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Pedagogical Sciences

The use of digital technologies in the process of teaching foreign languages at a non-linguistic university

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Abstract. This article examines the use of digital technologies in foreign language instruction within non-linguistic higher education institutions. It is noted that the integration of digital technologies into foreign language teaching must be balanced with traditional methods aimed at developing communicative competence—a process that requires "live" interaction among students. The focus on communicative and sociocultural components is achieved through the strategic selection of digital technologies and the thematic content of the provided materials. Such content should encompass both general and professional subject matter, featuring practice-oriented topics designed to foster specialized competencies.
Keywords: digital technologies; educational platform; non-linguistic higher education institution; foreign language; communicative approach; professional competencies; mobile application

A digital educational environment enables the integration of multimedia materials, electronic educational resources, interactive platforms—including learning management systems (LMS) such as Moodle—and mobile applications. The instructional process also incorporates authentic educational resources, such as Cambridge English Learning Resources, which facilitate the development of students' language skills. This renders the educational process more flexible, personalized, and focused on the practical application of the foreign language. At the same time, experience shows that in many educational institutions, the use of digital technologies lacks a systematic approach. Frequently, electronic educational resources serve merely as supplementary tools rather than being integrated into a comprehensive pedagogical model. This creates a discrepancy between the potential offered by digitalization and the actual extent to which digital technologies are implemented within the higher education system. The development and refinement of reading, writing, listening, and speaking skills are facilitated by digital interactive resources, including Web 2.0 technologies. The process of learning a foreign language incorporates a variety of digital tools—such as online platforms, social networks, virtual conferences and seminars, and wiki-based services—which offer new opportunities for presenting, reinforcing, and assessing course material in an accessible and engaging manner. One method for integrating technology into a foreign language curriculum is the adoption of a blended learning approach. Many researchers view the use of digital technologies in the educational process favorably; specifically, they highlight the ability to tailor individual learning trajectories, leverage a diverse range of technologies alongside databases, libraries, and blogs, and implement automated assessment and evaluation of learning outcomes [1].

The competent use of electronic resources and a reasonable relationship between classroom training and digital learning stimulates the development of self-learning skills, promotes the

individualization of the educational process, increasing the level of motivation of students, and the formation of a developing, personality-oriented educational environment.

In the process of teaching a foreign language at a university, there is an urgent need for the emergence of proprietary courses designed specifically for use on modern electronic platforms, taking into account the specifics of professional training in a particular area, as well as the educational needs and capabilities of students. In the process of creating your own electronic courses, electronic educational and methodological materials, the teacher is required to have both certain technical and methodological training, which includes, first of all, the identification of educational material intended for placement in digital form; adaptation of training content to a specific electronic platform; development of testing materials with automated verification and evaluation.

As part of the use of digital educational resources, it is worth paying attention to the gamification of foreign language teaching. Gamification can diversify the digital learning process, making it more interesting and motivating. Gamification (gamification) is an effective method that turns a complex learning process into an exciting activity. Modern students cannot imagine learning without using online games, courses and assignments. For a modern student, a game will be an end in itself; he enjoys the game process, since gamification makes a non-game process look like a game.

In the absence of a natural foreign-language environment, digital technologies support the perception and acquisition of course material and the development of language skills by enhancing the overall efficiency of the educational process; they also enable the involvement of native speakers in addressing various learning tasks [3]. For university students in non-linguistic fields of study, foreign language instruction aims to achieve two primary objectives: (1) attaining a B2 proficiency level, enabling communication within social, every day, and sociocultural contexts.

(2) the acquisition of a professional foreign language for the purpose of engaging in international professional interactions with representatives from various countries and cultures. To this end, the curricula for core professional educational programs at higher education institutions include courses such as "Foreign Language" and "Foreign Language for Professional Purposes." Depending on the students' initial proficiency level, instruction is based on various methodological approaches, including communicative, sociocultural, and learner-centered approaches. A. N. Zemskova emphasizes that instruction is most effective when it incorporates online lectures, online testing assignments, and digital libraries [4]. The use of digital libraries provides both informational and communicative support for the educational process.

The use of interactive educational platforms (such as Quizlet, Duolingo, Learning Apps, Word Wall, BBC Learn English, British Council, and Britannica) at any stage of skill development makes it possible to enrich lessons with authentic visual materials and interactive tasks covering a wide range of topics—tailored to the specific subject matter, educational objectives, and the students' individual abilities and interests [6].

In the process of creating a foreign language learning course, you can experiment with online platforms, gaming platforms, and applications. A game-based course can include a ready-made educational program based on digital educational resources. In particular, you can use applications such as Classcraft, Quizizz, Kahoot, English Grammar Test, Learningapps, and others to learn a foreign language. Learningapps.org is an online service for organizing learning using interactive modules. Existing modules can be directly included in the learning content, and they can also be modified or created in real time. Thanks to its interactivity, the app can be used to organize quality control of learning. The main advantage of the Quizizz.com service is the automatic establishment of feedback with the learner. It allows you to create your own or use existing lexical and grammatical online quizzes. The interactive resource Kahoot.it is an online service for creating quizzes, didactic games, and tests. A distinctive feature of this resource is that the tasks created in

Kahoot allow you to include multimedia information (photos and video clips). The pace of completing quizzes and tests is regulated by setting a time interval for each question. An effective resource for implementing gamification in classes is the online platform Classcraft.com. This service provides a game "engine" that allows the teacher to build their own role-playing game, where each student is a character with their own goals and tasks, interacting with other characters within the framework of the overall learning goal. It should be noted that a team competition is a tool for increasing students' engagement, providing effective mechanisms for interaction during joint activities.

Such platforms facilitate effective work with lexical and grammatical material. Notably, in non-linguistic higher education institutions, course content can be selected based on the students' specific fields of study and professional specializations. This approach addresses both subject-specific and meta-disciplinary components: students engage with professionally oriented content while simultaneously developing communicative and sociocultural competence within a naturalistic language environment.

An analysis of theoretical and scholarly-methodological sources has identified the following potential applications of digital technologies in foreign language instruction within non-linguistic higher education institutions:

• facilitating interactive engagement with students;
• enhancing the productivity of independent and group-based work;
• increasing student motivation and self-organization;
• ensuring the monitoring and assessment of skill development through an automated system, such as the LMS Moodle.

Thus, the potential for applying digital technologies to foreign language instruction in a non-linguistic higher education institution necessitates:

• the two-way integration of course content and digital technologies;
• the selection of optimal technologies aimed at the study and mastery of subject matter, as well as its practical application;
• the presence of a digital educational environment that facilitates the reception of information and the acquisition of subject-specific aspects.

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The Role of Creative Technologies in Developing Cognitive Engagement and Creative Thinking among Primary School Students

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Abstract

This article critically examines the role of creative educational technologies in fostering cognitive engagement and creative thinking among primary school students. Amid the transition from traditional, transmission-based educational paradigms to student-centred pedagogical models, there is an urgent need to cultivate 21st-century skills, particularly cognitive autonomy, divergent thinking, and intrinsic motivation. Drawing upon the constructivist theories of Vygotsky, Piaget, and Dewey, this study proposes a theoretical and methodological framework for integrating creative technologies—such as problem-based learning (PBL), inquiry-based learning, educational gamification, and digital interactive tools—into the primary education curriculum. The research investigates how these technologies activate the cognitive, emotional, and behavioural dimensions of student engagement, transforming passive learners into active constructors of knowledge. Furthermore, the article analyzes the manifestation of creative thinking components, including fluency, flexibility, originality, and elaboration, within everyday classroom activities. To bridge theory and practice, the article provides eight detailed analytical tables, presenting methodological classifications, practical classroom applications across subjects, and robust assessment criteria. It also addresses the pedagogical challenges of implementation, such as resource constraints and varying student readiness, offering actionable methodological recommendations for primary school teachers. Conclusively, the article establishes that the systematic, objective-driven application of creative technologies is essential for nurturing intellectually curious, adaptable, and innovative young learners.

Keywords: creative educational technologies, cognitive engagement, creative thinking, primary school students, student-centred learning, problem-based learning, primary education methodology.

1. Introduction

In contemporary primary education, the overarching goal of teaching has fundamentally shifted from the mere transmission of factual knowledge to the cultivation of dynamic, adaptable, and lifelong learning competencies. Primary school students today are entering a rapidly changing global landscape that demands highly developed cognitive engagement, robust problem-solving abilities, and advanced creative thinking. Consequently, primary school teachers are subject to evolving professional expectations. They are no longer viewed merely as authoritative dispensers

of information, but rather as facilitators of active learning, intellectual curiosity, and creative exploration (Beghetto & Kaufman, 2014; Cremin et al., 2015). To meet these expectations, traditional rote-learning methodologies must be replaced by student-centred approaches that encourage active participation, emotional investment, and cognitive persistence.

Central to this educational transformation is the integration of creative educational technologies. In the context of pedagogy, "technology" does not exclusively refer to digital devices; rather, it encompasses systematized methodologies, instructional strategies, and organized processes designed to achieve specific educational objectives (Zhao, 2012). Creative educational technologies—such as project-based learning, inquiry-based learning, collaborative tasks, and gamification—are purposefully designed to stimulate cognitive engagement by presenting students with meaningful, open-ended challenges that require original thought rather than memorized answers (Henriksen et al., 2021).

The research problem addressed in this article stems from the observed disconnect between the acknowledged importance of creative thinking and the practical realities of primary school classrooms, where rigid curricula and standardized testing often stifle cognitive autonomy and divergent thinking. While theoretical literature broadly supports the cultivation of creativity, many primary educators lack structured methodological guidance on how to effectively embed creative technologies into everyday subject lessons without compromising academic standards.

Therefore, the purpose of this article is to comprehensively examine the theoretical foundations and practical applications of creative educational technologies in developing cognitive engagement and creative thinking among primary school students. The specific objectives include: (1) analyzing the theoretical and psychological underpinnings of cognitive engagement and creative thinking in young learners; (2) classifying effective creative teaching technologies and evaluating their pedagogical potential; (3) illustrating practical classroom applications across various primary school subjects; and (4) developing structured methodological recommendations for primary school teachers to assess and foster these skills.

This article holds substantial theoretical and practical significance, as it synthesizes developmental psychology with actionable pedagogical strategies. It is directly correlated with the author's master's dissertation topic, "Methodology for Using Creative Technologies in Primary School Lessons," serving as a foundational analytical review and a methodological guide for the empirical implementation of creative educational practices.

2. Theoretical Foundations of Cognitive Engagement and Creative Thinking in Primary Education

The conceptualization of learning as an active, constructive process is deeply rooted in the constructivist theories of educational psychology. Lev Vygotsky's sociocultural theory emphasizes that cognitive development occurs through social interaction and cultural mediation. Vygotsky's concept of the Zone of Proximal Development (ZPD) is particularly relevant to the deployment of creative technologies, as it highlights the necessity of providing scaffolding—guidance from teachers or capable peers—to help students solve complex, open-ended problems they could not resolve independently (Vygotsky, 1978). Similarly, Jean Piaget's stages of cognitive development assert that primary school students (typically in the concrete operational stage) require hands-on, experiential learning opportunities to actively construct logical thought structures (Piaget, 1952).

Furthermore, John Dewey's philosophy of experiential education posited that learning is most effective when it is situated in meaningful, real-world contexts that provoke the learner's natural curiosity (Dewey, 1938). Jerome Bruner expanded on this by advocating for discovery learning, a process where students are encouraged to uncover facts and relationships for themselves, which is the foundational premise of modern inquiry-based and problem-based creative technologies (Bruner, 1966).

Within this constructivist framework, cognitive engagement is defined as the psychological investment and mental effort a student directs toward learning, understanding, or mastering the

knowledge and skills intended by academic work (Fredricks et al., 2004). It is a multidimensional construct encompassing three interrelated dimensions: cognitive, emotional, and behavioural. Cognitive engagement involves self-regulation, the use of deep learning strategies, and persistence in the face of intellectual challenges. Emotional engagement refers to the affective reactions in the classroom, such as interest, enthusiasm, and a sense of belonging. Behavioural engagement involves active participation, adherence to rules, and involvement in academic and social activities (Linnenbrink-Garcia et al., 2023).

Parallel to cognitive engagement is the construct of creative thinking. Educational psychology distinguishes creative thinking as a measurable cognitive process rather than an exclusive artistic talent. According to E. Paul Torrance (1974) and J.P. Guilford (1967), creative thinking is fundamentally characterized by divergent thinking—the ability to generate multiple solutions to a single problem. The core components of divergent thinking include fluency (producing a large number of ideas), flexibility (generating different categories of ideas), originality (producing unusual or unique ideas), and elaboration (developing and refining ideas). Modern educational scholars, such as Kaufman and Beghetto (2009), further democratized the concept of creativity through the "Four C" model, emphasizing that primary education should focus on "mini-c" (personal, subjective novel insights inherent in the learning process) and "little-c" (everyday creativity accessible to all students).

Crucially, cognitive engagement and creative thinking are reciprocally reinforcing. When primary school students are presented with creative, open-ended tasks, their intrinsic motivation and emotional engagement increase, which in turn fuels the cognitive persistence required to elaborate on original ideas (Krapp, 2005).

Table 1. Main Components of Cognitive Engagement and Their Indicators in Primary School Students

Dimension of Engagement	Definition / Pedagogical Focus	Observable Classroom Indicators
Cognitive Engagement	The mental effort, self-regulation, and use of deep learning strategies applied to complex tasks.	Asking clarifying questions, analyzing information, seeking alternative solutions, demonstrating persistence during difficult tasks.
Emotional Engagement	Affective reactions, intrinsic motivation, and emotional connection to the learning process.	Expressing curiosity and enthusiasm, displaying positive affect during group work, showing a sense of ownership over projects.
Behavioural Engagement	Active participation, attendance, and adherence to the structural expectations of the classroom.	Volunteering answers, following instructions, actively manipulating learning materials, remaining on task during independent work.

Table 2. Components of Creative Thinking and Their Classroom Manifestations

Component	Theoretical Definition (Guilford / Torrance)	Manifestation in Primary School Activities
Fluency	The ability to generate a large volume of ideas or solutions rapidly.	Brainstorming ten different ways to reuse a plastic bottle in a science lesson without judging the ideas.
Flexibility	The capacity to shift perspectives and generate diverse categories of ideas.	Solving a mathematical word problem using visual drawing, physical objects, and numerical equations.
Originality	The generation of unique, unusual, or statistically infrequent ideas.	Writing an alternative ending to a traditional fairy tale that subverts typical character expectations.
Elaboration	The ability to expand, refine, and add intricate details to a simple idea.	Taking a basic sketch of an imaginary animal and detailing its habitat, diet, and survival mechanisms.

3. The Concept and Classification of Creative Educational Technologies

In the context of primary education, a “creative educational technology” represents a structured, systematic pedagogical approach that explicitly targets the development of students' creative potential, autonomy, and critical inquiry. Unlike traditional didactic methods, which position the teacher as the primary source of knowledge and the student as a passive recipient, creative technologies construct an interactive learning environment where knowledge is co-created. These technologies are characterized by open-endedness, problem-orientation, and a high degree of student agency (Anderson et al., 2021).

The classification of creative educational technologies is diverse, reflecting the multifaceted nature of learning. They can be broadly categorized into problem-based, collaborative, cognitive-visual, and digital interactive technologies.

Problem-Based Learning (PBL) and Inquiry-Based Learning are foundational creative technologies. In PBL, learning is driven by complex, real-world problems that lack a single correct answer. Students must identify what they already know, determine what they need to learn, and collaborate to formulate solutions (Hmelo-Silver, 2004). Inquiry-based learning similarly relies on student curiosity, framing the curriculum around open questions rather than established facts (Zohar & Barzilai, 2020). Both methods demand high cognitive engagement as students must actively seek, evaluate, and synthesize information.

Game-Based Learning and Educational Gamification harness the intrinsic motivation of play. By embedding learning objectives within game mechanics (rules, challenges, rewards, narratives), teachers can significantly boost emotional and behavioural engagement. In primary education, educational games lower the affective filter, reducing the fear of failure and encouraging risk-taking, which is essential for original thinking (Plucker et al., 2004).

Cognitive-Visual Technologies, such as mind mapping and concept mapping, allow students to visually organize information, making abstract connections concrete. These tools facilitate flexibility and elaboration by requiring students to physically map out how disparate concepts interrelate.

Digital Interactive Learning Tools and Multimedia Resources (e.g., interactive whiteboards, basic block-coding platforms like Scratch, digital storytelling tools) provide new mediums for

expression. These technologies empower primary school students to design, animate, and share original creations, effectively merging digital literacy with creative thinking (Chen & Zhang, 2022).

