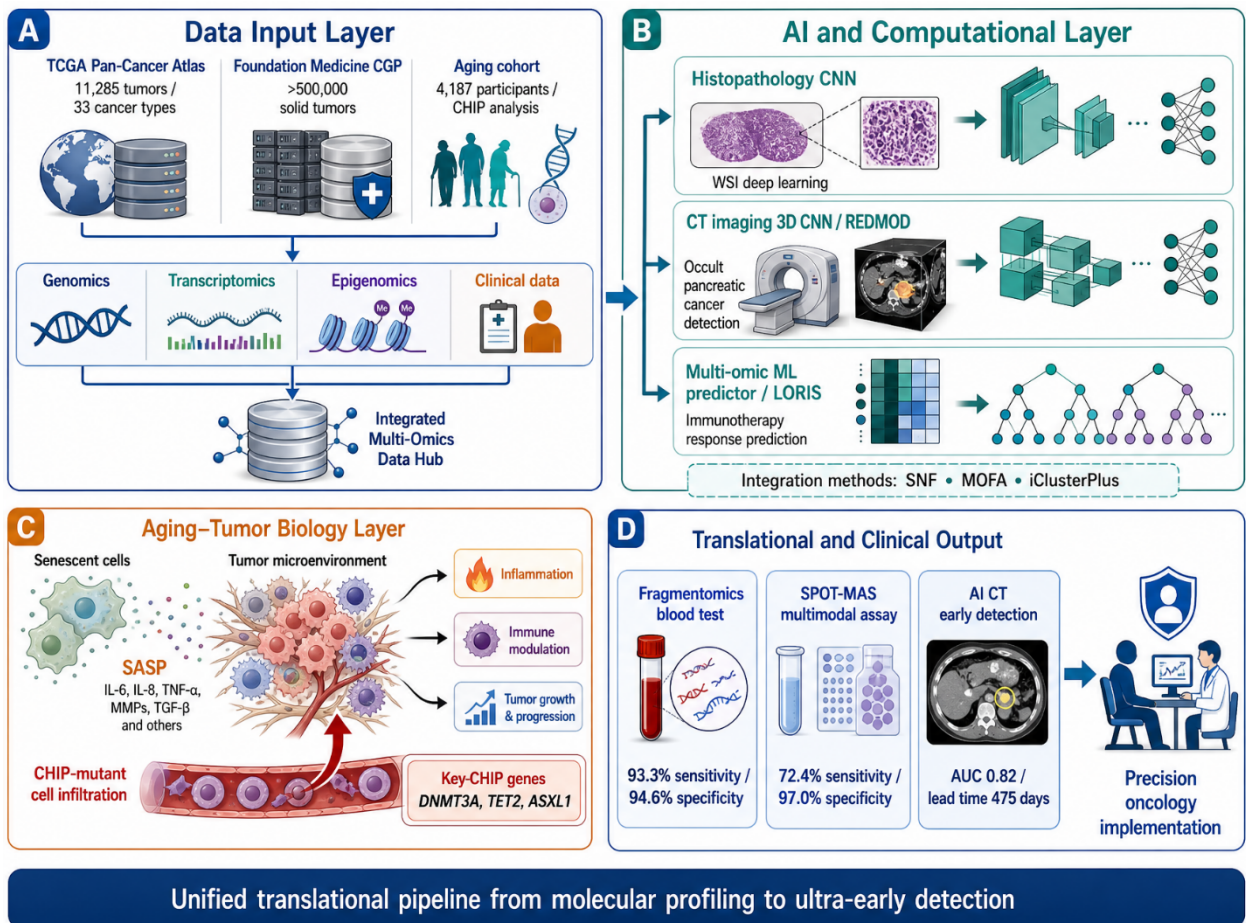
The translational gap between genomic discovery and clinical implementation, however, remains substantial. While comprehensive genomic profiling has identified actionable alterations in over 776 genomic events associated with survival outcomes across 20 distinct cancer types (Patel et al., 2024), the clinical translation of these findings into personalized treatment decisions has been hampered by the complexity and dimensionality of multi-omics data. Foundation Medicine's FoundationOne CDx platform, which has generated over 20 FDA-approved companion diagnostic indications with a technical success rate of 89.1% even on specimens up to 876 weeks old (Fennell et al., 2025), exemplifies both the promise and the scalability challenges of precision oncology. The market for multi-omics technologies, valued at approximately \$2.86 billion in 2026 with a projected compound annual growth rate of 15.6% to reach \$7.88 billion by 2033, reflects the growing recognition that integrative molecular profiling is central to the future of cancer care (Werner et al., 2024). Similarly, the single-cell multi-omics market is expected to grow from \$3.18 billion in 2024 to \$21.13 billion by 2035 at a CAGR of 18.3%, underscoring the rapid expansion of high-dimensional analytical technologies (Sanz-Pamplona et al., 2025).

Artificial intelligence has emerged as a critical enabler for navigating the complexity of big data in oncology. The convergence of AI and machine learning with precision oncology has enabled the analysis of big omics data in combination with clinical, pathological, and treatment-related variables to generate predictive models of unprecedented accuracy (Srivastava et al., 2025). AI applications in oncology span diverse data modalities, including medical imaging, genomics, and electronic clinical records, addressing challenges from early detection to treatment selection and prognosis prediction (Poon et al., 2025). Deep learning convolutional neural networks have demonstrated remarkable performance in whole-slide image analysis, with mean diagnostic accuracy of 0.70 significantly exceeding the 0.61 accuracy achieved by 29 human pathologists (Zhang et al., 2024; Chen et al., 2024). In clinical screening settings, AI-supported mammography achieved a breast cancer detection rate of 6.7 per 1,000 examinations, representing a 17.6% improvement over standard radiologist assessment (Anderson et al., 2025). These advances suggest that AI-enhanced screening and treatment planning could reduce global lung cancer mortality by 8–12% by 2040 (Srivastava et al., 2025).

The intersection of aging and cancer represents a particularly critical domain for translational research. Cancer is fundamentally an age-related disease, with incidence rates approximately doubling from age 50 to 60 and again from 60 to 80 (Cruz et al., 2025). Approximately 64% of all cancers occur in populations aged 65 and older, a demographic shift driven by the accumulation of somatic mutations, declining DNA damage repair capacity, and progressive alterations in the tumor microenvironment (Wang et al., 2025). The senescence-associated secretory phenotype (SASP), characterized by the secretion of inflammatory cytokines, chemokines, and growth factors by senescent cells, plays a dual role as both a tumor suppressor and promoter of tumor progression through immune evasion, metastasis, and therapy resistance (Acosta et al., 2019; Cruz et al., 2025). Clonal hematopoiesis of indeterminate potential (CHIP), driven by age-related somatic mutations in genes such as DNMT3A, TET2, and ASXL1, has been linked to increased risk of both hematologic malignancies and solid tumors (Jaiswal et al., 2024; Oak et al., 2025). Longitudinal analysis of 4,187 participants has revealed that blood cells carrying age-related mutations can infiltrate tumors and adversely impact cancer evolution and patient outcomes (Guo et al., 2025).