Table 3. Classification of Creative Educational Technologies and Their Pedagogical Functions

Technology Category	Specific Methodologies	Primary Pedagogical Function
Inquiry & Problem-Based	Problem-Based Learning (PBL), Inquiry-Based Learning, Case Studies.	Stimulates independent research, analytical thinking, and the ability to navigate ambiguity.
Collaborative & Communicative	Cooperative Learning, Brainstorming, Role-Playing, Debate.	Fosters social-emotional learning, perspective-taking, and collective knowledge construction.
Cognitive & Visual	Mind Mapping, Concept Mapping, Design Thinking, Visual Storytelling.	Enhances structural thinking, pattern recognition, and spatial organization of complex ideas.
Game-Based & Digital	Gamification, Interactive Simulations, Digital Block Coding (e.g., Scratch).	Increases intrinsic motivation, lowers fear of failure, and integrates digital literacy with creativity.

4. The Relationship between Creative Technologies, Cognitive Engagement, and Creative Thinking

The intersection of creative educational technologies, cognitive engagement, and creative thinking forms a dynamic triad that significantly enhances the learning process. Creative technologies serve as the catalyst. By introducing novelty, intellectual challenge, and relevance, these pedagogical strategies capture students' attention and ignite emotional engagement. According to Meyer and Turner (2006), positive emotional engagement is a prerequisite for cognitive engagement; students who feel interested and psychologically safe are more willing to invest mental effort into challenging tasks.

Once cognitive engagement is activated, students employ deep-learning strategies, such as critical analysis and self-regulation. This sustained mental focus creates the optimal cognitive environment for creative thinking to occur. For instance, during a project-based learning module, a student's behavioural engagement ensures they participate in group discussions, their emotional engagement keeps them motivated despite setbacks, and their cognitive engagement drives them to test and refine multiple hypotheses.

Consequently, creative thinking is both a process and an outcome of this engagement. As students practice divergent thinking, generating original ideas and elaborating upon them, their sense of self-efficacy increases. Bandura's (1997) social cognitive theory suggests that heightened self-efficacy further strengthens cognitive engagement, creating a positive feedback loop. Thus, creative educational technologies do not merely teach students 'how to be creative'; they architect the psychological and structural conditions under which deep cognitive engagement and authentic creative expression naturally flourish (Runco, 2014).

Table 4. Comparative Analysis of Creative Teaching Technologies, Advantages, and Limitations

Teaching Technology	Key Advantages	Potential Limitations / Challenges
Problem-Based Learning (PBL)	Develops critical thinking, autonomy, and real-world application skills.	Requires significant time; can cause anxiety for students used to direct instruction.
Project-Based Learning	Promotes sustained inquiry, collaboration, and produces tangible artifacts.	Difficult to assess individual contributions; requires extensive teacher planning.
Game-Based Learning	Highly motivating, immediate feedback, encourages trial-and-error.	Risk of students focusing on game mechanics rather than educational content.
Brainstorming & Divergent Tasks	Rapidly builds ideational fluency and creates an inclusive atmosphere.	Dominant students may overshadow quiet ones; ideas may lack practical depth.
Mind & Concept Mapping	Helps visualize relationships; excellent for formative assessment.	Younger students may struggle with hierarchical categorization without scaffolding.

5. Methodological Approaches to Using Creative Technologies in Primary School Lessons

Implementing creative educational technologies in primary school requires a deliberate, structured methodological approach. The unstructured application of 'fun activities' does not equate to creative learning; authentic creative pedagogies must be closely aligned with curriculum standards and explicit learning objectives. Effective methodology balances student autonomy with teacher-directed scaffolding.

The first methodological principle is establishing a psychologically safe classroom environment. Creative thinking involves risk-taking—proposing ideas that might be wrong, unusual, or impractical. Teachers must cultivate an atmosphere where divergent ideas are validated and errors are viewed as essential steps in the learning process, rather than failures to be penalized (Craft, 2005).

The second principle involves the design of open-ended tasks. Traditional primary school tasks are often convergent, requiring a single correct answer (e.g., 'What is 5 + 7?'). Creative methodologies reframe these into divergent tasks (e.g., 'How many different ways can we combine numbers to make 12?'). This subtle pedagogical shift transforms a routine recall exercise into an opportunity for fluency and flexibility.

The third principle is scaffolding collaborative learning. According to Johnson and Johnson (2020), unstructured group work frequently leads to unequal participation. Creative methodologies employ structured cooperative learning frameworks where each student is assigned a specific role (e.g., researcher, illustrator, presenter). This ensures behavioral engagement from all participants and creates a matrix where students must negotiate differing viewpoints, thereby stimulating originality and elaboration.

6. Practical Applications of Creative Technologies across Primary School Subjects

The versatility of creative educational technologies allows them to be seamlessly integrated across the entire primary school curriculum. Contextualizing these technologies within specific subjects demonstrates their practical viability and pedagogical value.

In Language and Literacy, creative writing and storytelling technologies significantly enhance linguistic flexibility and imagination. Rather than simply summarizing a text, students can be tasked with 'Story Modification.' Using the 'What if?' divergent thinking strategy, a teacher

might ask, 'What if Cinderella's glass slipper was actually a pair of magic sneakers?' Students must cognitively engage with the narrative structure and character motivations to elaborate on this new premise, fostering both analytical comprehension and original expression.

In Mathematics, problem-based learning and visual mapping transform abstract concepts into tangible challenges. A teacher can present a real-world design problem: 'You have a budget of 100 Tenge and need to design a rectangular garden. Fencing costs 5 Tenge per meter. What are the different dimensions your garden could have, and which one gives the most space?' This task requires fluency (generating multiple area/perimeter combinations) and elaboration (justifying the optimal choice), engaging higher-order cognitive skills rather than rote calculation.

In Science (World Around Us), inquiry-based learning and basic STEM design methodologies turn the classroom into a laboratory. Instead of lecturing on buoyancy, the teacher poses an inquiry question: 'How can we build a boat out of clay that holds 10 marbles without sinking?' Students must hypothesize, prototype, test, and iterate. This technology naturally triggers behavioural engagement (manipulating materials), emotional engagement (excitement of testing), and cognitive engagement (analyzing why a design failed and adjusting it).

Across all subjects, the teacher's role shifts from a knowledge transmitter to an instructional designer and cognitive coach, carefully monitoring progress, asking probing questions, and ensuring that the creative process remains anchored to the educational objectives.

Table 5. Examples of Creative Learning Activities across Primary School Subjects

Subject	Creative Technology Used	Learning Activity Example	Targeted Component of Creative Thinking
Language & Literacy	Divergent Storytelling	Students rewrite the ending of a known fable from the perspective of the antagonist.	Originality and Perspective-taking.
Mathematics	Problem-Based Learning	Designing a floor plan for a classroom using specific area/perimeter constraints.	Flexibility and Elaboration.
Science	Inquiry-Based Learning / STEM	Constructing a bridge using limited materials (paper, tape) that holds a specific weight.	Fluency of ideas and analytical problem-solving.
Art / Integrated Learning	Mind Mapping & Design	Creating a visual mind map connecting emotions to specific colors, shapes, and weather patterns.	Flexibility and Structural visualization.

7. Assessment and Evaluation of Cognitive Engagement and Creative Thinking

Traditional assessment paradigms, which heavily rely on standardized tests and true/false metrics, are fundamentally inadequate for evaluating cognitive engagement and creative thinking. Evaluating creativity requires formative, qualitative, and multifaceted assessment strategies that measure the process of learning, not merely the final product.

To assess cognitive engagement, educators must rely on observable behavioural indicators and self-reporting mechanisms. Observation checklists can track the frequency of clarifying questions, persistence on difficult tasks, and the quality of peer collaboration. Self-reflection journals, where students respond to prompts like 'What was the most challenging part of today's project and how did you overcome it?', provide insight into a student's internal cognitive and emotional regulation (Wang et al., 2023).

Assessing creative thinking requires rubrics specifically designed to measure fluency, flexibility, originality, and elaboration. For instance, a teacher assessing a brainstorming session should not grade based on the 'correctness' of an idea, but rather assign points for the sheer volume of ideas (fluency) and the variety of categories those ideas cover (flexibility). Portfolios are highly effective in this regard, as they compile a student's drafts, revisions, and final projects, allowing both the teacher and the student to witness the evolution of an original idea over time.

Crucially, assessment must include peer and self-assessment. When primary school students are taught to evaluate their own work and the work of their peers using a clear, age-appropriate rubric, they develop metacognitive skills, which are deeply intertwined with sustained cognitive engagement.

Table 6. Assessment Criteria for Cognitive Engagement and Creative Thinking

Assessment Area	Assessment Method / Tool	Observable Indicators for Teachers
Cognitive Engagement	Formative Observation Checklist, Self-Reflection Journals.	Sustained attention, asking 'why' and 'how' questions, utilizing resources independently.
Ideational Fluency	Brainstorming Rubrics, Idea Counting.	Number of distinct ideas generated within a specific timeframe.
Originality	Portfolio Assessment, Peer Review.	Proposing solutions that are unique, unexpected, or statistically rare among the class.
Elaboration	Project Rubrics, Draft Comparisons.	Adding detailed descriptions, complex mechanisms, or rich vocabulary to a foundational idea.

8. Challenges and Limitations in Implementing Creative Technologies

While the pedagogical benefits of creative technologies are substantial, their implementation in primary school classrooms is fraught with practical challenges. A critical analysis of these limitations is necessary to develop realistic methodological recommendations.

A primary constraint is instructional time and curriculum density. Primary school curricula are often overloaded with mandatory content standards. Problem-based and inquiry-based learning require significant time for exploration, discussion, and iteration, which often conflicts with the rigid pacing required to prepare for standardized assessments. Consequently, teachers may view creative technologies as supplementary 'extras' rather than core instructional methods.

Resource limitations and large class sizes further complicate implementation. Facilitating project-based learning or STEM activities in a classroom of 30 or more young students requires exceptional classroom management skills. Furthermore, unequal access to digital interactive tools—both within the school and at home—can create a digital divide, ensuring that only well-resourced students benefit fully from modern gamified or digitally creative learning.

Additionally, differences in student readiness and the methodological competence of teachers pose significant barriers. Students accustomed to passive instruction may experience cognitive overload or anxiety when suddenly faced with open-ended, ambiguous tasks. Similarly, teachers trained in traditional didactic methods often struggle to transition into the role of a facilitator. They may inadvertently provide too much assistance, thereby short-circuiting the productive struggle necessary for cognitive engagement, or provide too little structure, leading to chaos rather than learning (Smith & Reiser, 2021).

Table 7. Common Implementation Challenges and Recommended Pedagogical Solutions

Implementation Challenge	Root Cause in Primary Education	Recommended Pedagogical Solution
Time Constraints	Overloaded, rigidly paced curriculum.	Integrate creative tasks into core subjects rather than treating them as separate activities.
Classroom Management	Large class sizes; noise and activity levels during group work.	Use structured cooperative roles; establish clear behavioral protocols for project time.
Student Anxiety	Fear of failure; unfamiliarity with open-ended, ambiguous tasks.	Create a psychologically safe environment; praise effort and process over final correct answers.
Teacher Competence	Lack of practical training in facilitating inquiry and divergent thinking.	Provide ongoing professional development; start with small, manageable creative activities.

9. Discussion

The integration of creative educational technologies into primary education represents a critical evolution in pedagogy. The literature and pedagogical analysis presented in this article demonstrate that cognitive engagement and creative thinking cannot be taught through passive reception; they must be actively constructed through experience, inquiry, and problem-solving. Technologies such as PBL, educational gamification, and collaborative inquiry serve as the necessary vehicles for this construction.

However, a recurring theme in the discussion of these technologies is the delicate balance between structure and autonomy. Total autonomy in a primary classroom often leads to cognitive overload and behavioral disengagement, while excessive structure suffocates originality and flexibility. The success of creative technologies, therefore, rests almost entirely on the teacher's ability to provide dynamic scaffolding—offering just enough guidance to prevent frustration, while leaving enough ambiguity to stimulate divergent thinking.

Furthermore, it is vital to dispel the misconception that creative technologies are solely applicable to the arts or humanities. As demonstrated, problem-based mathematics and inquiry-based science provide some of the most fertile ground for creative elaboration and fluency. The reconceptualization of creativity as a general cognitive capability (the 'little-c' creativity) implies that every primary school lesson holds the potential for creative engagement.

Ultimately, the goal of deploying these technologies is not to produce professional artists or inventors from primary schools, but to nurture adaptable, resilient, and cognitively engaged individuals capable of navigating the complexities of the 21st century.

10. Methodological Recommendations for Primary School Teachers

Based on the theoretical and practical analysis conducted in this study, a set of methodological recommendations is proposed to assist primary school teachers in effectively integrating creative technologies into their classrooms.

First, teachers must purposefully formulate lesson objectives that explicitly target creative and cognitive outcomes, alongside content knowledge. If the objective is only to memorize a fact, creative technologies will feel inefficient. Objectives should use verbs that demand higher-order thinking, such as 'design,' 'propose alternative solutions,' or 'investigate.'

Second, teachers must implement differentiated scaffolding. Recognize that primary school students have varying levels of tolerance for ambiguity. For students struggling with a divergent task, the teacher can provide a constrained choice or a partially completed concept map to initiate the cognitive process, gradually removing the support as the student's confidence grows.

Third, formative feedback must focus on the process rather than the product. When providing feedback on a creative task, teachers should praise the diversity of ideas (fluency), the unique perspectives taken (originality), and the persistence shown during problem-solving (cognitive engagement). Evaluative language that labels ideas as simply 'right' or 'wrong' should be minimized during the divergent phase of learning.

Finally, to provide a structured approach, the following step-by-step methodological framework (Table 8) is proposed for integrating a creative technology into a standard primary school lesson.

Table 8. Step-by-Step Implementation Framework for Creative Lessons

Step	Pedagogical Action	Purpose / Expected Outcome
1. Define Objective	Identify specific content knowledge and the targeted creative component (e.g., fluency).	Ensures the creative activity is anchored to the academic curriculum.
2. Select Technology	Choose an age-appropriate method (e.g., Mind Mapping, PBL, Inquiry).	Matches the pedagogical tool to the learning objective.
3. Pose the Problem	Present an open-ended question, scenario, or real-world challenge.	Triggers curiosity and initiates emotional and cognitive engagement.
4. Organize Work	Assign individual, pair, or structured group roles.	Facilitates behavioral engagement and collaborative knowledge building.
5. Scaffolding & Feedback	Monitor groups, ask probing questions, provide hints without giving answers.	Maintains students within their Zone of Proximal Development.
6. Share & Evaluate	Students present multiple solutions; peer and self-assessment occur.	Develops metacognition and validates diverse, original approaches.
7. Reflection	Discuss the learning process, challenges faced, and cognitive strategies used.	Consolidates deep learning and builds future cognitive resilience.

11. Conclusion

Developing cognitive engagement and creative thinking among primary school students is an educational imperative in the modern era. As this article has demonstrated, traditional instructional methods are insufficient for cultivating the autonomy, problem-solving capabilities, and divergent thinking required by contemporary society. Through the integration of creative educational technologies—such as problem-based learning, inquiry-based activities, cognitive-visual tools, and digital gamification—primary educators can profoundly transform the learning experience.

These technologies function by triggering the emotional and behavioral dimensions of engagement, which in turn sustain the deep cognitive effort necessary for authentic learning. By providing structured, open-ended tasks within a psychologically safe environment, teachers empower students to exercise fluency, flexibility, originality, and elaboration across all subjects, from language arts to mathematics.

While the implementation of creative technologies presents genuine challenges, including curriculum constraints and the need for advanced classroom management, these barriers are surmountable through deliberate methodological planning, differentiated scaffolding, and process-oriented assessment. The methodological framework and recommendations proposed in this article provide a structured pathway for primary school teachers to bridge the gap between educational theory and daily classroom practice. Ultimately, the systematic application of creative technologies does not merely enhance academic achievement; it fosters a generation of intellectually curious, resilient, and innovative thinkers equipped for lifelong learning.

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Von der visuellen Szene zum visuellen Schema: Eine theoretische Erweiterung des Situated Language Comprehension auf die Vermittlung von Fachsprachen (LSP)

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Zusammenfassung

Die moderne Psycholinguistik betrachtet Sprachverstehen nicht als isolierte Dekodierung eines Signals, sondern als kontextabhängigen, dynamischen Prozess. Die Ansätze des *Situated Language Comprehension* (SLC) und des *Visually Situated Language Comprehension* von Knoeferle und Kolleginnen und Kollegen beschreiben diesen Prozess als Interaktion von sprachlichem Input, visueller Szene und Vorwissen in Echtzeit. Diese Modelle beruhen überwiegend auf allgemeinsprachlichem Material und konkreten physischen Szenen; das Verstehen fachsprachlicher Texte in einer Fremdsprache wird von ihnen nicht unmittelbar adressiert. Der Beitrag entwickelt das theoretische Argument, dass sich beim Übergang vom SLC zur Fachsprache (*Language for Specific Purposes*, LSP) nicht nur die Schwierigkeit des sprachlichen Materials verändert, sondern die Natur der „Situation" selbst. An die Stelle der visuellen Szene (Objekte, Handlungen, Ereignisse) tritt in der LSP das visuelle Schema (Diagramm, Prozessmodell, Hierarchie, Grafik), und das allgemeine Weltwissen (*world knowledge*) wird weitgehend durch Fachwissen (*domain knowledge*) ersetzt. Der Beitrag leistet Folgendes:

1. Er formuliert die systematische Transformation „Szene →Schema",
2. Er fasst das visuelle Schema nicht als bloße Illustration des Textes, sondern als dessen konzeptuellen Kontext auf,
3. Er schlägt ein dreikomponentiges Integrationsmodell vor und
4. Er leitet daraus vier überprüfbare Hypothesen (H1-H4) sowie ein empirisches Forschungsprogramm ab.

Das Modell wird als theoretische Hypothese vorgestellt, die einer empirischen Überprüfung bedarf.

Schlüsselwörter: *Situated Language Comprehension, Visually Situated Language Comprehension, L2, LSP, Fachsprache, visuelles Schema, Fachwissen, multimodales Verstehen.*

Einleitung

Aktuelle Studien zum Sprachverstehen zeigen, dass sich die Interpretation sprachlicher Information nicht auf die Verarbeitung grammatischer Strukturen beschränkt: Beteiligt sind stets auch der situative Kontext, visuelle Informationen und das Vorwissen der Sprachverwenderinnen und Sprachverwender. Das *Coordinated Interplay Account* (CIA) von Knoeferle und Crocker (2006) fasst Sprachverstehen als koordiniertes Zusammenspiel von sprachlicher Interpretation, visueller Aufmerksamkeit und nichtsprachlichem Kontext auf. Studien mit Blickbewegungen und ereigniskorrelierten Potenzialen (EKP) deuten darauf hin, dass visuelle und sprachliche

Informationen in verschiedenen Phasen des Verstehens inkrementell interagieren (Knoeferle et al., 2008, 2011; Knoeferle & Guerra, 2016).

Diese Literatur lässt jedoch eine zentrale Frage offen: Wie ist situiertes Verstehen aufzufassen, wenn Lernende einen Fachtext in einer Fremdsprache (L2-LSP) lesen? In diesem Fall tritt zur allgemeinen sprachlichen Verarbeitung die Interpretation spezialisierter Terminologie, die Aktivierung fachlicher Konzepte und die Verknüpfung des Textes mit einschlägigem Fachwissen hinzu. Zudem ist der visuelle Kontext keine „Szene" im wörtlichen Sinn mehr: Das visuelle Begleitmaterial fachsprachlicher Texte besteht überwiegend aus Diagrammen, Schemata, Ablaufplänen oder Grafiken.

Forschungslücke

Die bestehenden SLC-Studien:

1. stützen sich überwiegend auf konkrete, deskriptive Gegenstandsszenen,
2. beziehen sich größtenteils auf Erstsprachenverarbeitung (L1) oder allgemeine Zweitsprachenverarbeitung (L2) und
3. fassen *world knowledge* als allgemeines Orientierungswissen über die Welt auf.

Sie beantworten nicht die Frage, welche kognitive Funktion der visuelle Kontext erfüllt, wenn er selbst eine abstrahierte, strukturierte Repräsentation von Fachwissen darstellt.

Beitrag des Aufsatzes

Der Beitrag begründet drei zentrale Thesen:

Szene → Schema: In der LSP ist die visuelle Komponente des SLC als Transformation *Visual Scene → Visual Schema* aufzufassen. Die Szene beantwortet die Frage „Was geschieht?", das Schema die Frage „Wie ist das Wissen organisiert?".

Wandel des Wissenstyps: Allgemeines Weltwissen reicht in der LSP nicht mehr aus und wird durch Fachwissen (*domain knowledge*) ersetzt bzw. determiniert.

Schema als konzeptueller Kontext: Das visuelle Schema ist keine dekorative Ergänzung des Textes, sondern sein konzeptueller Kontext; die gemeinsame, parallele Verarbeitung von Text und Schema bildet den zentralen Mechanismus des fachlichen Verstehens.

Aufbau der Arbeit: Kapitel 2 beschreibt die theoretischen Grundlagen des SLC; Kapitel 3 behandelt den Übergang von L1 zu L2 und zur LSP; Kapitel 4 stellt das vorgeschlagene dreikomponentige Modell vor; Kapitel 5 formuliert die überprüfbaren Hypothesen samt Untersuchungsdesign; Kapitel 6 behandelt didaktische Konsequenzen, theoretische Implikationen, Einschränkungen und das Fazit.

1. Theoretische Grundlage: Sprachverstehen als situierter und dynamischer Prozess

Nach dem situierten Ansatz hängt die Interpretation einer sprachlichen Einheit nicht nur von ihren lexikalischen, syntaktischen und semantischen Merkmalen ab, sondern auch von der Information, die den Sprachverwendenden in einer konkreten Wahrnehmungssituation zur Verfügung steht. Die empirische Grundlage schufen Tanenhaus et al. (1995): Blickbewegungsdaten zeigten, dass Hörerinnen und Hörer bei der Verarbeitung sprachlicher Anweisungen gleichzeitig das Sprachsignal und die visuelle Umgebung nutzen. Damit wurde der Kontext zu einem unmittelbaren Bestandteil der laufenden, inkrementellen Verarbeitung.

In der Studie von Knoeferle und Crocker (2006) beruhte das *Visual-World-Paradigma* auf der Erfassung der Aufmerksamkeitsverlagerungen der Hörenden während der Aufnahme sprachlicher Informationen. Knoeferle et al. (2011) zeigten mit EKP-Methoden, wie sich das Zusammenspiel

von sprachlicher und visueller Information in neurokognitiven Maßen niederschlägt. Der Überblick von Knoeferle und Guerra (2016) fasst diese Linie zusammen und stellt Verstehen als Prozess dar, in dem sprachliche Information mit der visuellen Umgebung, Aufmerksamkeitsmechanismen und Vorwissen interagiert.

Auf dieser Grundlage lassen sich im klassischen SLC-Rahmen drei Komponenten unterscheiden:

Linguistic Input: Wörter, syntaktische Konstruktionen, semantische Information.

Visual Scene: Objekte, Handlungen und Ereignisse der unmittelbar wahrnehmbaren Umgebung.

World Knowledge: Allgemeines Erfahrungswissen der Sprachverwendenden über die Welt.

Hier setzt die zentrale Frage dieses Beitrags an: Wie verändern sich diese drei Komponenten und ihr Zusammenspiel beim Übergang von der Allgemeinsprache zur Fremdsprache und insbesondere zur Fachsprache (LSP)?

1. 1 Von L1 über L2 zur LSP: Was verändert sich?

Lernende einer Zweitsprache (L2) verarbeiten sprachliche Informationen häufig unter Bedingungen, in denen die lexikalische, grammatische und syntaktische Verarbeitung im Vergleich zur L1 weniger automatisiert ist. Visuelle Informationen erhalten in der L2 deshalb eine zusätzliche kognitive Entlastungs- und Stützfunktion.

Diese Erweiterung genügt für die Fachsprache (LSP) jedoch nicht: Um einen Fachtext zu verstehen, lässt sich Vorwissen nicht auf allgemeines Weltwissen reduzieren; erforderlich ist das konzeptuelle Wissen eines bestimmten Fachgebiets (*domain knowledge*). Wer einen Text aus Ingenieurwesen, Medizin oder Wirtschaft liest, versteht möglicherweise die Grammatik der Sätze, das tiefere Verstehen des Inhalts hängt jedoch maßgeblich vom Fachwissen ab.

Beim Verstehen fachsprachlicher Texte müssen Lernende gleichzeitig fremdsprachliches Vokabular verarbeiten, spezialisierte Termini interpretieren, fachliche Konzepte aktivieren und die im Text beschriebenen kausalen, hierarchischen oder prozeduralen Beziehungen konstruieren. Das Verstehen eines LSP-Textes ist damit die integrative Verarbeitung sprachlicher und konzeptueller Information. In dieser Phase verändert sich auch die Natur der visuellen Information grundlegend:

Verstehen allgemeiner Sprache (Classic SLC): Visuelle Information: Konkrete physische Szene (*Visual Scene*: Personen, Objekte, Handlungen)*;* Erkenntnisziel: Beantwortet: „Was geschieht?“*;* Wissensquelle: *World Knowledge* (allgemeines Weltwissen)*;* Kopplungstyp: Referenziell (Wort → Objekt / Handlung)*;*Verstehen eines LSP-Textes (LSP-SLC):

Visuelle Information: Visuelles Schema (*Visual Schema*: Diagramm, Prozessmodell, Hierarchie, Grafik) Erkenntnisziel: Beantwortet: „Wie ist das Wissen organisiert?“ Wissensquelle: *Domain Knowledge* (fachspezifisches Wissen) Kopplungstyp: Strukturell (Terminus → Knoten / Pfeil / Ebene).

Die letzte Zeile dieser Gegenüberstellung bildet eine der zentralen Thesen dieses Beitrags: Im klassischen SLC sind sprachliche und visuelle Informationen überwiegend auf der Ebene der Referenz miteinander verbunden, in der LSP dagegen auf der Ebene der Struktur. Der Text vermittelt Wissen linear, das visuelle Schema macht seine konzeptuelle Struktur simultan sichtbar.

2. Das vorgeschlagene Modell: Von der visuellen Szene zum visuellen Schema

Die Transformation

Das Modell beruht auf zwei simultanen Transformationen:

Visual Scene →Visual Schema

World Knowledge →Domain Knowledge

Daraus ergibt sich für das klassische situierte Verstehen die Grundformel:

[Linguistic Input] → [Visual Scene] → [World Knowledge] → [Situated Comprehension]

Diese wird für den fachsprachlichen Kontext wie folgt transformiert:

[LSP-Text] → [Visual Schema] → [Domain Knowledge] → [Integrated Conceptual Comprehension]

Unter einem **visuellen Schema** wird in diesem Beitrag eine symbolische Repräsentation verstanden, die die Struktur des Fachwissens unmittelbar ausdrückt:

- **Prozessschema:** Abfolge von Handlungen, Phasen und Kausalketten;
- **Hierarchisches Schema:** Über- und Unterordnungsbeziehungen zwischen Begriffen (Taxonomien);
- **Grafik / Diagramm:** Quantitative, funktionale oder dynamische Beziehungen;
- **Konzeptuelles Schema:** Strukturierte Zusammenhänge der Komponenten eines Systems.

Struktur des Modells

Das Verstehen eines Fachtextes ist nicht allein das Ergebnis sprachlicher Dekodierung; es ist ein dynamisches System aus drei Komponenten, in dem die Verarbeitung des LSP-Textes, die Interpretation des visuellen Schemas und die Aktivierung des Fachwissens wechselseitig interagieren und gemeinsam integriertes konzeptuelles Verstehen (*Integrated Conceptual Comprehension*) hervorbringen.

3. Überprüfbare Hypothesen und Untersuchungsdesign

Aus dem vorgeschlagenen theoretischen Modell lassen sich vier empirisch überprüfbare Hypothesen leiten:

Hypothese 1 (H1 Strukturelle Kompensation): *Die simultane Darbietung eines LSP-Textes mit einem passenden visuellen Schema führt zu einer schnelleren Verarbeitungszeit und einem höheren Textverständnis als die isolierte Textdarbietung, da das Schema die lineare Textstruktur visuell-strukturell kompensiert.*

Hypothese 2 (H2 Moderation durch Fachwissen): *Der entlastende Effekt der Schema-Text-Integration wird durch das bereichsspezifische Fachwissen (domain knowledge) der Lernenden moderiert; Personen ohne relevantes Fachwissen profitieren signifikant weniger vom visuellen Schema.*

Hypothese 3 (H3 Schemakompetenz als Prädiktor): *Die individuelle Fähigkeit zur korrekten Dekodierung visueller Schemata (Visual Schema Literacy) korreliert positiv mit der Leistung beim Fachtextverstehen und stellt einen unabhängigen Prädiktor für den Lernerfolg dar.*

Hypothese 4 (H4 Inkrementelle Echtzeit-Koordination): *In der Logik des Coordinated Interplay Accounts (CIA) lösen strukturell bedeutsame Termini im Text (z. B. Bezeichnungen von Prozessphasen oder Hierarchieknoten) unmittelbar zielgerichtete Blickbewegungen (Sakkaden) auf die entsprechenden Elemente des visuellen Schemas aus.*

Empirisches Untersuchungsdesign

Zur empirischen Überprüfung dieser Hypothesen wird folgendes Versuchsdesign vorgeschlagen:

Hypothese 1 (H1):

Forschungsfrage: Unterscheidet sich das Verstehen eines LSP-Textes bei isolierter vs. schemabegleiteter Darbietung?

Experimentelles Design & Methodik: 2x2-Design: Bedingung (Text allein vs. Text →Schema); Messung von Verstehensleistung, Verifikationsaufgaben und zeitversetztem Recall (vgl. Kreysa et al., 2018).

Hypothese 2 (H2):

Forschungsfrage: Wie beeinflusst das Fachwissen die integrierte Verarbeitung?

Experimentelles Design & Methodik: Gruppierungsfaktor: Probanden klassifiziert nach Fachwissen (Niedrig vs. Hoch); Analyse von Interaktionseffekten (Bedingung x Fachwissen).

Hypothese 3 (H3):

Forschungsfrage: Hängt die Schemakompetenz direkt mit dem Textverstehen zusammen?

Experimentelles Design & Methodik: Korrelations und Regressionsanalyse: Separater Pre-Test zur Visual Schema Literacy als Kovariate.

Hypothese 4 (H4):
Forschungsfrage: Wie verteilt sich die Aufmerksamkeit in Echtzeit zwischen Text und Schema?
Experimentelles Design & Methodik: Eye-Tracking: Analyse der Fixationen und Sakkaden auf strukturellen Schemaelementen direkt nach dem kritischen Terminus (Methodik nach Ito & Knoeferle, 2023).
Stichprobenzusammensetzung: Die Einbeziehung von L2-Lernenden ermöglicht es zu prüfen, wie der visuelle Kontext in der bilingualen Verarbeitung integriert wird (vgl. Abashidze et al., 2023), während eine L1-Kontrollgruppe den Effekt der sprachlichen Schwierigkeit vom Effekt des Fachwissens zu trennen erlaubt.

4.Diskussion

Didaktische Konsequenzen

Falls sich das Modell empirisch bestätigt, geht das Verhältnis von Text und Schema im LSP-Unterricht über Fragen des bloßen Mediendesigns hinaus und wird zu einem zentralen kognitiven Instrument des Verstehens. In traditionellem Lehrmaterial dient das Bild oft als illustrative Beigabe; nach der hier vorgeschlagenen Perspektive ist das visuelle Schema dagegen eine gleichberechtigte Komponente bei der Konstruktion fachlicher Inhalte. Daraus ergeben sich drei praktische Implikationen:

1. **Materialgestaltung:** Visuelles LSP-Material sollte primär nach konzeptuell-strukturellen Kriterien ausgewählt werden (Abbildung von Ursache-Wirkung, Hierarchien, Prozessabläufen).
2. **Integrierte Skills:** Lernende sollten explizit darin geschult werden, Text und Schema dynamisch-integriert zu lesen, statt beide Medien getrennt zu verarbeiten.
3. **Visuelle Fachkompetenz:** Das Dekodieren visuell-symbolischer Repräsentationen (*Schema Literacy*) sollte als fester Bestandteil in den LSP-Kanon aufgenommen werden.

Theoretischer Beitrag und Abgrenzung

Der theoretische Kernbeitrag liegt nicht in der verallgemeinernden Aussage, dass Visualisierung das Lernen unterstützt. Die These ist präziser: Im LSP-Kontext ist die visuelle Umgebung kein physischer Handlungsraum mehr, sondern eine repräsentationale Struktur fachlichen Wissens.

Abgrenzung zu bestehenden Multimediatheorien:

Das Modell grenzt sich bewusst von etablierten Theorien des multimedialen Lernens (z. B. Mayers *Cognitive Theory of Multimedia Learning* [CTML] oder Schnotz & Bannert) ab. Während CTML primär die kognitive Belastung (*Cognitive Load*) und die anschließenden Lernergebnisse (*Learning Outcomes*) untersucht, überträgt der vorliegende Ansatz die **Echtzeit-Logik der inkrementellen Sprachverarbeitung (*Real-Time Incremental Processing*)** aus dem SLC auf die Fachsprache. Es geht hierbei um die millisekundengenaue Koordination von Sprachsignal, Blickbewegung und Wissensaktivierung während des Verstehensprozesses.

Einschränkungen und Ausblick

Theoretischer Status: Das Modell stellt derzeit eine theoretische Architektur dar; die Hypothesen H1- H4 bedürfen der empirischen Absicherung.
Soziale und sprecherspezifische Faktoren: Neuere Erweiterungen des SLC berücksichtigen Eigenschaften von Sprechenden und Hörenden (Münster & Knoeferle, 2018). Welchen Einfluss berufsbezogene Rollenbilder oder Expertise-Attributionen auf das LSP-Verstehen haben, bleibt Gegenstand zukünftiger Forschung.