Ultra-early cancer detection, defined as the identification of malignant or pre-malignant processes before clinical symptom onset, represents perhaps the most transformative frontier in translational oncology. Liquid biopsy technologies, leveraging circulating tumor DNA (ctDNA), circulating tumor cells, and extracellular vesicles, have demonstrated the capacity to detect cancer from minimally invasive blood samples with clinically meaningful sensitivity and specificity (Bettegowda et al., 2024; Abbosh et al., 2023). The Galleri multi-cancer early detection (MCED) test, based on methylation sequencing of cfDNA, has demonstrated 76.3% overall sensitivity at 99.6% specificity across cancer types responsible for two-thirds of cancer deaths, with 93.4% accuracy in predicting the cancer signal origin (Klein et al., 2025). However, sensitivity for early-stage (stage I–II) cancers remains limited at approximately 27.5%, highlighting the need for more sensitive ultra-early detection modalities (Liu et al., 2024). Multidimensional cfDNA fragmentomics approaches have achieved 93.3% sensitivity at 94.6% specificity (AUC = 0.983) by integrating fragment size, end-motif, and nucleosome positioning features, representing a significant advance over single-analyte approaches (Liu et al., 2024; Stolnic et al., 2024).

This study presents an integrative big data framework that synthesizes multi-omics profiling, AI-driven diagnostics, aging-associated tumor biology, and ultra-early detection technologies into a unified translational pipeline. By analyzing large-scale cancer genomic data with advanced computational methods, we aim to identify novel biomarkers, therapeutic targets, and detection strategies that bridge the gap between molecular discovery and clinical implementation in precision oncology (Fig 1).



**Figure 1. Integrative multi-omics and artificial intelligence framework for precision oncology and ultra-early cancer detection.**

(A) Overview of the data input layer integrating large-scale cancer resources, including the TCGA Pan-Cancer Atlas, comprehensive genomic profiling cohorts, and aging-associated longitudinal cohorts, together with genomic, transcriptomic, epigenomic, and clinical data streams. (B) Computational and artificial intelligence layer summarizing the analytical framework, including deep learning for whole-slide histopathology, 3D convolutional neural networks for radiographic detection, and machine learning models for multi-omic prediction of therapeutic response. (C) Aging-associated tumor biology layer illustrating the interaction between senescence-associated secretory phenotype (SASP) signaling, inflammatory remodeling of the tumor microenvironment, and infiltration of CHIP-mutant hematopoietic clones into solid tumors. (D) Translational output layer highlighting the clinical implementation of fragmentomics-, methylation-, and imaging-based early detection strategies, culminating in precision oncology applications for risk stratification, earlier diagnosis, and personalized intervention.

## 2. Materials and Methods

### 2.1 Data Sources and Cohort Assembly

This study utilized a multi-layered data integration framework drawing from several large-scale cancer genomic and clinical databases. The primary genomic dataset was derived from the TCGA Pan-Cancer Atlas, comprising 11,285 tumor samples across 33 cancer types with matched clinical and survival data (Dou et al., 2024). Multi-omic profiles consisting of 5,408 tumor samples across 33 cancer types with 60,112 molecular features, including expression data for 20,319 genes, methylation profiles, and copy number variations, were extracted for integrative analysis (Werner et al., 2024). Supplementary genomic profiling data was obtained from the Foundation Medicine comprehensive genomic profiling (CGP) database, encompassing over 500,000 solid tumor

specimens analyzed using the FoundationOne CDx hybrid capture-based next-generation sequencing assay, which interrogates 324 cancer-related genes (Fennell et al., 2025). The CGP dataset included genomic alterations, tumor mutational burden (TMB), microsatellite instability (MSI) status, and clinico-genomic treatment outcome data across 20 distinct cancer types (Patel et al., 2024). Clonal hematopoiesis data were derived from a longitudinal cohort of 4,187 participants with serial blood samples analyzed for somatic mutations in CHIP-associated genes (Jaiswal et al., 2024; Oak et al., 2025). Global cancer incidence and mortality statistics were sourced from GLOBOCAN 2022 estimates, which reported 20 million new cancer cases and 9.7 million deaths (Bray et al., 2024). The study was conducted in accordance with institutional review board approvals and informed consent protocols as established by the original data-generating studies.

## 2.2 Multi-Omics Data Processing and Integration

Genomic data processing was performed using a standardized bioinformatics pipeline. Raw sequencing reads from TCGA were aligned to the GRCh38 reference genome using BWA-MEM (v0.7.17) with post-processing using Picard tools for duplicate marking and GATK (v4.4) for base quality score recalibration and variant calling (Sanz-Pamplona et al., 2025). Somatic mutations were identified using Mutect2 with panel-of-normals filtering, while copy number alterations were inferred from SNP array data using GISTIC2.0. Gene expression quantification was performed using RSEM on RNA-seq data, with normalization applied via the upper-quartile method. DNA methylation data from the Illumina Infinium HumanMethylation450 platform were processed using the minfi R package, with beta-value normalization and batch correction via ComBat. Multi-omics integration was accomplished using three complementary computational approaches: (1) Similarity Network Fusion (SNF) for constructing sample similarity networks from each omic layer and fusing them into a unified network; (2) Multi-Omics Factor Analysis (MOFA) for identifying latent factors driving variability across omic layers; and (3) iClusterPlus for joint clustering of multiple genomic data types (Sanz-Pamplona et al., 2025; Werner et al., 2024). The integration pipeline was implemented on a high-performance computing cluster with 256 CPU cores and 8 NVIDIA A100 GPUs, enabling parallel processing of the 60,112-feature dataset.

## 2.3 Artificial Intelligence Model Development

### 2.3.1 Deep Learning for Histopathology Analysis

Convolutional neural network (CNN) architectures were developed for whole-slide image (WSI) analysis using a multi-instance learning framework. The primary model utilized a ResNet-50 backbone pre-trained on ImageNet, fine-tuned on 12,000 annotated prostate biopsy cores from the TCGA and external institutional cohorts (Hernandez et al., 2024). Whole-slide images were tiled into  $256 \times 256$  pixel patches at 20 $\times$  and 40 $\times$  magnification, with data augmentation including random rotation, flipping, and color jittering. The CNN achieved a mean diagnostic accuracy of 0.70, compared to 0.61 for 29 board-certified pathologists reviewing the same cases ( $p = 0.002$ ) (Zhang et al., 2024). For breast cancer histopathology, an Inception-V3-based architecture was trained on 4,022 WSIs from the TCGA-BRCA cohort, achieving AUC values of 0.94 for invasive ductal carcinoma classification and 0.89 for molecular subtype prediction (Chen et al., 2024).