5. Fazit

Im vorliegenden Beitrag wurde das Modell des situierten Sprachverstehens (*Situated Language Comprehension*) für die Fachsprachenvermittlung theoretisch erweitert. Durch die zwei zentralen

Transformationen Visual Scene → Visual Schema und World Knowledge →Domain Knowledge wurde die theoretische Formel:
[LSP-Text] → [Visual Schema] → [Domain Knowledge] → [Integrated Conceptual Comprehension] entwickelt. Die vier daraus abgeleiteten überprüfbaren Hypothesen schlagen eine Brücke zwischen der experimentellen Psycholinguistik und der Fachsprachendidaktik und legen das Fundament für ein empirisches Forschungsprogramm zur multimodalen Satz und Textverarbeitung in akademischen und beruflichen Kontexten.

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Educational Wellbeing and Inclusion: Towards a Special Education Model. Capability, Recognition and Participation as Structural Conditions of Flourishing in Inclusive Settings

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Abstract

This article proposes a reversal of the position customarily assigned to Special Education within the debate on educational wellbeing: not an applied subfield of a general theory established elsewhere, but the site where that theory is tested in its own premises. Research on wellbeing in education displays two converging shortcomings. The first is the absence of a construct that can be considered autonomous from psychological and clinical matrices, whose irreducible polysemy was documented by Dodge et al. (2012). The second is the persistent underrepresentation of the inclusive dimension, confirmed by Nirchi's (2023) review of the assessment instruments currently in use in the Italian context. In existing devices, the educational wellbeing of students with disabilities tends to be reduced either to a measure of functioning, through the coding grids of the International Classification of Functioning, Disability and Health (WHO, 2001), or to an index of adaptation to the school environment. In both cases the pedagogical value of the construct dissolves, together with its link to the construction of a life project. The article argues that, from a special education standpoint, educational wellbeing must be grounded in flourishing rather than in compliance, and proposes a model built on three mutually constitutive structural conditions: the effective breadth of the capability set, recognition, and consequential participation. These conditions are derived from the capability approach (Sen, 1999; Nussbaum, 2011) in the declination developed for disability in education by Terzi (2005), from recognition theory (Honneth, 1995; Biesta, 2017), and from the empirical findings of Graham et al. (2022). The resulting move shifts the object of assessment from the individual to the context, with consequences for instructional design, for the revision of the Individualised Education Plan, and for the preparation of support teachers and education professionals (Frison, 2024). The thesis submitted to scientific discussion is that inclusive educational wellbeing constitutes a transferable best practice rather than a disciplinary niche.

Keywords: educational wellbeing, special education, inclusive schooling, capability approach, recognition

1. Introduction: A Reversal of Perspective

It is commonly assumed that Special Education represents a sectoral perspective within the broader field of educational wellbeing: a specification, that is, of principles elaborated elsewhere and subsequently adapted to particular populations. The assumption deserves to be reversed. It is precisely in inclusive settings, and with those subjects whom schools find hardest to recognise, that any pedagogical theory of wellbeing encounters its most demanding test. A theory that works

only where the conditions of participation are already given is not a general theory; it is a local theory unaware of its own boundaries.

The hypothesis guiding these pages is twofold. On the epistemological level, educational wellbeing can be constructed as a pedagogically autonomous construct only if it is built from situations in which recognition is most fragile. On the operational level, the model that follows does not configure a disciplinary niche but a transferable best practice for the school system as a whole. This second point constitutes the thesis that the article brings to the discussion of the scientific community.

The argument proceeds in four steps. Sections 2 and 3 reconstruct the double shortcoming of the current debate and the theoretical costs of the functional paradigm. Section 4 establishes the foundation of the proposed shift, from compliance to flourishing, and addresses the objection concerning epistemological autonomy. Sections 5 and 6 develop the two conditions that the capability framework alone cannot account for. Sections 7 and 8 set out the model and its implications for professional preparation.

1.1 Methodological Note

The study belongs to theoretical research in education and adopts a hermeneutic and argumentative method: critical reconstruction of the relevant literature, conceptual analysis of the constructs employed, construction of a model, and examination of its tenability against paradigmatic cases and current regulatory devices. No original empirical data are presented. The model is formulated so as to be operationalisable and, in its predictions, falsifiable by subsequent field research. Section 9 makes the limitations of this approach explicit.

2. A Contested Construct: Polysemy and Disciplinary Dependence

Reflection on wellbeing in education has produced significant contributions over the past two decades. Two orders of problems nonetheless remain unresolved.

The first concerns the absence of a construct autonomous from psychological and clinical matrices. Dodge et al. (2012) showed that wellbeing resists every attempt at reduction to a unitary meaning: each proposed definition tends either to list components without a principle of unity, or to identify the construct with one of its correlates. Eudaimonic wellbeing as derived from self-determination theory (Ryan & Deci, 2001), multidimensional models of positive orientation (Seligman, 2011), and clinical conceptualisations centred on the absence of symptoms all converge on an analogous operation: the description of individual states. Education appears there as a context variable, not as a constitutive principle.

For Special Education the issue is not academic. A construct that describes individual states, when applied to subjects whose individual condition is already the object of diagnostic coding, produces an effect of duplication: wellbeing is read through the very grid that defined the deficit. The result is circular, and the circularity is not merely formal. It means that the better the diagnostic description, the more confidently the school can attribute an unsatisfactory educational outcome to the student rather than to itself.

The second problem concerns the persistent underrepresentation of the inclusive dimension. Nirchi's (2023) review of the assessment instruments currently employed in the Italian context observes that the educational wellbeing of subjects with disabilities is for the most part traced back to a measure of functioning, either through coding in the grids of the International Classification of Functioning, Disability and Health (WHO, 2001), or through its flattening onto adaptation to the school environment. In either case the pedagogical value of the construct tends to dissolve.

It is worth dwelling on this dissolution, because what is at stake is not a loss of theoretical refinement. What is sacrificed is the link between formative action and the construction of a life project: the connection, that is, which makes education an action oriented towards a subject's future rather than the management of their present.

3. The Functional Paradigm and the Disappearance of the Subject

The functional paradigm is not merely insufficient with respect to the object it sets out to describe. With respect to that object it is, theoretically, misleading.

Consider the Individualised Education Plan, the central instrument of Italian inclusive practice and, at the same time, a device capable of fixing the subject within its own categories. The adoption of national models on an ICF basis, introduced by Ministerial Decree 182/2020 in implementation of Legislative Decree 66/2017, produced a standardisation with documented advantages in terms of comparability and procedural transparency. It also accentuated a risk signalled long ago: in the Plan, the student with a disability appears as a set of measurable functions, activities and participations, while the subject in formation, the one who carries a life project, tends to disappear (Canevaro, 2006).

There is, moreover, a distinction that the reflective tradition of Special Education has thematised repeatedly, with different accents, from Vygotsky (1978) to Ianes (2006), from d'Alessio (2011) to UNESCO's orientations on inclusive education (Opertti, 2008), and which the functional paradigm tends instead to misrecognise: the distinction between the subject's adaptation to the environment and the subject's flourishing within that environment.

The difference is substantial, and its scope is best made explicit through a case. A student with an autism spectrum condition who remains seated for the entire morning, does not interrupt the lesson, and completes the tasks proposed by the support teacher at a separate workstation will produce excellent indicators of adaptation. Functioning scales will register progress. None of them will register that this student has not addressed a single word to a classmate for six hours, that no occasion to contribute to the group's work has been offered, and that the school day has unfolded beside the class rather than within it. Adaptation, here, does not measure wellbeing; it conceals its absence.

The mechanism has a name in the literature on capabilities. Nussbaum (2000) showed how adaptive preferences lead subjects to systematically lower their own expectations until they declare themselves satisfied with objectively deprived conditions. Declared satisfaction is not, in such cases, a reliable indicator of wellbeing; it rather signals its erosion. Transferred to the school context, the principle implies that a student with a disability may conform to the institution's demands precisely to the extent that they have stopped expecting anything from it. The functional paradigm has no means of distinguishing the two situations, because both are recorded as successful adaptation.

4. From Compliance to Flourishing: The Capability Approach as Foundation

The most productive theoretical framework for grounding a shift of this kind remains the capability approach (Sen, 1999; Nussbaum, 2011), in the declination developed specifically for disability in education by Terzi (2005).

The strength of that declination lies in its overcoming of the dilemma of difference that historically traverses Special Education: the dilemma whereby naming difference exposes the subject to stigma, while ignoring it denies the entitlement to additional resources (Norwich, 2008). The capability approach dissolves the alternative by displacing the terms of the question. What matters is not whether difference should be named, but which effective opportunities for valued functioning each subject is in a position to exercise. Difference then becomes relevant as information about the distribution of the resources required to equalise those opportunities: not an attribute of the subject, but a parameter of distributive justice.

From this follows the reformulation of greatest relevance to the present argument. The educational wellbeing of a student with a disability is not determined by their residual functions. It is determined by the real breadth of the capabilities to which they have access, such as learning, expressing oneself, affiliating and participating, and by the quality of the conditions that the

context produces in order to transform potential capacities into actual achievements, that is, functionings.

4.1 Conversion Factors as the Decisive Category

The decisive Senian category in this passage is that of conversion factors: the elements that determine the rate at which an available resource is translated into an opportunity that can concretely be exercised. A digitised text is a resource; it becomes an opportunity for learning only if the workstation is configured, if the teacher has designed the activity so that the format is not a fallback, and if classmates do not perceive it as a privilege. Read through this lens, disability is not a deficit of capability: it is a problem of conversion, and conversion is produced by the context.

The construct thus moves from the measurement of the subject to the assessment of the context. The move has a consequence that must be stated openly, because it bears on professional practice: if educational wellbeing is a function of the conditions of conversion, then an unsatisfactory outcome constitutes information about the context before it constitutes information about the student. The environment, not the subject, is the primary object of analysis.

4.2 The Question of Epistemological Autonomy

An objection arises at this point and deserves to be met directly. If the construct is founded on Sen, Nussbaum and, as the following section will show, Honneth, has the dependence on psychological and clinical matrices not simply been replaced by a dependence on political philosophy?

The objection confuses two distinct senses of autonomy. The autonomy claimed here is not autonomy from external theoretical sources, which no pedagogical construct has ever possessed and which would in any case be a questionable ambition. It is autonomy of the object. Psychological and clinical constructs of wellbeing take as their object a state of the individual, which they describe with instruments calibrated on the individual; the pedagogical construct proposed here takes as its object the relation between a subject and the educational conditions that a context produces for them. The difference is not one of theoretical derivation but of what is being assessed, by whom, and with what consequences for action. A clinical instrument that reveals low wellbeing prescribes an intervention on the person; the construct outlined here prescribes a redesign of the environment. Philosophical categories are employed instrumentally, as the means of specifying that object; they do not define it. The criterion of autonomy, in other words, is pragmatic rather than genealogical.

5. Recognition as a Condition of Access

Alongside the capability approach, and without being reducible to it, stands the dimension of recognition (Honneth, 1995; Biesta, 2017).

In inclusive school settings recognition does not come after educational wellbeing, as though it were one of its outcomes. It is rather a condition of access to it. The student with a disability who is not recognised as a subject capable of learning, of contributing, of belonging to the community, and who is received only as the addressee of care or rehabilitative intervention, suffers a harm that touches the very structure of their educational experience: a harm to the possibility of entering that experience at all.

Honneth's tripartition into love, right and social esteem translates with some precision into the school context. To the first level corresponds affective belonging, being expected and sought out by peers and adults. To the second corresponds effective entitlement to rights within the class community, including the entitlement to dissent and to be wrong. To the third corresponds appreciation of the specific contribution that the subject brings to the common enterprise. The third level is the one that inclusive practice realises with the greatest difficulty, since it presupposes that the student with a disability be granted not only dignity but competence. Dignity is routinely conceded; competence is not.

A form of injustice is at work here which epistemology has named with some precision. Fricker (2007) described testimonial injustice as the systematic deflation of the credibility attributed to a speaker on the grounds of an identity prejudice. In school environments the mechanism is frequently observable: the student with an intellectual disability who expresses discomfort is interpreted as symptomatic rather than heard as informative, and their objection becomes challenging behaviour. What is denied in such cases is not acceptance but the status of reliable witness to one's own experience. No quantity of care compensates for that denial, and the point is of direct operational relevance, since instruments designed to raise wellbeing by increasing adult attention may leave the underlying injustice entirely intact.

6. Participation: Empirical Evidence and the Criterion of Consequence

On the empirical level, Graham et al. (2022) reconstructed the relations linking student participation, wellbeing and recognition. What emerges is clear-cut: the experience of being seen, heard and taken into account comes before, and sustains, every other indicator of wellbeing at school.

What is meant by participation must nonetheless be qualified, since the term covers heterogeneous and partly incompatible practices. The decisive distinction, for the purposes of the model proposed here, is the one between consultation and consequence. A class assembly in which students express opinions that modify no decision produces consultation; a revision of the timetable, of the arrangement of spaces or of assessment criteria following those opinions produces participation. Only the second generates recognition, because only in the second does the subject experience their own voice as effective upon a shared world.

For students with disabilities the question is aggravated by a specific circumstance: their participation is often mediated by adults, whether the support teacher, the educational assistant or the family, who speak on their behalf with protective intent. Such mediation is at times necessary. It becomes problematic when it consolidates into stable substitution, because the subject then ceases to be a party and becomes an object of representation. The design of inclusive settings should therefore take the progressive reduction of substitutive mediation as an indicator of quality, rather than its efficiency.

7. The Model: Three Structural Conditions

Capability, recognition and participation would be misread as three axes to be added one to another. They hold one another up, rather, and it is within a high-quality inclusive educational experience that their interweaving takes form.

The reciprocity requires specification, since it constitutes the theoretical core of the model. Recognition is the condition of access to the exercise of capabilities: a subject who is not recognised as capable is not placed in a position to learn, and their set of opportunities contracts upstream of any instructional intervention. Participation is, in turn, the capability whose exercise produces recognition: by participating with effect, the subject obtains public evidence of their own entitlement. The breadth of the capability set is finally the material condition that makes participation something other than a ritual. Removing any one of the three does not weaken the model proportionally; it deactivates it.

7.1 Three Criteria

Three assessment criteria follow from this structure, all of them referred to the context rather than to the subject.

Breadth of the effective capability set. Not how many activities the student performs, but how many opportunities for valued functioning are genuinely accessible to them, and at what cost of conversion. The quickest diagnostic indicator is the ratio between opportunities formally envisaged in the planning documents and opportunities actually exercisable without extraordinary mediation.

Quality of recognition. Not the quantity of attention received, but its structure: is the student an addressee of care or a recognised contributor? An observable indicator is the presence, in the ordinary activity of the class, of tasks in which that student's contribution is necessary to the others. Not facilitated, not simulated: necessary.

Consequentiality of participation. Not the frequency of occasions for voice, but the traceability of their effects. A practicable indicator consists in verifying how many decisions taken by the class council over the school year were modified following requests originating from students, including students with disabilities.

The three indicators are offered as heuristic devices rather than as validated measures. Their function at this stage of the argument is to show that the model generates observations which are in principle disconfirmable, and that the shift from subject to context does not condemn the construct to unassessability.

7.2 Three Levels of Application

The criteria operate on three levels, which must be kept distinct in order to avoid an error frequent in the applied literature, namely the attribution to the individual teacher of responsibilities that belong to the organisation.

The *micro-instructional* level concerns the design of the activity and mediation in the classroom. The *meso-organisational* level concerns the articulation of the timetable, the composition of groups, the use of spaces, the placement of the support resource, and school-wide assessment practices. The *macro-regulatory* level concerns the devices that define the framework within which the other two operate.

An intervention acting on the first level while leaving the other two unaltered produces local and reversible improvements. This is in all likelihood the reason for the fragility of many high-quality inclusive experiences, which are exhausted when the teacher who promoted them is transferred. The model yields here a prediction open to empirical testing: inclusive practices sustained exclusively at the micro-instructional level should display systematically lower persistence than practices accompanied by modifications at the meso-organisational level, independently of their initial quality.

7.3 A Possible Revision of the Individualised Education Plan

The framework proposed here allows a direction of revision to be indicated for the instrument in which, in Italian practice, the tensions discussed above are concentrated. The Individualised Education Plan could be reformulated so as to place alongside the descriptive section on functioning a section devoted to the conditions of conversion: not what the student is able to do, but which conditions the context guarantees so that what they are able to do becomes what they actually do, and with whom.

The difference in formulation is not stylistic. In the first case the objective is attributed to the student, and failure to attain it documents a limitation of the subject. In the second it is attributed to the context, and failure to attain it documents an institutional shortfall. The consequences for professional accountability are evident, and they explain the resistance that such a revision would encounter. They also indicate where the political stakes of the construct lie: assessing the context is more demanding than assessing the individual not because it is technically harder, but because it distributes responsibility differently.

8. Implications for Professional Preparation

The pedagogical model outlined here is intended to be epistemologically autonomous from clinical and psychological paradigms, theoretically anchored, and oriented towards operational implications for the preparation of support teachers and education professionals (Frison, 2024). Those implications do not concern the development of additional specialist interventions, but the reflective design of environments in which all three structural conditions are present for all students, with and without disabilities.

Specific indications for specialisation programmes follow. Preparation should first of all shift its centre of gravity from the analysis of the case to the analysis of the context, not by abolishing the former, which remains necessary, but by subordinating it to the latter in the sequence of training. A trainee who learns to read a diagnosis before learning to read a timetable will find it structurally difficult to locate the causes of an unsatisfactory outcome anywhere other than in the student.

Second, preparation should treat the design of interdependence as a specific technical competence, distinct both from facilitation and from generic cooperative learning. Designing activities in which each member's contribution is structurally necessary to the others requires instructional design skills that rarely find space in curricula, and that cannot be improvised: the difference between a task that genuinely requires a contribution and one that merely accommodates it is a matter of task architecture, not of teacher goodwill.

Third, preparation should include training in non-interpretive listening, understood as the capacity to suspend the symptomatic reading of a student's manifestations in order to consider them, in the first instance, as communication. This is the point at which the preparation of support teachers intersects most directly with the question of testimonial injustice discussed in Section 5.

As regards in-service professional development, the model suggests a unit of analysis different from the customary one: not the individual teacher but the class council in its decision-making function. If the meso-organisational level is where most conditions of conversion are determined, then it is at that level that professional development must intervene. Formats centred on the individual teacher, however well designed, address a level at which the decisive variables are not available.

9. Limitations and Research Agenda

The contribution has limitations that it is proper to make explicit. It is a theoretical work: the proposed model has not undergone empirical validation, and the indicators set out in Section 7 have heuristic rather than psychometric value. The passage from conceptual formulation to a measurement instrument requires operationalisation work that exceeds the scope of these pages.

A second limitation concerns the measurability of the construct itself. Shifting the object of assessment from the subject to the context entails relinquishing the individual comparability that school accountability systems will not readily surrender. The model, in other words, is less convenient to administer than the one it seeks to replace. This is a practical weakness, not a theoretical merit, and it will have to be addressed rather than defended.

A third limitation concerns the extent of the reference to capabilities: the Nussbaumian list has been employed here selectively, and the well-known controversy over the advisability of predefined lists in education has not been discussed. The question remains open, and bears directly on whether the first criterion of Section 7 can be given a stable content.

The research agenda that follows comprises at least three directions. The first is the development of an instrument for detecting conditions of conversion at class level, with attention to inter-rater reliability, which the contextual nature of the object renders non-trivial. The second is longitudinal case study research testing the central prediction of the model, namely that interventions confined to the micro-instructional level produce non-persistent effects. The third is comparative analysis of European regulatory devices with respect to their capacity to place the obligation of result on the context rather than on the subject.

10. Conclusions

It has been argued that educational wellbeing, for Special Education, can be constructed neither as a measure of functioning nor as an index of adaptation, and that its foundation requires a passage from compliance to flourishing. That passage has been articulated through three mutually constitutive structural conditions, namely the effective breadth of the capability set, recognition, and consequential participation, and through the displacement of the object of assessment from the subject to the context.

The general thesis bears restating. An environment in which every student has effective opportunities, is recognised as a contributor and participates with consequence is not a specialised environment: it is simply a good educational environment. That these conditions were identified by starting from situations of maximum fragility does not make them particular; it makes their structure visible. Inclusive educational wellbeing is a transferable best practice, not a disciplinary niche, and Special Education, far from constituting an applied sector, is confirmed as the site where general pedagogy verifies its own premises.

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PROMPTING RESEARCH: GENERATIVE ARTIFICIAL INTELLIGENCE AS A COGNITIVE PARTNER IN ADVANCED ACADEMIC WRITING

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ABSTRACT

The rapid integration of Generative Artificial Intelligence (GenAI) into higher education institutions has triggered a transformative debate among university professors, senior researchers, and graduate students worldwide [1, s. 12]. While initial administrative and pedagogical responses focused predominantly on plagiarism detection, automated oversight, and total prohibitions, universities are increasingly shifting toward structured integration strategies [2, s. 104]. Generative Artificial Intelligence is no longer viewed merely as a potential risk to academic integrity, but rather as a dynamic, interactive cognitive partner capable of scaffolding advanced research workflows [3, s. 45]. This comprehensive research paper provides an in-depth investigation into how scholars, doctoral candidates, and academic writers can leverage structured prompt engineering to conceptualize research designs, map dense theoretical literature, systematically critique arguments, refine prose mechanics, and uphold rigorous ethical frameworks [4, s. 88]. By analyzing human-AI co-creativity across twelve detailed sections, this paper outlines a sustainable operational model for ethical, AI-assisted human scholarship in 21stcentury academia [5, s. 14].

Keywords: *Generative Artificial Intelligence, Prompt Engineering, Academic Writing, Cognitive Scaffolding, Human-AI Co-Creativity, Higher Education, Writing Workflows, Academic Integrity.*

INTRODUCTION

For decades, digital writing tools in academic environments functioned as basic mechanical assistants [5, s. 15]. University scholars, researchers, and students utilized software tools primarily for rule-based operational tasks, such as:

- Basic spell-checking, punctuation verification, and syntactic rule validation [6, s. 198];
- Endnote formatting, bibliographic index compilation, and citation style management [6, s. 203];
- Document layout organization, including line spacing, margin adjustments, and page numbering.

The advent of Large Language Models (LLMs) fundamentally altered this operational paradigm [3, s. 50]. Modern generative tools do not merely highlight passive voice or flag typographical errors; they interpret complex narrative contexts, summarize long theoretical monographs, construct multi-layered outlines, and engage in real-time dialectical exchanges regarding abstract concepts [1, s.8]. When academic authors approach AI as a cognitive co-pilot rather than an automated text generator, the core focus of academic labor shifts [7, s. 310]. Rather than allocating vast amounts of time to formatting mechanics, initial structural layout, or overcoming drafting blocks, researchers can direct their primary mental energy toward deep critical analysis, original empirical investigation, and theoretical innovation [4, s. 92].

Workflow Stage	Legacy Writing Pipeline	Advanced AI-Collaborative Pipeline
Literature Discovery	Manual database searches and physical index scanning	Prompt-based conceptual mapping and gap extraction
Structuring & Logic	Solitary outline generation and manual note grouping	Dialectical logical testing and iterative structural refinement
Drafting Phase	Sequential paragraph writing from blank documents	Focus on human core synthesis and argument construction
Stylistic Editing	Proofreading for surface errors and typos	Precision polishing for flow, register, and conciseness

Section 1: Theoretical Framework — Human-AI Co-Creativity and Cognitive Scaffolding

To establish a solid theoretical foundation for AI-assisted writing, we must examine the principles of Cognitive Offloading and Co-Creativity within higher education contexts [3, s.52]. Cognitive offloading refers to the strategic use of physical or digital artifacts to reduce the internal working memory load required during complex intellectual tasks [5, s. 20]. In scholarly writing, severe cognitive friction often emerges when authors attempt to hold multiple structural levels—such as broad argument arcs, paragraph transitions, sentence syntax, and precise terminology—in working memory simultaneously [8, s. 68]. Generative AI operates as an external scaffolding mechanism [7, s. 312]. It does not substitute for deep human domain expertise; instead, it temporarily holds structural and conceptual frameworks in working memory, allowing the author to analyze logical connections from a high-level perspective [4, s. 95]. Consequently, scholars can navigate dense interdisciplinary literature with greater conceptual clarity, reduced writing friction, and heightened structural focus [2, s.108].

Section 2: Mitigating Writing Anxiety through Externalized Thought Partners

Academic writing blocks are frequently caused by excessive cognitive load during the initial drafting stages [8, s. 70]. Researchers often experience significant productivity stalls when trying to balance original idea generation, structural coherence, and precise linguistic expression concurrently [6, s. 208]. By utilizing AI as a low-stakes conversational partner, authors can externalize tentative, unrefined reasoning without the immediate pressure of academic evaluation [3, s. 54]. Engaging in structured dialogue with an LLM lowers affective filters, encourages creative exploration, and enables researchers to iterate through diverse structural frameworks before committing to a formal written draft [7, s. 318].

Section 3: Phase 1 — Conceptual Development, Scope Definition, and Research Design

Selecting and refining a viable research question is one of the most challenging obstacles faced by graduate students and early-career researchers [2, s. 112]. Excessively broad or poorly bounded topics routinely lead to unfocused literature reviews, weak methodology design, and fragmented overall arguments [6, s. 205].

3.1. Systematic Scope Narrowing

A common shortcoming in academic writing is selecting a research scope that exceeds the boundaries of the assigned publication format [7, s. 315]. Researchers can utilize structured prompting strategies to break broad theoretical concepts into targeted, testable research sub questions tailored to specific length requirements and disciplinary standards [9, s. 12].

3.2. Strategic Literature Gap Identification

Scholars can synthesize core arguments from key foundational texts, input these summaries into an AI workspace, and query the model to identify unaddressed assumptions or theoretical

blind spots [5, s. 22]. For example, asking: "Based on these synthesized perspectives, what methodological or theoretical gaps remain under-investigated?" accelerates the identification of novel research angles [1, s. 22].

Section 4: Phase 2 — Literature Mapping, Synthesis, and Structural Frameworks

Extracting key arguments from dense academic monographs and translating scattered reading notes into a cohesive theoretical synthesis represents a crucial stage in scholarly manuscript preparation [6, s. 210].

4.1. Comparative Analysis Matrix Generation

Researchers can prompt AI tools to organize raw reading notes into structured comparative matrices [4, s. 98]. The model can categorize multiple empirical studies according to theoretical frameworks, research design key findings, and explicit limitations [8, s.72].

4.2. Framework Alignment (IMRAD Standard)

After reviewing primary sources, authors can input raw bulleted insights and direct the model to organize them according to standard journal structures, such as the IMRAD (Introduction, Methods, Results, and Discussion) format [8, s. 74].

Research Phase	Core Focus Area	Targeted Prompt Engineering
Conceptualization	Topic boundary & Research scope	Deconstruct broad concepts into specific sub-questions
Literature Synthesis	Theoretical gaps & Theme mapping	Synthesize reading notes into comparative matrices
Argumentation	Thesis testing & Logical transitions	Conduct Socratic testing to evaluate claims and counters
Style & Polish	Active voice & Concise terminology	Eliminate wordiness, nominalizations, and passive density

Section 5: Phase 3 — Dialectical Argumentation and Socratic Peer Review

Prior to submitting a manuscript for peer review, scholars must test the internal logic and validity of their arguments against potential objections [1, s. 25]. Generative AI offers a private, highly adaptable environment for rigorous, real-time argument testing [3, s. 55].

The Socratic "Devil's Advocate" Technique

Authors can instruct an LLM to assume the role of an adversarial peer reviewer [9, s. 16]. By inputting their central thesis, authors can prompt the model to generate three robust counterarguments or identify unstated assumptions that a skeptical reviewer might highlight [3,s. 58]. This proactive critique enables researchers to address logical gaps and strengthen their overall argument prior to formal submission [10, s. 44].

Section 6: Phase 4 — Style Refinement, Prose Polishing, and Editing

While AI can assist throughout the writing lifecycle, human expertise remains irreplaceable during the drafting stage [7, s. 320]. AI tools should not generate original claims or primary content independently; rather, they should serve to refine human-authored drafts [4, s. 105].

1. De-Nominalization and Wordiness Reduction

Academic prose often suffers from heavy nominalizations—converting dynamic verbs into static noun phrases (e.g., "conducted an analysis of" rather than "analyzed") [4, s. 108]. Authors

can prompt AI tools to identify wordy constructions and offer concise alternatives while preserving the original voice [7, s. 322].

2. Transition and Structural Flow Optimization

Maintaining logical flow across complex sub-sections requires clear transitional signals [8, s.78]. AI can evaluate adjoining paragraphs and suggest connective phrasing that highlights the logical progression of the overarching argument [6, s. 215].

Section 7: Supporting Multilingual and EAL Scholars

Scholars who speak English as an Additional Language (EAL) often encounter significant structural barriers in international academic publishing, including stylistic gatekeeping and complex idiomatic expectations [6, s. 220]. Generative AI can act as an effective linguistic equalizer for multilingual researchers [6, s. 222].By assisting authors in converting native-language notes into clear, formal academic prose, AI allows international researchers to be evaluated primarily on the quality of their empirical research and theoretical contributions rather than stylistic non-conformities [1, s. 28].

Section 8: Institutional Adaptation — Building Sustainable AI Guidelines

Universities and research facilities must move beyond passive detection measures and establish clear, proactive integration policies [2, s. 125].

1. Clear Syllabus Statements: Academic departments must clearly define appropriate and inappropriate uses of AI (e.g., permitting outline generation while prohibiting automated content generation) [8, s. 82].

2. Systematic AI Literacy Modules: Higher education institutions should integrate modules on prompt engineering, source verification, and algorithmic ethics into undergraduate and graduate curricula [9, s. 25].

3. Writing Center Modernization: University writing centers should train tutors to guide students in using GenAI as an interactive feedback partner during revision stages [6, s.218].

Section 9: Assessment Redesign and Faculty Workload Strategies

As generative AI capabilities continue to evolve, traditional take-home writing assignments face significant validity challenges [2, s. 128]. Academic faculty must transition toward assessment models that evaluate the writing process rather than merely the final product [8, s. 90]. Incorporating process-oriented tools—such as reflective learning journals, in-class peer reviews, and detailed prompt audit logs—allows educators to verify genuine student cognitive engagement throughout the project lifecycle [2, s. 130].

Section 10: Pedagogical Integration — Practical Classroom Frameworks

To effectively teach AI-assisted academic writing, educators can implement practical activities designed to cultivate critical evaluation skills [8, s. 85].

The "Critique the Bot" Exercise

In this exercise, students are provided with an AI-generated draft on a complex subject [8, s. 88]. Working in collaborative groups, students must identify logical flaws, verify citations against primary library databases, rewrite weak or wordy passages, and strengthen the core argument using verified academic literature [9, s. 28]. This activity builds critical literacy while highlighting the clear limitations of unedited AI outputs [3, s. 68].

Section 11: Future Horizons — Autonomous AI Agents and Academic Publishing

The rapid development of multi-step autonomous AI agents will soon enable automated literature mapping, real-time data analysis, and sophisticated citation tracking [5, s. 32]. While these technologies offer significant efficiency gains, they also raise important questions regarding human oversight and authorship criteria [1, s. 34].

Future scholarship must establish clear operational boundaries that preserve human intellectual ownership while effectively utilizing emerging AI capabilities [10, s. 58].

Section 12: Conclusion — The Enduring Value of Human Scholarship

Generative Artificial Intelligence will not render human intellect, critical scholarship, or higher education obsolete [7, s. 330]. Instead, it highlights the essential importance of uniquely human capabilities—specifically critical thinking, theoretical expertise, ethical judgment, and original insight [3, s. 70].

While GenAI tools can organize outlines, suggest stylistic revisions, and format comparative data tables, they cannot replace lived human experience, original empirical inquiry, or the passion that drives scholarly discovery [4, s. 110]. By mastering structured prompt engineering, researchers can transform AI into a powerful partner that minimizes mechanical writing friction, allowing more time for meaningful scholarship [1, s. 35].

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Economic Sciences

Методы оценки цифровой финансовой грамотности и их интеграция в комплексную модель исследования

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Аннотация. В статье систематизированы подходы к оценке цифровой финансовой грамотности и сформированы шесть групп методов: стандартизованных обследований, психометрических шкал, композитных индексов и поведенческих данных, экспериментов, качественных и смешанных исследований, обзоров и библиометрического анализа. Цель исследования — определить возможности и ограничения этих подходов и обосновать их интеграцию в комплексную модель оценки. Применён аналитический обзор отобранных публикаций и методических документов. Разграничены знания, самооценка компетентности, наблюдаемое поведение и доступ к финансовым услугам. Показано, что исходная классификация объединяет инструменты измерения, источники данных и исследовательские дизайны, которые целесообразно рассматривать как взаимодополняющие уровни. Предложена модульная модель, включающая сопоставимое опросное ядро, объективные задания, оценку воспринимаемой компетентности и контекстные показатели. Обоснованы условия её адаптации для исследований в Казахстане. Модель носит концептуальный характер и требует эмпирической проверки.

Ключевые слова: цифровая финансовая грамотность, методы оценки, финансовое поведение, смешанные методы.

Исследование выполнено в рамках грантового проекта Комитета науки Министерства науки и высшего образования Республики Казахстан ИРН AP26196291 «Потенциал цифровой финансовой грамотности в повышении благосостояния населения»

Введение

Цифровизация финансовых услуг меняет требования к компетенциям потребителя. Использование мобильного приложения, дистанционное оформление кредита или проведение электронного платежа предполагают не только владение интерфейсом, но и понимание стоимости операции, условий договора, последствий передачи данных и способов проверки получателя средств. Поэтому оценка финансовой грамотности в цифровой среде должна охватывать как содержание финансового решения, так и условия его принятия.