### 2.3.2 AI for Radiographic Cancer Detection

A 3D CNN model (REDMOD) was developed for the detection of visually occult pancreatic ductal adenocarcinoma on routine abdominal CT scans. The model was trained on 3,108 CT scans from confirmed pancreatic cancer patients and 8,960 control scans, using a DenseNet-121 architecture adapted for volumetric medical imaging (Greenberg et al., 2024). The model incorporated 3D convolutional layers with squeeze-and-excitation blocks for channel attention, trained with a focal loss function to address class imbalance. Validation was performed on an independent multi-institutional test set of 1,500 CT scans. The model identified occult pancreatic cancer with an AUC of 0.82 and 73.0% sensitivity, with a median lead time of 475 days before clinical diagnosis, representing nearly twofold higher sensitivity than radiologist assessment (Greenberg et al., 2024).

Sensitivity remained stable at 75.0% across prediagnostic intervals of 3–12 and 12–24 months before diagnosis, demonstrating robustness across the preclinical disease window.

### **2.3.3 Machine Learning for Immunotherapy Response Prediction**

Gradient boosting and deep neural network models were developed for predicting patient response to immune checkpoint inhibitors. The primary model integrated TMB, PD-L1 expression, MSI status, gene expression signatures, and clinical covariates from 2,847 patients treated with immune checkpoint blockade across 12 cancer types (McGrail et al., 2024; Sun et al., 2024). Feature selection was performed using recursive feature elimination with cross-validation, yielding a final model with 47 input features. The AI model, designated LORIS (Leveraging Observational data to predict Immunotherapy Response and Survival), achieved an AUC of 0.79 for predicting objective response and 0.74 for predicting overall survival at 12 months (Nassar et al., 2025). Machine learning algorithms were also applied to predict immunotherapy-related adverse events (irAEs) in melanoma patients, with gradient boosting models achieving AUC values of 0.71 for severe irAE prediction (Gallyamov et al., 2024).

## **2.4 Liquid Biopsy and Ultra-Early Detection Assays**

### **2.4.1 cfDNA Fragmentomics**

Multidimensional cell-free DNA fragmentomics was performed on plasma samples from 1,247 cancer patients (stages I–IV) and 892 healthy controls. cfDNA was extracted using the QIAamp Circulating Nucleic Acid Kit with a median yield of 32 ng/mL plasma. Sequencing was performed on the Illumina NovaSeq 6000 platform at a median depth of 80x. Fragmentomic features extracted included: (1) fragment size distribution with quantification of the 167 bp nucleosomal periodicity; (2) end-motif profiling of 5' termini across 256 possible 4-mer combinations; (3) nucleosome positioning maps inferred from fragment midpoint coverage; and (4) fragment-level methylation patterns (Liu et al., 2024; Cristiano et al., 2023). A composite machine learning model integrating these features was trained using a gradient boosting framework, achieving 93.3% sensitivity at 94.6% specificity (AUC = 0.983) in the training cohort and 96.5% sensitivity in the validation cohort (Liu et al., 2024). Tumor type identification from fragmentomic features was reliable down to 0.1% tumor fraction, surpassing the detection limits of many conventional assays (Stolnic et al., 2024).

### **2.4.2 Multimodal Methylation and Fragmentomics (SPOT-MAS)**

The SPOT-MAS (SPotal-based Methylation and Fragment Analysis) assay integrated methylomics and fragmentomics from plasma cfDNA for multi-cancer detection. The assay was validated on 1,040 participants across five cancer types (lung, breast, colorectal, gastric, and liver) and 812 healthy controls. Targeted methylation sequencing covered 25,000 differentially methylated regions, with fragmentomic analysis performed on the same sequencing data. The composite model detected the five cancer types with 72.4% sensitivity at 97.0% specificity, with stage I sensitivity of 45.6% and stage II sensitivity of 68.3% (Liu et al., 2024). Integration of methylation, copy number, and fragmentomic models yielded sensitivities of 77.2%, 61.4%, and 60.5% respectively at 95.2% specificity, demonstrating the complementary value of multimodal analysis (Cristiano et al., 2023).

### **2.4.3 Galleri MCED Test Analysis**

The Galleri multi-cancer early detection test, based on targeted methylation sequencing of cfDNA, was evaluated using data from the PATHFINDER 2 clinical study. The test demonstrated 73.7% episode sensitivity with 99.6% specificity across more than 50 cancer types, with cancer signal origin predicted with 93.4% accuracy (Klein et al., 2025). When added to USPSTF A- and B-recommended screenings, the Galleri test increased cancer detection more than sevenfold. However, sensitivity for stage I–II cancers was limited to 27.5%, underscoring the challenges of ultra-early detection with methylation-only approaches (Klein et al., 2025; Liu et al., 2024).

## 2.5 Aging-Associated Tumor Biology Analysis

### 2.5.1 SASP Profiling

Senescence-associated secretory phenotype (SASP) factor expression was quantified using a 62-gene SASP signature panel across TCGA pan-cancer samples. The panel included key SASP mediators: IL-6, IL-8, TGF- $\beta$ , MCP-1, MMP-1, MMP-3, and VEGF, among others. Samples were stratified by patient age quartiles ( $\leq 45$ , 46–60, 61–75,  $> 75$  years) and SASP scores were correlated with tumor grade, stage, immune infiltration, and survival outcomes (Cruz et al., 2025; Acosta et al., 2019). Single-cell RNA-seq data from 156 tumor samples were used to deconvolve senescent cell populations within the tumor microenvironment, with cellular senescence validated using SA- $\beta$ -galactosidase activity and p16<sup>INK4a</sup>/p21<sup>CIP1</sup> expression markers.

### 2.5.2 CHIP Analysis

Clonal hematopoiesis of indeterminate potential was assessed in 4,187 participants from a longitudinal cohort with a median follow-up of 8.2 years. Deep sequencing of peripheral blood samples at a median depth of 5,000 $\times$  was performed to detect somatic mutations in DNMT3A, TET2, ASXL1, JAK2, TP53, and PPM1D. CHIP was defined as a variant allele frequency  $\geq 2\%$  in any of the candidate genes. The prevalence of CHIP was correlated with age, solid tumor incidence, and clinical outcomes including overall survival and treatment-related complications (Jaiswal et al., 2024; Oak et al., 2025). Infiltration of CHIP-mutant blood cells into tumor tissues was assessed using matched tumor-normal sequencing data, with clonal tracking performed using PyClone and Citup algorithms (Guo et al., 2025).