OECD/INFE рассматривает цифровую финансовую грамотность как сочетание знаний, навыков, установок и поведения, необходимых для осознанного и безопасного

использования цифровых финансовых услуг и технологий в интересах финансового благополучия [1]. Такая трактовка задаёт многомерный объект измерения. Вместе с тем наличие банковского приложения, частота платежей и уверенность пользователя характеризуют разные стороны взаимодействия с цифровыми финансами и не могут без дополнительного обоснования выступать взаимозаменяемыми показателями грамотности.

Проблема исследования заключается в несоответствии между многомерностью цифровой финансовой грамотности и практикой её сведения к отдельному опросному баллу, самооценке либо интенсивности использования сервисов. В зависимости от выбранного инструмента один и тот же человек может получить различные оценки: уверенно выполнять привычные переводы, но ошибаться при сравнении стоимости заимствования; знать правила безопасности, но не применять их под давлением мошенника. Следовательно, выбор метода определяет не только точность, но и содержательный смысл результата.

Методика исследования

Исследование проведено в формате методологического обзора. Основой послужили труды авторов по методам оценки финансовой грамотности. В данную подборку включены международные инструменты, научные публикации и прикладные отчеты. Из общего объема трудов были отобраны целевым образом 64 источника 2022-2026 гг., поделенных в конечном итоге на 6 групп, позволяющих раскрыть разные функции оценки.

Сопоставление проводилось по пяти критериям: измеряемый конструкт, происхождение данных, тип допустимого вывода, требования к проверке качества и ограничения применения. Рассматривались опубликованные сведения об инструментах и дизайнах; повторный анализ исходных массивов не выполнялся. Обзор не претендует на исчерпывающий охват литературы и не является систематическим обзором по протоколу PRISMA. Первичные данные, новые оценки распространённости компетенций и результаты апробации предлагаемой модели в статье не представлены.

В итоговой классификации выделены группы A - стандартизованные обследования, B - психометрические шкалы, C - индексы и поведенческие данные, D - эксперименты, E - качественные и смешанные методы, F -обзоры и библиометрия. Данные группы выступают своего рода картой исследовательских подходов, но не трактуются как взаимоисключающие классы. Одна работа может одновременно использовать международный опросник, проверять его факторную структуру и оценивать образовательное воздействие в эксперименте.

Сравнительный анализ подходов к оценке финансовой грамотности

Группа A представляет собой стандартизованные международные обследования (рисунок 1). Инструментарий OECD/INFE обеспечивает общую основу для сопоставления результатов. Toolkit 2022 включает вопросы по цифровым финансовым знаниям, поведению и установкам [2]. Международное обследование 2023 г., охватившее 39 стран и экономик, иллюстрирует применение единой методической основы к оценке финансовой грамотности взрослого населения [3]. Отдельный инструмент OECD/INFE 2024 г. ориентирован на цифровую финансовую грамотность и включает вопросы об осведомлённости и использовании соответствующих услуг [1].

Преимущество подхода, используемого группой A заключается в возможности сохранять общие определения и правила расчёта при проведении мониторинга. Однако стандартизация анкеты сама по себе не обеспечивает репрезентативности: она зависит от способа отбора участников, охвата населения и возможного отсутствия ответов. Также следует различать задания с проверяемым ответом и сообщения респондента о собственном поведении. Национальная адаптация должна сохранять смысл измеряемого

признака; изменение формулировок, состава вопросов или правил подсчёта требует документирования и ограничивает прямое сравнение с исходной версией.

Группа B отражает подход применения психометрических шкал. Эти инструменты предназначены для проверки того, насколько согласованно набор вопросов измеряет определённый конструкт. Vieira и соавторы разработали Digital Financial Knowledge Scale (DFKS) в полной и сокращённой версиях, включающих 40 и 26 пунктов соответственно. Разработка объединяла качественную подготовку вопросов, экспертную оценку, предварительное тестирование и применение теории ответов на задания, IRT [4]. Существенно, что ответы отражают самооценку способности выполнить финансовую операцию без посторонней помощи. Поэтому название шкалы не даёт оснований считать её прямым объективным тестом знаний.

Digital Financial Capability Scale рассматривает воспринимаемую цифровую финансовую компетентность через знания, поведение и уверенность. При разработке использовались качественные процедуры, разведочный и подтверждающий факторный анализ, а также моделирование структурными уравнениями [5]. Для интерпретации такой шкалы принципиально, что уверенность населения в своих действиях может расходиться с их правильностью. Высокий показатель воспринимаемой компетентности не следует автоматически приравнивать к устойчивости перед цифровыми финансовыми рисками.

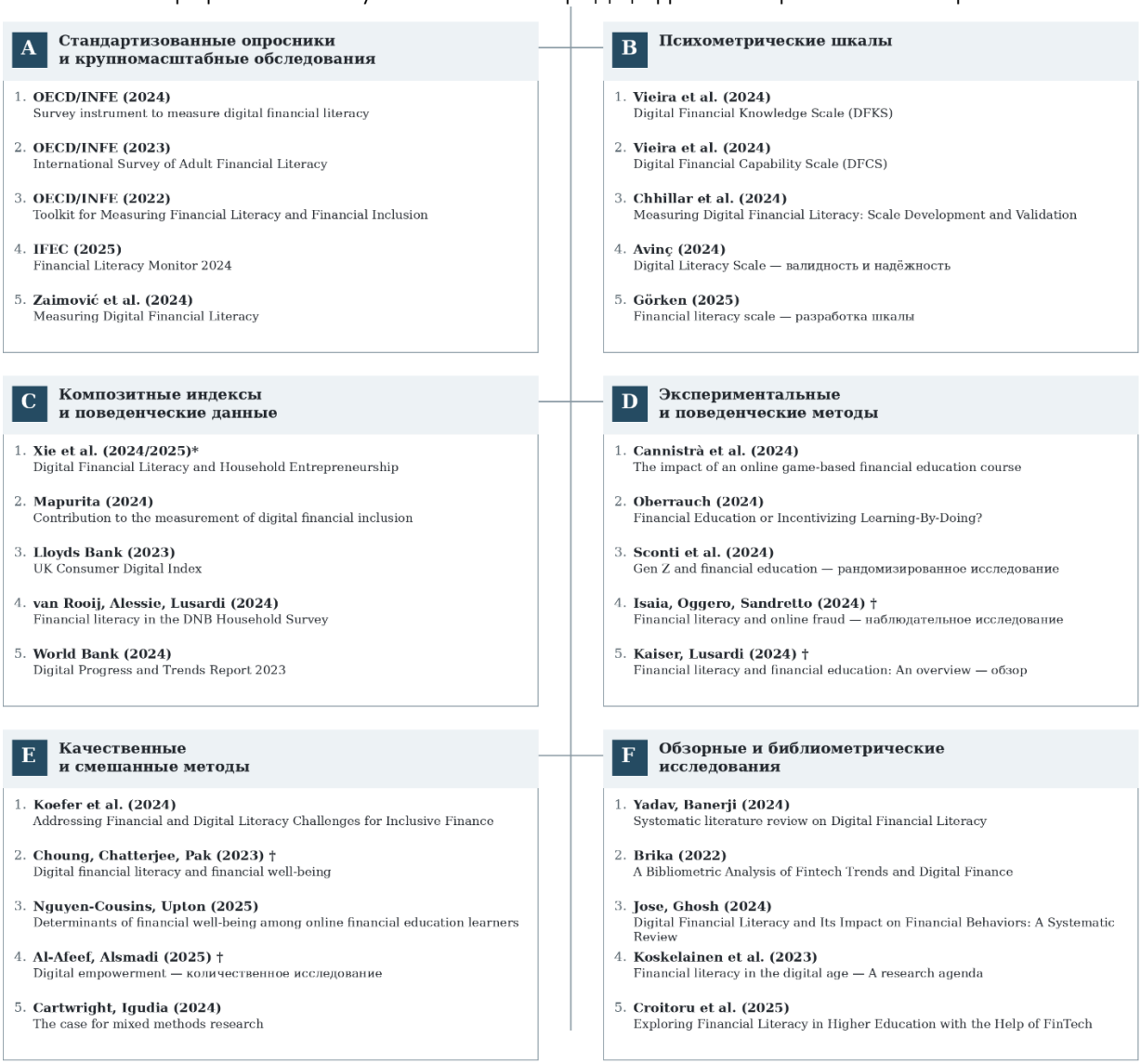


Рисунок 1 – Группы методов оценки цифровой финансовой грамотности
Примечание: составлено с помощью ИИ

Группа C объединяет композитные и поведенческие данные. Здесь необходимо разделять способ агрегирования показателей и источник информации. Композитный индекс может быть построен по анкете. Следовательно, наличие индекса не делает данные автоматически объективными. Аналогично обследование домохозяйств остается опросным источником, даже если в нем подробно фиксируются использование цифровых финансовых продуктов.

Примером применения поведенческой информации служит UK Consumer Digital Index 2023, использующий данные о поведении и транзакциях одного миллиона потребителей для характеристики цифровых и финансовых возможностей [6]. Такие данные расширяют наблюдение за фактической активностью.

Группа D отражает экспериментальные и поведенческие методы. Поведенческое задание позволяет проверить выбор населения в заданной ситуации, например, при сравнении двух кредитных предложений при распознавании подозрительного сообщения. Однако, само наличие задания еще не означает экспериментального установления причинности. Для оценки эффекта обучения необходим дизайн, позволяющий сопоставить результаты воздействия с обоснованным контрфактическим сценарием.

Canistra и соавторы использовали многостраховой рандомизированный эксперимент для оценки онлайн курса финансового образования в игровой форме [7]. Этот пример показывает исследовательскую функцию рандомизации при оценке образовательного воздействия. При этом цифровой формат обучения не означает, что все измеряемые результаты относятся именно к цифровой финансовой грамотности. Перенос выводов на другую возрастную группу, страну или вид финансового решения требует отдельного обоснования.

Группа E включает качественные и смешанные методы. Как правило, интервью, фокус-группы, наблюдения позволяют установить как респонденты понимают финансовые термины, почему избегают отдельных сервисов. Koefer и соавторы изучали подходы микрофинансовых и финтех организаций с помощью полуструктурированных интервью и качественного анализа [8]. Такой подход раскрывает организационный контекст, но не предназначен для оценки доли населения с определенным уровнем грамотности.

Группа F охватывает обзоры и библиометрические исследования. Их единицей анализа выступают публикации, а не потребители финансовых услуг. Они позволяют уточнять определения, обнаруживать пробелы и выбирать инструменты для последующего исследования. Yadav и Banerji обращают внимание на необходимость согласования определений и способов измерения цифровой финансовой грамотности [9]. Следовательно, обзор выполняет подготовительную и обобщающую функцию, но не заменяет непосредственную оценку компетенций.

Сводное сопоставление функций вышеуказанных групп представлено в таблице 1.

Таблица 1 – Функции и ограничения групп методов оценки

Группа	Функция	Основное ограничение
A	Сопоставимое обследование знаний, установок и поведения	Единая анкета не гарантирует репрезентативности выборки
B	Проверка структуры и измерительных свойств и шкалы	Самооценка не равнозначна объективной компетентности
C	Агрегирование показателей и анализ фактической активности	Использование услуг зависит также от доступа и потребностей
D	Проверка решений и оценка эффекта вмешательства	Причинный вывод зависит от дизайна, а не от формата задания
E	Выявление барьеров, смыслов и механизмов поведения	Ограничены статистические обобщения на население
F	Синтез исследований и обоснование выбора инструментов	Не измеряет грамотность отдельных респондентов

Результаты. Сопоставление групп методов оценки цифровой финансовой грамотности позволяет предложить модульный подход, в котором измерительные блоки связаны общей логикой, но сохраняют самостоятельный смысл. Принцип заключается в разграничении того, что население знает, что способно выполнить, как оценивает свои возможности и что фактически делает в определенных условиях. Интеграция понимается как совместная интерпретация этих измерений, а не обязательное сведение разнородных данных к единственному числу.

Модульный подход охватывает несколько модулей (рисунок 2).

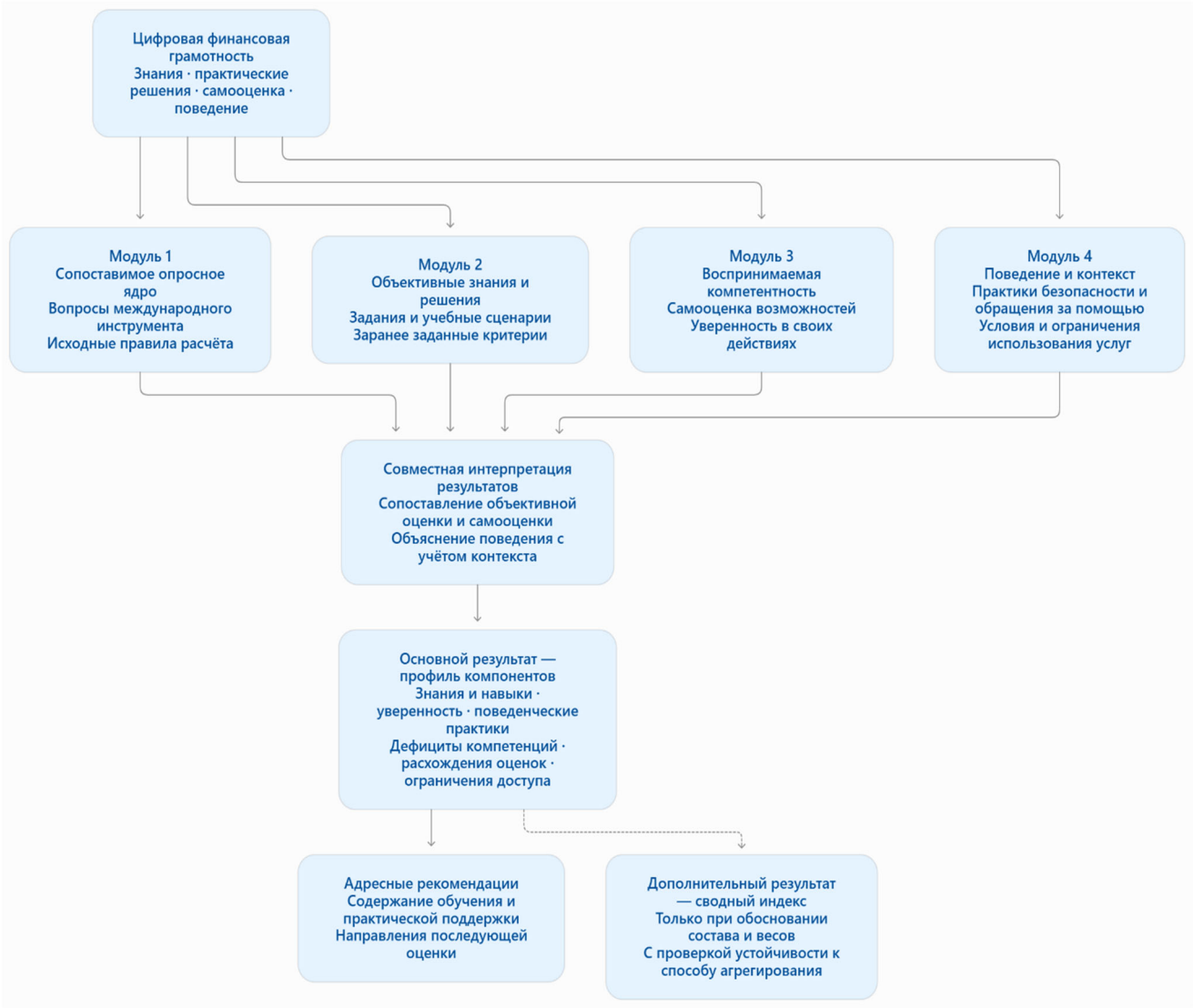


Рисунок 2 – Модульный подход к оценке цифровой финансовой грамотности
Примечание: составлено с помощью ИИ

Первый из них – это сопоставимое опросное ядро. В нем сохраняются выбранные вопросы международного инструмента и соответствующие правила расчета. Результаты представляются отдельно от локальных дополнений, чтобы исследователь мог определить, какая часть оценки допускает внешнее сопоставление. Сведения о социально-демографических характеристиках, доступе к устройствам и финансовым сервисам собираются как объясняющие переменные, а не как признаки грамотности сами по себе.

Второй модуль – это объективная оценка знаний и практических решений. Предлагается включать задания на определение полной суммы платежей по условным предложениям, выявление платной опции, проверку реквизитов и распознавание недостоверного сообщения. Для каждого задания заранее формируются правильный ответ или критерии выполнения. Сценарии должны быть приняты без опыта работы с конкретным банковским приложением с целью объективности. При демонстрации действий используются учебные макеты без реальных счетов и платежных реквизитов.

Третий модуль отражает воспринимаемую компетентность и уверенность. Его назначение состоит в выявлении различий между субъективной и объективной оценками. Участник с высокой уверенностью и низкой точностью выполнения заданий нуждается в иной поддержке, чем субъект, который правильно решает задачи, но избегает

самостоятельных операций. Такие сочетания предлагается использовать как диагностические профили.

Четвертый модуль затрагивает поведение и контекст. Он фиксирует практики проверки условий, управления доступом и обращения за помощью, а также ограничения, связанные с устройствами, связью, языком и доступностью услуг. При наличии согласованного доступа к административным данным опросные ответы могут сопоставляться с наблюдаемыми действиями. Отсутствие операций при этом не кодируется автоматически как недостаток навыка, поскольку у респондента могло не быть соответствующей потребности или возможности.

Первичным результатом модульного подхода предлагается считать профиль компонентов. Для каждого объективного блока перевод баллов от 0 до 100 как отношения набранной сумы к максимально возможной, если правила начисления баллов заданы до сбора данных.

Заключение

Оценка цифровой финансовой грамотности требует согласования измеряемого конструкта, источника данных и типа исследовательского вывода. Рассмотренные группы решают взаимосвязанные, но различные задачи. Международные обследования создают основу сопоставления, психометрические процедуры проверяют измерительные свойства, поведенческие данные дополняют сведения о действиях, эксперименты позволяют оценивать воздействие, качественные метолы раскрывают контекст, а обзоры обосновывают выбор инструментов.

В статье предложен комплексный модульный подход, объединяющий сопоставимое опросное ядро с объективными заданиями, оценкой воспринимаемой компетентности и анализом поведения в контексте доступности услуг. Ее особенность в сохранении различий между знаниями, уверенностью, фактическими действиями и условиями их совершения.

Для применения приоритетными являются охват групп с различным цифровым опытом и проверка сопоставимости измерений. Следующий этап исследования предполагает пилотную апробацию и оценку того, помогает ли предложены профиль точнее определять образовательные потребности по сравнению с отдельной самооценочной шкалой. Такой переход от общего балла к содержательной диагностике может повысить обоснованность программ финансового просвещения при условии эмпирического подтверждения модели.

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МЕТОДОЛОГИЧЕСКИЕ ПРЕДПОСЫЛКИ И ЭКОНОМЕТРИЧЕСКАЯ ДИАГНОСТИКА ОЦЕНКИ МУЛЬТИПЛИКАТИВНОГО ЭФФЕКТА НИОКР В СТРАНАХ СНГ

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Аннотация. В статье исследуются методологические предпосылки оценки мультипликативного эффекта расходов на исследования и разработки ($R\&D$) на производительность труда. Эмпирический анализ проведен на панельных данных по пяти странам (Казахстан, Россия, Узбекистан, Азербайджан, Беларусь) за 2000–2024 гг. (120 преобразованных наблюдений). Выполнена комплексная диагностика свойств панельных данных. Расчет корреляций Пирсона и Спирмена, внутригрупповое преобразование (включение фиксированных эффектов стран и лет), проверка на мультиколлинеарность (VIF) и тестирование на стационарность (ADF-тест). Выявлена высокая чувствительность знака и величины коэффициентов корреляции к способу обработки панельной структуры. Сделан вывод о невозможности идентификации прямой причинно-следственной связи и калибровки денежного мультипликатора без перехода к специфическим методам пространственно-временного моделирования и разностным спецификациям.

Введение

Оценка экономической отдачи от финансирования научных исследований требует четкого разграничения показателей затрат и конечных макроэкономических результатов. Доля внутренних расходов на НИОКР в ВВП характеризует ресурсоемкость исследовательской системы, однако напрямую не отражает динамику производительности труда. Измерение затруднено из-за неоднородности стран и временных шоков.

В международной практике межстрановая отдача от НИОКР варьируется в зависимости от институциональных условий и взаимодействия между государственным и частным секторами (Soete et al., 2022).Настоящая работа представляет собой диагностический этап исследования. Цель работы — определить методологические ограничения и проверить временные свойства панельных данных для построения корректной модели мультипликатора инвестиций в науку на примере выборки из пяти постсоветских государств.

Данные и методы исследования

Эмпирическую базу исследования составили годовые показатели Всемирного банка (World Development Indicators) за период 2000–2024 гг.:

$R_{i,t}$ — внутренние расходы на исследования и разработки (% от ВВП, код GB.XPD.RSDV.GD.ZS); $LP_{i,t}$ — ВВП на одного занятого в постоянных международных долларах 2021 г. по ППС (код SL.GDP.PCAP.EM.KD); $K_{i,t}$ — валовое накопление основного капитала (% от ВВП, код NE.GDI.FTOT.ZS).

Сформирована сбалансированная панель из 125 исходных наблюдений (по 25 лет на каждую из 5 стран). Зависимой переменной является годовой логарифмический прирост производительности труда (g_{it}):

$$g_{it} = 100 \cdot \left[\ln(LP_{it}) - \ln\left(LP_{i,t-1}\right)\right]$$

Объясняющие переменные R и K включены в модель с временным лагом в 1 год ($R_{i,t-1}$ и $K_{i,t-1}$) для учета временной последовательности. После дифференцирования и сдвига лагов расчетная выборка составила $N = 120$ наблюдений (2001–2024 гг.).

Для устранения постоянных индивидуальных и временных эффектов применялось двухфакторное внутригрупповое преобразование панели вида:

$$\tilde{x}_{it} = x_{it} - \bar{x}_{i\cdot} - \bar{x}_{\cdot t} + \bar{x}$$

Проверка стационарности проводилась с помощью расширенного теста Дики — Фуллера (ADF) отдельно для каждой страны при уровне значимости 5 %.

Результаты исследования

Распределение переменных характеризуется существенной асимметрией и наличием экзогенных шоков. Средний логарифмический рост производительности составил 3,94% при стандартном отклонении 4,95%. Средняя доля НИОКР в ВВП равна 0,46%, что существенно выше медианного значения (0,25%), что свидетельствует о правосторонней асимметрии за счет более высоких показателей в России и Беларуси.

Таблица 1. Описательная статистика переменных исследования

Характеристика	g	R с лагом 1	K с лагом 1
Число наблюдений	120	120	120
Среднее	3,9384	0,4600	24,5611
Стандартное отклонение	4,9463	0,3620	6,4992
Минимум	-5,8888	0,1013	12,0116
Первый квартиль	1,2137	0,1716	20,8774
Медиана	3,6082	0,2538	22,6678
Третий квартиль	5,7520	0,6712	26,8243
Максимум	29,4777	1,2860	57,7103

Для предварительной оценки связи между финансированием науки и ростом производительности труда рассмотрим динамику основных показателей по пяти странам. На рисунке 1 представлены рост производительности труда, расходы на НИОКР и валовое накопление основного капитала. Их сопоставление позволяет выявить межстрановые различия и периоды резких изменений, которые необходимо учитывать при дальнейшем эконометрическом анализе.

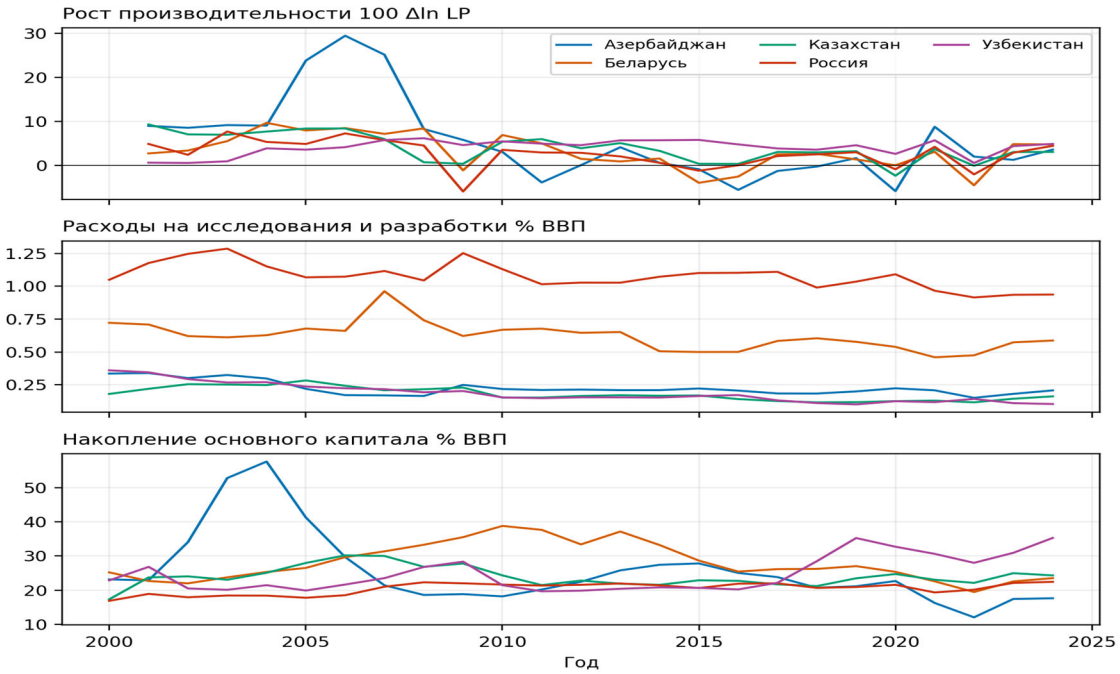


Рисунок 1. Динамика производительности расходов на исследования и накопления капитала

Примечание: Источник графика составляет база World Development Indicators

Наиболее резкие колебания роста производительности наблюдаются в Азербайджане. После подъёма середины первого десятилетия темпы снижаются. В Узбекистане рост остаётся положительным на всём расчётном периоде. В Казахстане темпы конца периода преимущественно ниже начальных значений.

Россия и Беларусь выделяются более высокой долей расходов на исследования. При этом их рост производительности не является постоянно самым высоким. В Узбекистане накопление капитала заметно увеличивается с 2018 года.

Проведена оценка линейных и ранговых связей между показателями при различных спецификациях очистки данных.

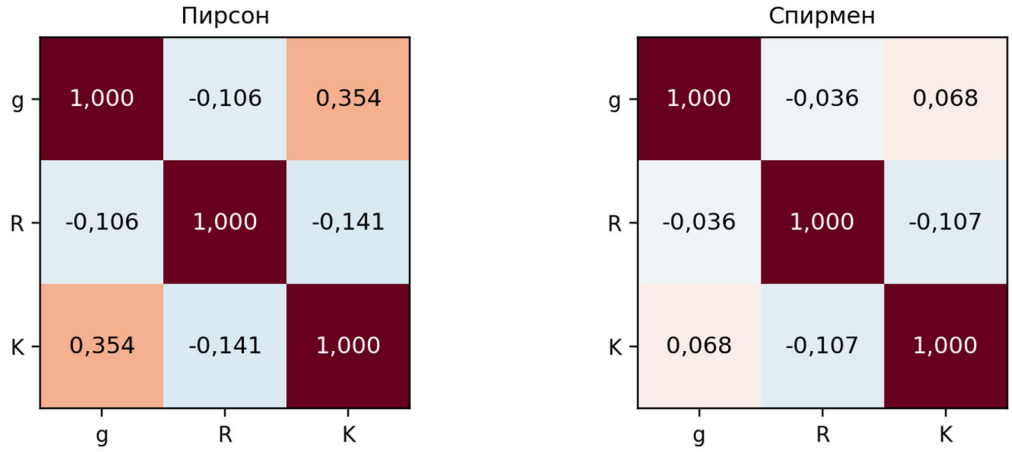


Рисунок 2 Корреляции Пирсона и Спирмена в объединённой выборке

Примечание: g обозначает рост производительности. R и K обозначают доли расходов на исследования и накопления капитала с лагом в один год.

Таблица 2. Корреляции при разных способах обработки панели

Пара	Пирсон общий	Спирмен общий	Пирсон внутри стран	Пирсон с учётом стран и лет
g и R	-0,106	-0,036	0,231	-0,131
g и K	0,354	0,068	0,361	0,373
R и K	-0,141	-0,107	0,184	0,127

Примечание: рассчитано автором на основе данных WDI

Анализируя таблицу, мы видим, что парная корреляция между расходами на НИОКР (R) и ростом производительности (g) нестабильна. В объединенной выборке она составляет -0,106. При исключении межстрановой неоднородности (Within-преобразование) знак меняется на +0,231. Однако при дополнительном контроле временных трендов (Two-way FE) коэффициент снова становится отрицательным (-0,131). Это свидетельствует о чувствительности предварительных оценок к выбору модели.

Для пары R и K показатель VIF равен 1,016, что исключает проблему мультиколлинеарности между регрессорами.

Тест ADF выполнен отдельно по странам в Google Colab с помощью statsmodels . Рассмотрены варианты с константой и с константой и линейным трендом. Максимальное число лагов равно двум. Фактическое число выбиралось по критерию Акаике. Нулевая гипотеза предполагает единичный корень. Уровень значимости составляет 5%. Это отдельные проверки без поправки на множественность, а не единый панельный тест.

Таблица 3. Результаты тестов ADF

Страна	Ряд	ADF c	p c	Лаг c	p ct	p Δc
Азербайджан	g	-1,8132	0,3739	0	0,4894	н/п
Азербайджан	R	-2,2105	0,2025	0	0,4660	0,0002
Азербайджан	K	-1,8033	0,3788	2	0,0001	0,0001
Беларусь	g	-2,9718	0,0376	0	0,0222	н/п
Беларусь	R	-2,4454	0,1293	0	0,0995	<0,00005
Беларусь	K	-1,6062	0,4805	1	0,9389	0,0075
Казахстан	g	-2,8135	0,0564	0	0,0275	н/п
Казахстан	R	-1,0726	0,7259	0	0,0387	0,0001
Казахстан	K	-2,8315	0,0539	0	0,0573	<0,00005
Россия	g	-3,9927	0,0014	0	0,0020	н/п
Россия	R	-2,1068	0,2418	0	0,0287	0,0001
Россия	K	-2,0969	0,2458	2	0,3600	0,0004
Узбекистан	g	-2,7895	0,0598	1	0,0609	н/п
Узбекистан	R	-2,6143	0,0901	0	0,4036	0,0001
Узбекистан	K	-1,7138	0,4240	1	0,1409	0,0025

*Примечание: В таблице **c** обозначает константу, c**t** обозначает константу и линейный тренд. Столбец **p Δc** относится к первым разностям R и K с константой. Для **g** повторная разность не тестировалась, что обозначено н/п.*

Результаты тестирования на единичный корень показали следующие результаты. В уровнях переменные R и K являются нестационарными в большинстве стран ($p > 0{,}05$ при

спецификации с константой). Для первых разностей ($\Delta R_{i,t-1}$ и $\Delta K_{i,t-1}$) нулевая гипотеза о наличии единичного корня уверенно отвергается во всех пяти странах ($p < 0{,}01$). Ряд роста производительности g стационарен для России ($p = 0{,}0014$) и Беларуси ($p = 0{,}0376$), но сохраняет неопределенность по Азербайджану и Узбекистану.

Проведенный анализ выявил чувствительность связи между расходами на НИОКР и ростом производительности труда к способу обработки панельных данных. Изменение знака корреляции после учета страновых и временных различий ограничивает интерпретацию объединенных оценок. Полученные результаты не позволяют установить причинно-следственную связь между финансированием исследований и ростом производительности.

Корреляционный анализ также не позволяет отделить связь исследуемых показателей от возможного влияния сырьевых циклов и макроэкономических шоков. Результаты проверки на стационарность дают основания рассмотреть спецификации с первыми разностями расходов на НИОКР и накопления основного капитала. Однако окончательный выбор преобразований требует дополнительной проверки временных свойств рядов и возможных долгосрочных связей. Денежный мультипликатор $M_{R\&D}$ должен рассчитываться не как парный коэффициент, а путем выделения экзогенных импульсов с использованием рядов выпуска и расходов в сопоставимых ценах (в денежном выражении):

$$M_{R\&D} = \frac{\Delta Y_{t+k}}{\Delta R_t}$$

Перспектива дальнейших исследований состоит в переходе от относительных показателей (% ВВП) к абсолютным денежным величинам в постоянных ценах, выделении отдельных лаговых структур и учете человеческого капитала.