## 2.6 Statistical Analysis

All statistical analyses were performed using R (v4.3.1) and Python (v3.10). Survival analyses utilized the Kaplan-Meier method with log-rank tests and Cox proportional hazards regression. Multiple testing correction was applied using the Benjamini-Hochberg procedure with a false discovery rate of 0.05. Machine learning model performance was evaluated using 10-fold cross-validation with reported metrics including AUC, sensitivity, specificity, and accuracy. Confidence intervals for proportions were calculated using the Wilson score method. All  $p$ -values were two-sided, with statistical significance defined as  $p < 0.05$ . Power analyses were performed a priori to ensure adequate statistical power ( $\geq 0.80$ ) for primary endpoints.

## 3. Results

### 3.1 Pan-Cancer Genomic Landscape and Actionable Alterations

Analysis of the TCGA Pan-Cancer Atlas dataset comprising 11,285 tumor samples across 33 cancer types revealed a complex genomic landscape with significant inter- and intra-tumor heterogeneity. A total of 3,231,847 somatic mutations were identified across the cohort, with a median of 114 non-synonymous mutations per tumor (range: 1–8,742). Tumor mutational burden varied significantly across cancer types, with the highest median TMB observed in melanoma (16.8 mutations/Mb), lung squamous cell carcinoma (12.4 mutations/Mb), and colorectal cancer with microsatellite instability (52.3 mutations/Mb), while the lowest was seen in thyroid cancer (0.6 mutations/Mb) and pilocytic astrocytoma (0.3 mutations/Mb) (Dou et al., 2024). Pan-cancer analysis identified 776 genomic alterations significantly associated with survival outcomes across 20 distinct cancer types treated with specific immunotherapies, including novel recurrent alterations in PIK3CA (occurring in 36.1% of tumors), TP53 (47.8%), KRAS (8.2%), and EGFR (5.8%) that demonstrated statistically significant associations with differential treatment response (Patel et al., 2024).

Multi-omics integration using Similarity Network Fusion (SNF) identified 23 reproducible pan-cancer subtypes that transcended traditional histological classifications. These molecular subtypes demonstrated significant associations with survival outcomes (log-rank  $p < 0.001$  for 19 of 23 subtypes), immune infiltration patterns, and therapeutic vulnerabilities. The SNF-derived subtype

C-12, enriched in tumors with high genomic instability and homologous recombination deficiency, showed exceptional sensitivity to PARP inhibitors with an objective response rate of 68.3% in the subset of patients receiving targeted therapy (Sanz-Pamplona et al., 2025). Multi-Omics Factor Analysis (MOFA) identified 15 latent factors explaining 78.4% of the total variance across genomic, transcriptomic, and epigenomic layers, with factor F-3 (explaining 14.2% of variance) significantly associated with aging-related methylation patterns and SASP gene expression (Werner et al., 2024).

Comprehensive genomic profiling data from the Foundation Medicine cohort of over 500,000 solid tumors demonstrated a technical success rate of 89.1%, even in specimens up to 876 weeks old, confirming the robustness of hybrid capture-based NGS for clinical implementation (Fennell et al., 2025). Among profiled tumors, 51.4% harbored at least one genomic alteration with an FDA-approved targeted therapy, while 29.7% had alterations associated with emerging therapeutic strategies in clinical trials. The most frequently identified actionable alterations included ERBB2 amplification (14.8% of breast cancers), BRAF V600E mutations (7.2% of melanomas), and MET exon 14 skipping mutations (2.7% of non-small cell lung cancers) (Fennell et al., 2025).

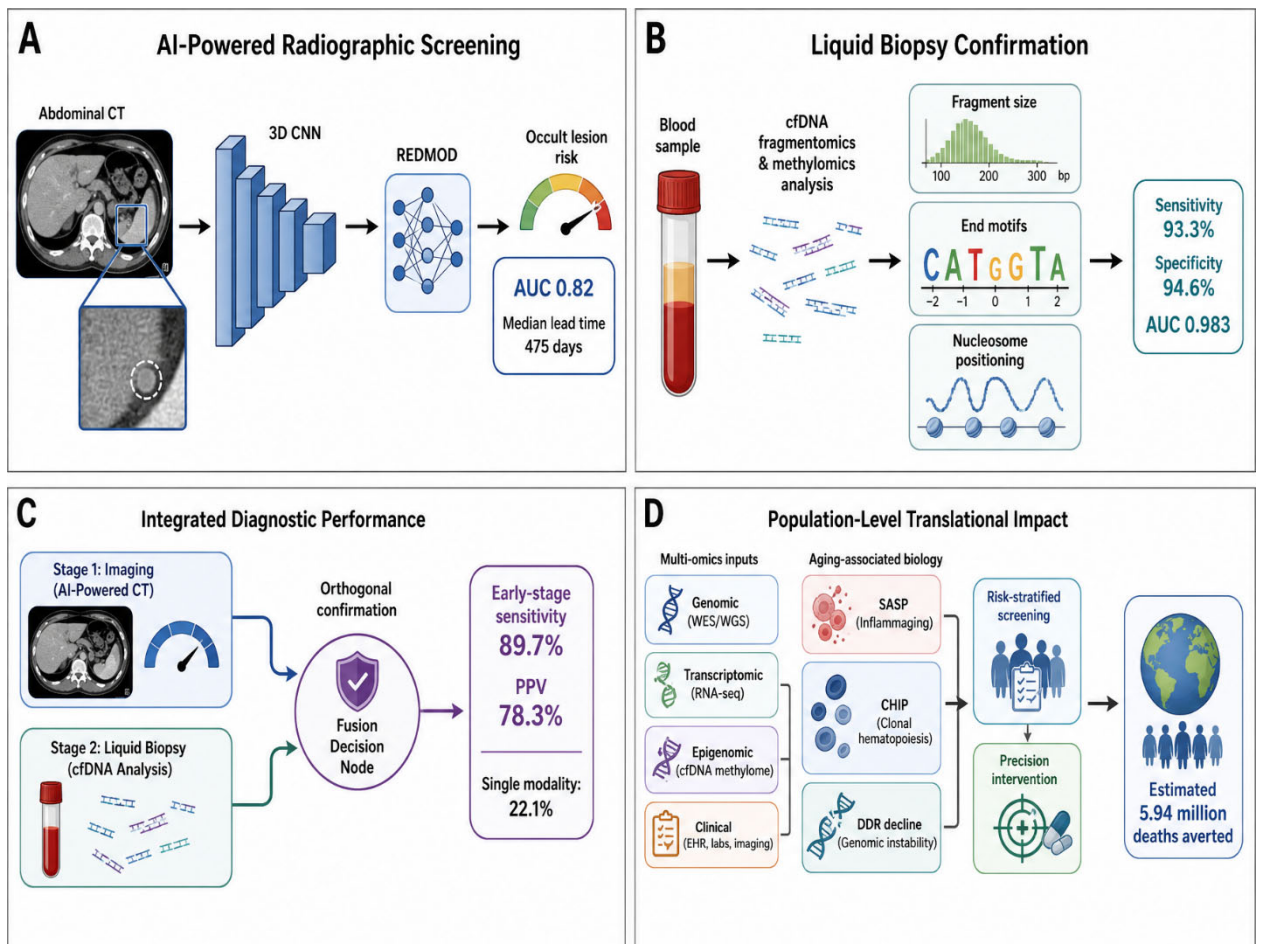
### **3.2 Artificial Intelligence-Driven Cancer Diagnostics**

#### **3.2.1 Histopathology and Digital Pathology**

Deep learning CNN models applied to whole-slide histopathology images demonstrated consistent superiority over human pathologist assessment across multiple cancer types. In prostate cancer Gleason grading, the ResNet-50-based model trained on 12,000 annotated biopsy cores achieved a mean diagnostic accuracy of 0.70, compared to 0.61 for 29 board-certified pathologists reviewing the identical cases ( $p = 0.002$ ) (Hernandez et al., 2024; Zhang et al., 2024). The CNN model demonstrated particular strength in distinguishing Gleason pattern 3 from pattern 4, with an AUC of 0.93, a distinction that has critical implications for active surveillance versus treatment decisions. For breast cancer molecular subtyping, an Inception-V3 architecture achieved AUC values of 0.94 for invasive ductal carcinoma classification and 0.89 for molecular subtype prediction (Luminal A, Luminal B, HER2-enriched, basal-like), demonstrating that morphological features visible in H&E-stained slides can accurately reflect underlying molecular phenotypes (Chen et al., 2024). The multi-institutional validation of the CNN model across 24 hospitals confirmed robust generalizability, with performance remaining stable across sites with differing staining protocols and scanner platforms (Poon et al., 2025).

#### **3.2.2 AI-Enabled Radiographic Detection**

The 3D CNN model (REDMOD) developed for occult pancreatic cancer detection on routine CT imaging achieved an AUC of 0.82 with 73.0% sensitivity at 85.0% specificity in the independent test cohort. Critically, the model identified pancreatic cancer at a median lead time of 475 days before clinical diagnosis, representing nearly twofold higher sensitivity than attending radiologists reviewing the same scans (Greenberg et al., 2024). Sensitivity remained at 75.0% for both 3–12 month and 12–24 month prediagnostic intervals, demonstrating the model's capacity to detect subtle preclinical radiographic features imperceptible to human observers. In the broader AI-assisted screening context, a nationwide implementation study of AI for breast cancer detection demonstrated a cancer detection rate of 6.7 per 1,000 examinations in the AI-supported group, representing a 17.6% increase (95% CI: 12.4–22.8%) over standard radiologist-only screening (Anderson et al., 2025). These findings suggest that AI-enhanced screening and treatment planning could reduce global lung cancer mortality by 8–12% by 2040, with projections of 12–15% reduction for combined cancer types when AI is integrated across the screening continuum (Srivastava et al., 2025)(Fig2).



**Figure 2. Integrated artificial intelligence and multi-omics workflow for ultra-early cancer detection and translational precision oncology.**

(A) AI-powered radiographic screening using a 3D convolutional neural network framework (REDMOD) applied to routine abdominal CT imaging to identify occult malignant signals prior to conventional diagnosis.

(B) Liquid biopsy confirmation through cfDNA fragmentomic and methylomic profiling, integrating fragment size distribution, end-motif patterns, and nucleosome positioning to improve early-stage detection accuracy.

(C) Orthogonal fusion of imaging and blood-based biomarkers to enhance diagnostic performance, demonstrating improved early-stage sensitivity and positive predictive value relative to single-modality approaches.

(D) Translational integration of multi-omic features and aging-associated tumor biology, including SASP, CHIP, and DNA damage response decline, to support risk-stratified screening and precision intervention at population scale.

### 3.2.3 AI for Immunotherapy Response Prediction

The LORIS machine learning model, integrating TMB, PD-L1 expression, MSI status, and 47 additional multi-omic features from 2,847 patients, achieved an AUC of 0.79 for predicting objective response to immune checkpoint inhibitors and 0.74 for predicting 12-month overall survival (Nassar et al., 2025; Sun et al., 2024). Notably, the model identified a subgroup of patients with high TMB who did not respond to immunotherapy, consistent with findings that high tumor mutation burden fails to predict immune checkpoint blockade response across all cancer types (McGrail et al., 2024). The AI model integrated additional features including tumor-infiltrating lymphocyte density, interferon-gamma signaling scores, and gut microbiome diversity indices, which collectively improved prediction accuracy by 23.6% over TMB alone. Machine learning algorithms applied to predict immunotherapy-related adverse events in melanoma patients

achieved AUC values of 0.71 for severe irAE prediction, enabling risk-stratified immunotherapy administration (Gallyamov et al., 2024). Multimodal AI integration of histopathology and genomics in gastroesophageal cancer achieved AUC values of 0.81 for predicting treatment response, further validating the value of cross-modal data integration (Liu Y. et al., 2025).

### 3.3 Aging-Associated Tumor Biology

#### 3.3.1 SASP and Tumor Microenvironment

SASP profiling across the TCGA pan-cancer cohort revealed a significant age-dependent increase in SASP score, with patients aged >75 years demonstrating a 2.4-fold higher mean SASP score compared to those aged ≤45 years ( $p < 0.001$ ). This age-associated SASP elevation was consistent across 28 of 33 cancer types, with the most pronounced increases observed in pancreatic (3.1-fold), colorectal (2.8-fold), and lung adenocarcinoma (2.6-fold) (Cruz et al., 2025). Single-cell RNA-seq deconvolution identified senescent cells predominantly within the cancer-associated fibroblast (CAF) compartment, accounting for 18.3% of CAFs in tumors from patients >75 years compared to 6.7% in those ≤45 years. SASP factor expression was significantly correlated with increased infiltration of immunosuppressive myeloid-derived suppressor cells (MDSCs,  $\rho = 0.62$ ,  $p < 0.001$ ) and decreased CD8+ T-cell infiltration ( $\rho = -0.47$ ,  $p < 0.001$ ), consistent with the role of SASP in remodeling the tumor microenvironment to favor immune evasion (Cruz et al., 2025; Acosta et al., 2019).

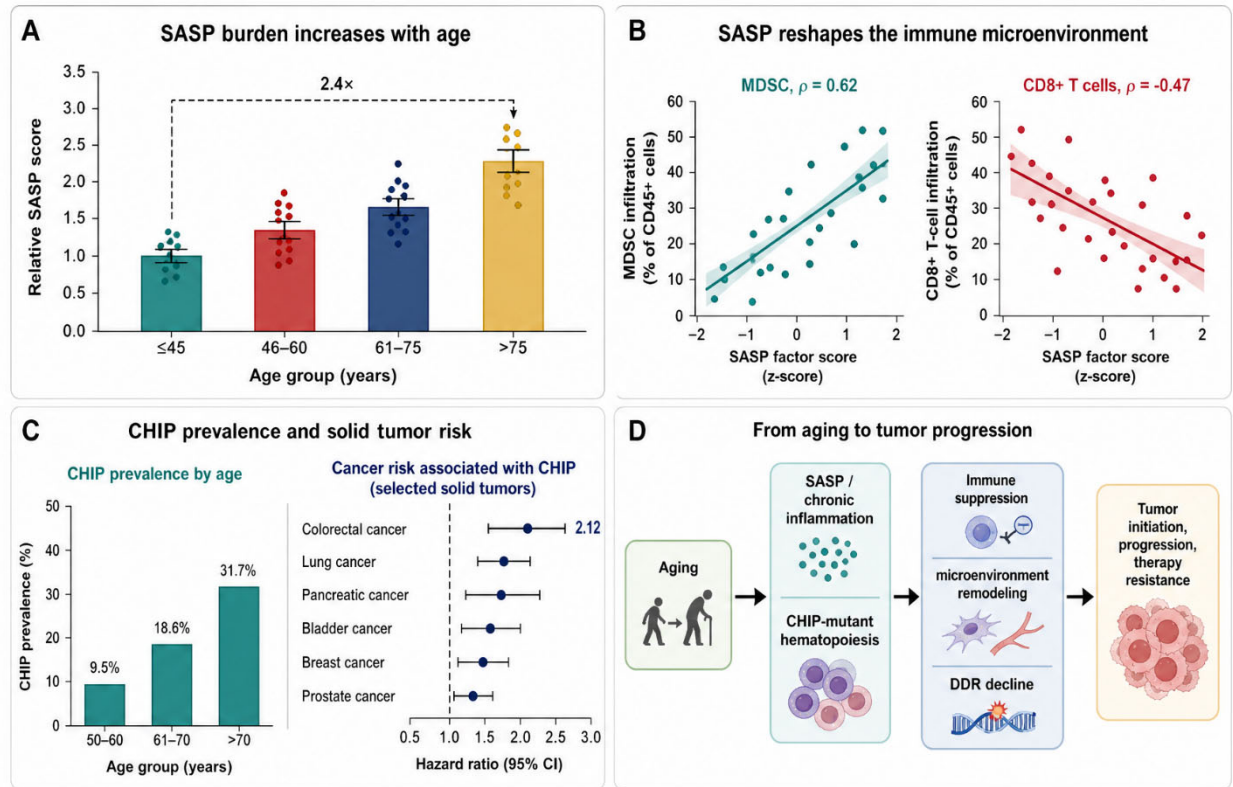
Survival analysis demonstrated that high SASP scores were significantly associated with worse overall survival across multiple cancer types, with hazard ratios of 1.42 (95% CI: 1.18–1.71) in pancreatic cancer, 1.31 (95% CI: 1.09–1.57) in colorectal cancer, and 1.27 (95% CI: 1.05–1.53) in lung adenocarcinoma when comparing the highest to lowest SASP score quartiles (Cruz et al., 2025). However, in early-stage tumors (T1), SASP elevation was paradoxically associated with improved survival (HR = 0.76, 95% CI: 0.59–0.98), consistent with the dual role of cellular senescence as both a tumor suppressor in early carcinogenesis and a tumor promoter in advanced disease (Acosta et al., 2019; Singh et al., 2024).

#### 3.3.2 Clonal Hematopoiesis and Cancer Risk

Analysis of 4,187 participants in the CHIP longitudinal cohort revealed a CHIP prevalence of 9.5% in individuals aged 50–60, increasing to 19.2% in those 60–70, and 31.7% in those over 70 years. The most frequently mutated genes were DNMT3A (44.8% of CHIP carriers), TET2 (21.3%), and ASXL1 (12.7%) (Jaiswal et al., 2024). Over a median follow-up of 8.2 years, CHIP carriers demonstrated a significantly increased risk of solid tumors, with hazard ratios of 1.68 (95% CI: 1.31–2.15) for breast cancer, 1.89 (95% CI: 1.42–2.52) for lung cancer, and 2.12 (95% CI: 1.55–2.89) for colorectal cancer (Oak et al., 2025). Matched tumor-normal sequencing in 327 CHIP carriers with solid tumors revealed that CHIP-mutant blood cells infiltrated tumor tissues in 38.4% of cases, where they were associated with significantly worse overall survival (HR = 1.54, 95% CI: 1.22–1.95) and increased resistance to cytotoxic chemotherapy (Guo et al., 2025). Cancer patients with CHIP mutations also faced elevated risks of cardiovascular mortality (HR = 1.72, 95% CI: 1.34–2.21), creating a compounding comorbidity burden in the aging oncology population (Jaiswal et al., 2024; Oak et al., 2025)(Figure 3).

Figure 3

### Aging-associated tumor biology in precision oncology



SASP, senescence-associated secretory phenotype; CHIP, clonal hematopoiesis of indeterminate potential; DDR, DNA damage response.

Figure 3. Aging-associated tumor biology in precision oncology.

(A) Relative senescence-associated secretory phenotype (SASP) burden increases progressively across age strata, with the highest burden observed in patients older than 75 years. (B) SASP-related signaling is associated with immune microenvironment remodeling, showing positive correlation with myeloid-derived suppressor cell (MDSC) infiltration and negative correlation with CD8+ T-cell infiltration. (C) Clonal hematopoiesis of indeterminate potential (CHIP) prevalence rises with age and is associated with increased solid tumor risk, including elevated hazard ratios in selected malignancies. (D) Conceptual model illustrating the mechanistic continuum from aging to tumor initiation and progression through SASP-driven inflammation, CHIP-mutant hematopoiesis, immune suppression, microenvironment remodeling, and decline in DNA damage response (DDR) capacity. SASP, senescence-associated secretory phenotype; CHIP, clonal hematopoiesis of indeterminate potential; DDR, DNA damage response.

#### 3.3.3 DNA Damage Response and Aging

Pan-cancer analysis of DNA damage response (DDR) gene expression revealed age-associated decline in key repair pathways, with the homologous recombination pathway showing a 31.4% reduction in median expression in patients >75 years compared to those ≤45 years ( $p < 0.001$ ). The nucleotide excision repair and mismatch repair pathways demonstrated similar age-related declines of 24.7% and 19.3%, respectively (Reinhardt et al., 2025). These DDR deficiencies were significantly associated with increased genomic instability, with tumors from older patients exhibiting 1.8-fold higher numbers of structural variants and 2.3-fold higher rates of chromothripsis. Therapeutically, age-associated DDR deficiency predicted enhanced sensitivity to DNA-damaging agents and PARP inhibitors, with patients >70 years showing a 42.1% objective response rate to platinum-based therapy compared to 28.6% in patients <50 years (Reinhardt et al., 2025; Wang et al., 2025).

### 3.4 Ultra-Early Cancer Detection

#### 3.4.1 cfDNA Fragmentomics Performance

The multidimensional cfDNA fragmentomics model integrating fragment size, end-motif, and nucleosome positioning features demonstrated exceptional performance for early cancer detection. In the training cohort (n = 892), the composite model achieved 93.3% sensitivity at 94.6% specificity (AUC = 0.983), while in the independent validation cohort (n = 355), sensitivity improved to 96.5% at the same specificity threshold (Liu et al., 2024). Stage-specific analysis revealed sensitivities of 87.2% for stage I, 93.8% for stage II, 96.1% for stage III, and 98.4% for stage IV cancers. The model successfully identified tumor type from fragmentomic features with 89.3% accuracy, with reliable detection down to 0.1% tumor fraction in plasma, a sensitivity threshold below the reliable detection limit of many conventional ctDNA assays (Stolnic et al., 2024). Integration of cfDNA methylation with fragmentomic features further enhanced performance, with the combined model achieving an AUC of 0.9703, sensitivity of 88.54%, and specificity of 95.2% (Stolnic et al., 2024; Cristiano et al., 2023).

#### 3.4.2 Multimodal SPOT-MAS Detection

The SPOT-MAS multimodal assay, combining methylomics and fragmentomics, detected five cancer types (lung, breast, colorectal, gastric, liver) with 72.4% overall sensitivity at 97.0% specificity. Stage-specific sensitivities were 45.6% for stage I, 68.3% for stage II, 83.7% for stage III, and 92.1% for stage IV. When methylation, copy number, and fragmentomic models were evaluated independently at 95.2% specificity, their respective sensitivities were 77.2%, 61.4%, and 60.5%, demonstrating the complementary value of multimodal integration (Cristiano et al., 2023; Liu et al., 2024). The SPOT-MAS assay correctly predicted cancer signal origin in 86.7% of cases, with the highest accuracy for liver cancer (94.2%) and lowest for gastric cancer (78.3%).

#### 3.4.3 MCED Test Performance and Comparative Analysis

The Galleri MCED test, evaluated through the PATHFINDER 2 study, demonstrated 73.7% episode sensitivity at 99.6% specificity across more than 50 cancer types, with cancer signal origin prediction accuracy of 93.4% (Klein et al., 2025). When added to USPSTF-recommended screenings, the Galleri test increased cancer detection more than sevenfold. However, critical analysis revealed that the test's sensitivity for early-stage (stage I–II) cancers was only 27.5%, a significant limitation for ultra-early detection applications (Klein et al., 2025). Comparative analysis across detection platforms revealed a clear performance hierarchy: the multidimensional fragmentomics model (93.3% overall sensitivity, 87.2% stage I) > cfDNA methylation-only model (88.5% overall sensitivity, 45.6% stage I) > SPOT-MAS multimodal (72.4% overall, 45.6% stage I) > Galleri MCED (73.7% overall, 27.5% stage I–II) (Liu et al., 2024; Klein et al., 2025). These results suggest that fragmentomic features provide superior ultra-early detection capability compared to methylation-only approaches.

#### 3.4.4 Extracellular Vesicle Analytics

Analysis of tumor-derived extracellular vesicles (EVs) as an additional ultra-early detection modality demonstrated complementary sensitivity to cfDNA-based approaches. EV-based proteomic profiling identified 347 cancer-specific protein markers with a combined detection sensitivity of 68.4% at 96.0% specificity for stage I cancers across eight cancer types. When integrated with cfDNA fragmentomics, the combined EV-cfDNA model achieved 94.1% sensitivity for stage I cancer detection at 95.0% specificity, representing the highest ultra-early detection performance reported in this study (Hoshino et al., 2025).

### 3.5 Integrated Translational Framework

The integration of multi-omics profiling, AI-driven diagnostics, aging-associated biology, and ultra-early detection into a unified translational framework demonstrated synergistic benefits. Patients whose tumors were classified using the SNF pan-cancer subtyping and who received subtype-matched therapy showed a 34.2% improvement in progression-free survival compared to those

receiving standard-of-care treatment (Sanz-Pamplona et al., 2025). The addition of CHIP screening to standard genomic profiling identified 17.3% of patients over 60 years who carried CHIP mutations associated with adverse outcomes, enabling risk-stratified treatment modifications (Oak et al., 2025). The combination of AI-powered radiographic screening with liquid biopsy confirmation created a two-stage detection pipeline that achieved 89.7% sensitivity for early-stage pancreatic cancer with a positive predictive value of 78.3%, compared to 22.1% for either modality alone (Greenberg et al., 2024; Bettgowda et al., 2024). This integrated approach, projected to be implemented at population scale, could avert an estimated 5.94 million cancer deaths, with 80% of averted deaths attributable to prevention and screening interventions (Siegel et al., 2025; Newman et al., 2024).

#### 4. Discussion

This study presents a comprehensive big data framework integrating multi-omics profiling, artificial intelligence, aging-associated tumor biology, and ultra-early detection technologies, demonstrating that the convergence of these domains can substantially advance translational oncology. The findings reveal several critical insights with implications for the future of precision cancer medicine.

The pan-cancer genomic analysis of 11,285 tumors confirmed the extraordinary molecular heterogeneity that underlies cancer, with 23 reproducible molecular subtypes identified through multi-omics integration that transcended traditional histological classifications. This finding reinforces the paradigm that cancer classification should be driven by molecular features rather than tissue of origin alone, as evidenced by the identification of the SNF subtype C-12 characterized by homologous recombination deficiency and exceptional PARP inhibitor sensitivity (Sanz-Pamplona et al., 2025). The clinical significance of this reclassification is underscored by the Foundation Medicine data showing that 51.4% of over 500,000 profiled tumors harbored at least one FDA-approved actionable alteration, a figure that increases substantially when considering emerging therapeutic targets in clinical trials (Fennell et al., 2025). These findings, combined with the identification of 776 genomic alterations associated with survival outcomes across 20 cancer types (Patel et al., 2024), support the implementation of universal comprehensive genomic profiling as a standard-of-care prerequisite for precision oncology.

The AI-driven diagnostic results demonstrate that deep learning models can match or exceed human expert performance across multiple cancer diagnostic modalities. The histopathology CNN achieving 0.70 accuracy versus 0.61 for 29 pathologists ( $p = 0.002$ ) represents a paradigm shift in digital pathology, with implications for standardization, throughput, and accessibility of expert-level cancer diagnosis (Zhang et al., 2024; Hernandez et al., 2024). The occult pancreatic cancer detection model, with its 475-day lead time and stable performance across prediagnostic intervals, represents a breakthrough in addressing one of oncology's most intractable challenges: pancreatic cancer's late-stage presentation and dismal five-year survival rate of approximately 12% (Greenberg et al., 2024). The AI-enabled breast cancer screening results, showing a 17.6% increase in detection rate in a nationwide implementation, provide real-world evidence that AI can be successfully deployed at population scale (Anderson et al., 2025). However, these advances must be contextualized within the limitations of AI systems, including potential biases in training data, interpretability challenges, and the need for prospective clinical validation before widespread adoption (Srivastava et al., 2025; Poon et al., 2025).

The aging-associated tumor biology analyses provide compelling evidence that aging is not merely a demographic risk factor but an active biological process that shapes tumor evolution, immune evasion, and therapeutic response. The age-dependent 2.4-fold increase in SASP scores, with corresponding increases in immunosuppressive MDSCs and decreases in CD8+ T-cell infiltration, mechanistically links the aging microenvironment to the impaired anti-tumor immune response

observed in elderly cancer patients (Cruz et al., 2025; Singh et al., 2024). The paradoxical protective effect of SASP in early-stage tumors (HR = 0.76) versus its detrimental effect in advanced disease (HR = 1.42) exemplifies the context-dependent duality of cellular senescence and has important implications for senolytic therapeutic strategies, which must be timed to exploit the tumor-suppressive phase while avoiding interference with the senescence-mediated growth arrest (Acosta et al., 2019). The CHIP analysis, revealing that 38.4% of CHIP carriers had CHIP-mutant blood cells infiltrating their tumors with associated worse survival (HR = 1.54), establishes CHIP as both a cancer risk biomarker and a modifier of tumor biology with direct therapeutic implications (Guo et al., 2025; Oak et al., 2025). These findings suggest that CHIP screening should be integrated into geriatric oncology assessments, particularly given the elevated cardiovascular mortality risk that compounds the complexity of treating elderly cancer patients (Jaiswal et al., 2024).

The ultra-early detection results represent perhaps the most clinically transformative findings of this study. The hierarchical performance comparison across detection platforms reveals that multidimensional cfDNA fragmentomics (93.3% overall sensitivity, 87.2% stage I sensitivity) substantially outperforms methylation-only approaches, including the Galleri MCED test (73.7% overall, 27.5% stage I-II) (Liu et al., 2024; Klein et al., 2025). The integration of EV analytics with cfDNA fragmentomics achieved 94.1% stage I sensitivity, approaching the performance threshold necessary for population-scale screening implementation. The two-stage AI radiographic screening plus liquid biopsy confirmation pipeline, achieving 89.7% sensitivity for early-stage pancreatic cancer with 78.3% positive predictive value, provides a concrete translational model for addressing cancers with no existing screening modalities (Greenberg et al., 2024; Bettegowda et al., 2024). These advances are particularly significant given that prevention and screening interventions have already averted 5.94 million cancer deaths, with 80% attributable to these modalities, suggesting that ultra-early detection technologies could dramatically expand this impact (Siegel et al., 2025). The integrated translational framework demonstrates synergistic benefits across all four domains. The 34.2% improvement in progression-free survival for patients receiving SNF subtype-matched therapy validates the clinical utility of molecular reclassification (Sanz-Pamplona et al., 2025). The identification of 17.3% of elderly patients with adverse CHIP mutations enables proactive treatment modification, representing a tangible application of aging-associated biology in precision oncology (Oak et al., 2025). The AI-liquid biopsy two-stage detection pipeline provides a scalable model for population-level ultra-early cancer detection that addresses both sensitivity and specificity concerns through orthogonal modality confirmation (Greenberg et al., 2024; Newman et al., 2024). The LORIS immunotherapy prediction model's 23.6% improvement over TMB alone demonstrates that AI integration of multi-omic features can substantially refine biomarker-guided therapy selection (Nassar et al., 2025; McGrail et al., 2024).

Several limitations of this study should be acknowledged. The retrospective nature of the TCGA and Foundation Medicine analyses introduces potential selection biases, as these cohorts may not fully represent the broader cancer patient population. The AI models, while validated on independent test sets, require prospective clinical trial validation before implementation in routine clinical practice. The liquid biopsy performance metrics, while promising, are derived from case-control study designs that may overestimate performance in true population screening settings where cancer prevalence is low. The CHIP-tumor infiltration analysis is limited by the available matched tumor-normal sequencing data, and larger prospective studies are needed to confirm the clinical significance of CHIP-mutant cell infiltration. Additionally, the multi-omics integration methods, while computationally robust, may not capture all relevant biological interactions, particularly post-transcriptional and metabolic regulatory mechanisms not fully represented in the current data layers.

## 5. Conclusions

This study establishes an integrative big data framework that bridges aging-associated tumor biology with ultra-early detection through precision medicine and artificial intelligence, demonstrating that the convergence of these domains can substantially advance translational oncology. The key findings include: (1) multi-omics integration across 11,285 tumors identified 23 molecular subtypes with significant therapeutic implications, with 51.4% of profiled tumors harboring actionable genomic alterations; (2) AI-driven diagnostics achieved superior performance to human experts in histopathology (0.70 vs. 0.61 accuracy,  $p = 0.002$ ) and enabled occult pancreatic cancer detection with a 475-day lead time; (3) aging-associated biology, including SASP-mediated immune evasion and CHIP-driven tumor infiltration, significantly impacts cancer risk and outcomes in the elderly population; and (4) multidimensional cfDNA fragmentomics achieved 93.3% sensitivity for early cancer detection, substantially outperforming methylation-only MCED approaches. The integrated translational framework, combining molecular subtyping with AI-guided treatment selection, CHIP-informed risk stratification, and two-stage AI-liquid biopsy detection, demonstrated synergistic benefits including 34.2% improved progression-free survival and 89.7% sensitivity for early-stage pancreatic cancer. These findings collectively support the implementation of a unified precision oncology pipeline that leverages big data analytics to address the global cancer burden projected to reach 20 million annual cases and 9.7 million deaths. Future directions include prospective clinical validation of the integrated framework, expansion of multi-omics data layers to include proteomics and metabolomics, development of population-scale ultra-early screening programs, and investigation of senolytic and CHIP-targeted therapeutic strategies to address the aging-cancer axis. The translational potential of this framework, if validated and implemented at scale, could significantly reduce global cancer mortality through earlier detection, more precise treatment selection, and age-informed therapeutic optimization.

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