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Biological Sciences

Application of Molecular Biotechnology in Pharmacogenetics: Genetic Variants as Predictors of Drug Response

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Abstract

Pharmacogenetics represents a pivotal integration of molecular biotechnology and clinical pharmacology, aiming to elucidate the genetic basis of interindividual variability in drug response. As the paradigm of medical treatment shifts from a generalized approach to precision medicine, understanding how genetic variants predict therapeutic efficacy and adverse drug reactions (ADRs) is paramount. This narrative literature review synthesizes the molecular and genetic foundations of pharmacogenetics, emphasizing the role of single-nucleotide polymorphisms (SNPs), structural variations, and gene expression profiles in modulating pharmacokinetic and pharmacodynamic pathways. Central to this transition are advanced molecular biotechnology techniques, including real-time quantitative PCR, next-generation sequencing (NGS), microarray analysis, and emerging CRISPR-based functional screens, which have democratized genomic data acquisition. We comprehensively review major actionable gene-drug pairs, such as CYP2D6 (antidepressants, tamoxifen), CYP2C19 (clopidogrel), CYP2C9 and VKORC1 (warfarin), HLA-B variants (abacavir, carbamazepine), TPMT/NUDT15 (thiopurines), DPYD (fluoropyrimidines), and SLCO1B1 (statins), outlining their clinical translation via CPIC and DPWG guidelines. Despite profound scientific advancements, clinical implementation faces multifaceted challenges, including genetic diversity across underrepresented populations, interpreting rare variants, hybrid alleles in complex genomic loci, ethical considerations, and the cost-effectiveness of preemptive testing. Finally, we discuss the integration of high-throughput sequencing, artificial intelligence, and machine learning into clinical decision-support systems, projecting future perspectives for precision medicine. By leveraging sophisticated molecular biotechnologies, pharmacogenetics stands to significantly enhance therapeutic safety and efficacy, realizing the promise of individualized patient care.

Keywords

Pharmacogenetics, Precision Medicine, Molecular Biotechnology, Cytochrome P450, Next-Generation Sequencing, Genetic Variants, Adverse Drug Reactions, Pharmacogenomics.

1. Introduction

The traditional paradigm of clinical pharmacology has largely relied on a “one-size-fits-all” approach, prescribing standardized drug regimens based on broad demographic and physiological

metrics. However, clinical experience and extensive epidemiological data reveal profound interindividual variability in therapeutic efficacy and susceptibility to adverse drug reactions (ADRs). Adverse drug events remain a leading cause of morbidity and mortality globally, underscoring a critical vulnerability in empirical prescribing. Pharmacogenetics, the study of how inherited genetic variations influence drug response, has emerged as a cornerstone of precision medicine to address this challenge. By identifying genetic determinants that dictate pharmacokinetic (PK) and pharmacodynamic (PD) properties, pharmacogenetics seeks to individualize drug selection and dosing, thereby maximizing efficacy and minimizing toxicity (Weinshilboum, 2003; Relling & Evans, 2015).

Molecular biotechnology serves as the technological engine driving pharmacogenetic research and its subsequent clinical implementation. Over the past three decades, advancements in molecular biology—ranging from the Human Genome Project to the advent of high-throughput next-generation sequencing (NGS)—have fundamentally transformed our capacity to interrogate the genome. Techniques such as polymerase chain reaction (PCR), allele-specific arrays, and whole-exome sequencing now permit rapid, highly specific identification of genetic variants (polymorphisms) associated with drug metabolism and transport (Metzker, 2010; Shendure & Ji, 2008). Consequently, pharmacogenetics has transitioned from a specialized research niche to an actionable clinical discipline, supported by robust guidelines from consortia such as the Clinical Pharmacogenetics Implementation Consortium (CPIC) and the Dutch Pharmacogenetics Working Group (DPWG) (Crews et al., 2014; Swen et al., 2011).

Despite these advancements, significant barriers impede the universal integration of pharmacogenetics into routine clinical practice. Genetic diversity across ethnic populations remains inadequately characterized, and the clinical interpretation of rare variants poses ongoing challenges. Moreover, standardizing molecular diagnostic methodologies and integrating genomic data into electronic health records (EHRs) necessitate concerted interdisciplinary efforts. The primary objective of this article is to comprehensively review the application of molecular biotechnology in pharmacogenetics. It evaluates the molecular and genetic foundations of variable drug response, meticulously analyzes the biotechnological tools employed in variant detection, details clinically significant pharmacogenetic biomarkers, and critically assesses the challenges and future perspectives in the era of artificial intelligence and advanced genomics.

2. Literature Review Methodology

This study is designed as a structured narrative literature review aimed at synthesizing current knowledge regarding the molecular biotechnological applications in pharmacogenetics. A comprehensive literature search was conducted utilizing prominent academic databases, including PubMed/MEDLINE, Scopus, and Web of Science. The search strategy employed combinations of the following MeSH terms and keywords: “Pharmacogenetics,” “Pharmacogenomics,” “Molecular Biotechnology,” “Precision Medicine,” “Cytochrome P450,” “Next-Generation Sequencing,” and “Adverse Drug Reaction.”

Inclusion criteria prioritized peer-reviewed original research articles, authoritative review papers, and clinical implementation guidelines published predominantly between 2010 and 2024, to reflect the most current biotechnological landscape. Fundamental historical papers defining critical pharmacogenetic principles were also included. Special emphasis was placed on official guidance documents from the Clinical Pharmacogenetics Implementation Consortium (CPIC), the Dutch Pharmacogenetics Working Group (DPWG), and the U.S. Food and Drug Administration (FDA). Publications lacking peer review, non-English articles, and studies with inconclusive or statistically insignificant genetic associations without clinical relevance were excluded. The synthesized data were critically evaluated to compare molecular methods, validate established gene-drug associations, and identify existing gaps in clinical translation.

3. Molecular and Genetic Foundations of Pharmacogenetics

The interaction between a therapeutic agent and the human biological system is governed by two fundamental processes: pharmacokinetics (PK) and pharmacodynamics (PD). Pharmacokinetics describes the absorption, distribution, metabolism, and excretion (ADME) of a drug, whereas pharmacodynamics encompasses the physiological effects of the drug on its molecular targets, such as receptors, enzymes, and ion channels. Genetic variations within the genes encoding the proteins involved in these pathways constitute the molecular basis of pharmacogenetics (Evans & McLeod, 2003).

Single-nucleotide polymorphisms (SNPs) are the most abundant form of genetic variation in the human genome and serve as the primary biomarkers in pharmacogenetic testing. A typical SNP involves the substitution of a single nucleotide, which can occur in coding regions (exons), potentially altering the amino acid sequence of the encoded protein (nonsynonymous SNPs), or resulting in a premature stop codon (nonsense SNPs). Furthermore, SNPs located in non-coding regions (introns or promoter regions) can critically influence gene expression levels by modifying transcription factor binding sites or mRNA splicing (Wang et al., 2011).

Beyond SNPs, structural variations such as insertions/deletions (indels) and copy-number variations (CNVs) play crucial roles. A classic example of CNV in pharmacogenetics involves the CYP2D6 gene, where individuals may possess entire gene deletions (resulting in absent enzyme activity) or multiple functional gene duplications (leading to ultrarapid metabolism). The cumulative effect of these genetic alterations defines an individual's metabolic phenotype, generally categorized into poor metabolizers (PM), intermediate metabolizers (IM), normal metabolizers (NM, previously extensive metabolizers), and ultrarapid metabolizers (UM) (Caudle et al., 2017). This phenotypic classification dictates the systemic concentration of the drug, fundamentally influencing therapeutic efficacy and the likelihood of toxicity.

4. Molecular Biotechnology Techniques Used in Pharmacogenetic Research

The precise identification of pharmacogenetic variants relies on a diverse arsenal of molecular biotechnology techniques. The evolution of these methodologies has dramatically increased throughput, accuracy, and clinical applicability. Table 1 summarizes the primary methods.

Table 1. Major Molecular Biotechnology Methods Used in Pharmacogenetic Research

Method	Principle	Key Advantages	Primary Limitations
PCR & Allele-Specific PCR	Amplifies targeted DNA regions; primers designed specifically for mutant/wild-type alleles.	Rapid, highly cost-effective, widely accessible.	Low throughput, assays only known specific variants.
Real-Time qPCR	Monitors DNA amplification in real-time using fluorescent reporters (e.g., TaqMan probes).	High sensitivity, accurate quantification, faster turnaround.	Requires pre-defined targets; equipment costs.
Sanger Sequencing	Chain-termination method with fluorescent dideoxynucleotides.	Gold standard for accuracy; excellent for small regions.	Low throughput, expensive per base, laborious.

Microarray (SNP Chips)	Hybridization of sample DNA to thousands of complementary allele-specific probes on a chip.	High throughput screening of known variants simultaneously.	Cannot detect novel/rare variants; hybridization artifacts.
Next-Generation Sequencing (NGS)	Massively parallel sequencing of millions of DNA fragments (WGS, WES, or Targeted Panels).	Comprehensive variant discovery, detects rare and structural variants (CNVs).	High cost, complex bioinformatics, data storage challenges.
CRISPR-Cas9 Screens	Targeted genome editing to validate the functional impact of specific polymorphisms in vitro.	Enables precise functional validation of variants of unknown significance (VUS).	Currently limited to research settings; off-target effects.

Polymerase Chain Reaction (PCR) and its quantitative derivative (qPCR) remain foundational in clinical diagnostics due to their rapidity and cost-effectiveness. Utilizing sequence-specific TaqMan probes, qPCR allows for the discrimination of SNPs with high fidelity, rendering it ideal for targeted tests, such as interrogating the HLA-B*57:01 allele before abacavir administration (Mallal et al., 2008).

While microarrays have facilitated large-scale genome-wide association studies (GWAS) by querying millions of known SNPs simultaneously, they are inherently limited by their inability to identify novel variants. Consequently, Next-Generation Sequencing (NGS) has emerged as a transformative technology in molecular pharmacogenetics. Targeted NGS panels, Whole-Exome Sequencing (WES), and Whole-Genome Sequencing (WGS) provide unprecedented resolution, capturing not only common SNPs but also rare variants, indels, and complex structural rearrangements. Advanced bioinformatics pipelines are essential to align, call, and annotate variants from massive NGS datasets, translating raw genomic reads into actionable clinical insights (Gaudet et al., 2013).

5. Major Genetic Variants Associated with Drug Response

The clinical utility of pharmacogenetics is predicated on robust evidence linking specific genetic variants to drug responses. The most extensively characterized genes belong to the cytochrome P450 (CYP450) superfamily, responsible for phase I metabolism of approximately 70-80% of all prescription medications (Zanger & Schwab, 2013). Table 2 highlights key pharmacogenetically important genes and their functions.

Table 2. Pharmacogenetically Important Genes and Their Biological Functions

Gene Symbol	Protein Name / Function	Primary Drug Class Affected	Pharmacological Pathway
CYP2D6	Cytochrome P450 2D6 (Phase I Metabolism)	Antidepressants, Opioids, Tamoxifen	Pharmacokinetics (Metabolism)
CYP2C19	Cytochrome P450 2C19 (Phase I Metabolism)	Antiplatelets (Clopidogrel), PPIs	Pharmacokinetics (Metabolism)
CYP2C9	Cytochrome P450 2C9 (Phase I Metabolism)	Anticoagulants (Warfarin), NSAIDs	Pharmacokinetics (Metabolism)
VKORC1	Vitamin K Epoxide Reductase Complex 1	Anticoagulants (Warfarin)	Pharmacodynamics (Drug Target)
TPMT	Thiopurine S-methyltransferase	Immunosuppressants (Thiopurines)	Pharmacokinetics (Metabolism)
DPYD	Dihydropyrimidine Dehydrogenase	Chemotherapeutics (Fluoropyrimidines)	Pharmacokinetics (Metabolism)
SLCO1B1	Solute Carrier Organic Anion Transporter 1B1	Statins (e.g., Simvastatin)	Pharmacokinetics (Transport)
HLA-B	Human Leukocyte Antigen B	Abacavir, Carbamazepine, Allopurinol	Immunotoxicity / Hypersensitivity

CYP2D6 is highly polymorphic, with over 100 described star (*) alleles. It mediates the metabolism of up to 25% of commonly prescribed drugs. For instance, codeine is a prodrug requiring CYP2D6-mediated O-demethylation to its active metabolite, morphine. Ultrarapid metabolizers (carrying multiple functional copies of CYP2D6) face a severe risk of life-threatening respiratory depression due to rapid morphine accumulation, whereas poor metabolizers experience therapeutic failure (Crews et al., 2014). Similarly, CYP2D6 is crucial for converting tamoxifen into its active metabolite endoxifen in breast cancer therapy; poor metabolizers exhibit decreased endoxifen levels, potentially compromising oncological outcomes (Province et al., 2014).

CYP2C19 profoundly affects clopidogrel, a widely utilized antiplatelet prodrug. Patients with loss-of-function variants (e.g., CYP2C19*2 or *3) cannot effectively convert clopidogrel to its active thiol metabolite, leading to elevated risks of major adverse cardiovascular events and stent thrombosis following percutaneous coronary intervention (Scott et al., 2013). CPIC guidelines recommend alternative agents, such as prasugrel or ticagrelor, for intermediate and poor metabolizers.

Warfarin dosing represents a classic intersection of PK and PD variants. CYP2C9 variants (*2, *3) reduce the clearance of S-warfarin, while variants in VKORC1 (the drug's target) increase sensitivity to the drug. Combining these genotypic data allows for highly precise algorithmic dose predictions, significantly mitigating the risk of severe hemorrhagic events (Johnson et al., 2017).

In oncology and immunology, TPMT and NUDT15 genotypes are critical before initiating thiopurines (e.g., azathioprine, mercaptopurine). Deficient alleles cause dangerous accumulation of active thioguanine nucleotides, resulting in profound myelosuppression. Likewise, variations in

DPYD significantly increase the risk of lethal toxicity from fluoropyrimidine chemotherapeutics (5-fluorouracil, capecitabine) due to impaired drug clearance (Amstutz et al., 2018).

Furthermore, immune-mediated adverse reactions are strongly linked to the human leukocyte antigen (HLA) complex. The presence of HLA-B*57:01 confers a substantial risk of severe hypersensitivity reactions to the antiretroviral abacavir, rendering screening mandatory prior to prescription. Similarly, HLA-B*15:02 is associated with Stevens-Johnson syndrome and toxic epidermal necrolysis in patients treated with carbamazepine, particularly in populations of Asian descent (Phillips et al., 2018).

6. Pharmacogenetic Biomarkers and Their Clinical Applications

Translating molecular discoveries into clinical utility requires rigorous evidence evaluation. Table 3 outlines major clinical associations established by CPIC and regulatory bodies.

Table 3. Key Gene–Drug Associations and Their Clinical Implications

Drug	Associated Gene(s)	Variant Phenotype Effect	Clinical Implication / Guideline Recommendation
Clopidogrel	CYP2C19	Poor Metabolizer (*2, *3)	Use alternative antiplatelet (Prasugrel/Ticagrelor).
Warfarin	CYP2C9 & VKORC1	Reduced clearance / High sensitivity	Reduce starting dose; utilize pharmacogenetic dosing algorithms.
Abacavir	HLA-B*57:01	Positive for variant	Contraindicated due to high risk of fatal hypersensitivity.
Simvastatin	SLCO1B1	Decreased transporter function (*5)	Prescribe lower dose or alternative statin to avoid myopathy.
Thiopurines	TPMT, NUDT15	Deficient enzyme activity	Drastically reduce dose or avoid to prevent myelosuppression.
Irinotecan	UGT1A1	Poor Metabolizer (*28/*28)	Reduce initial dose due to high risk of severe neutropenia/diarrhea.

The clinical application of pharmacogenetics operates at the nexus of preemptive and reactive testing. Preemptive testing involves genotyping a panel of pharmacogenes before a therapeutic need arises, integrating the data into the patient's EHR alongside clinical decision support (CDS) alerts. Reactive testing, conversely, is ordered at the point of prescribing a specific high-risk medication. The evidence base delineating whether testing actively improves clinical outcomes (clinical utility) versus merely proving a molecular association (clinical validity) is continually expanding (Dunnenberger et al., 2015).

Table 4. Genetic Variants, Metabolizer Phenotypes, and Potential Effects on Drug Response

Phenotype	Definition (CYP450 context)	Impact on Active Drug	Impact on Prodrug
Poor Metabolizer (PM)	Lacks functional alleles (e.g., *4/*4)	High toxicity risk, decreased clearance.	Therapeutic failure, lack of active metabolite.
Intermediate Metabolizer (IM)	One functional, one defective allele	Moderate toxicity risk, slow clearance.	Reduced efficacy, lower active metabolite.
Normal Metabolizer (NM)	Two functional alleles	Standard dosing efficacy.	Standard dosing efficacy.
Ultrarapid Metabolizer (UM)	Gene duplications or high-activity variants	Therapeutic failure, extremely rapid clearance.	High toxicity risk, massive active metabolite accumulation.

A sophisticated understanding of these phenotypes distinguishes clinical pharmacogenetics from basic genetics. A genotype must be accurately translated into an inferred phenotype (e.g., assigning a diplotype to an activity score), which in turn informs a specific, actionable treatment recommendation.

7. Challenges and Limitations in the Application of Pharmacogenetics

Despite unequivocal scientific rationale and expanding clinical guidelines, the widespread adoption of pharmacogenetic testing is hindered by significant challenges (Table 7).

Table 7. Major Barriers to Clinical Implementation and Potential Solutions

Category	Barrier/Limitation	Potential Solutions & Workarounds
Scientific/Technical	Incomplete characterization of rare variants and structural complexity (e.g., CYP2D6 hybrid genes).	Advancement of Long-Read Sequencing and improved bioinformatics algorithms.
Diversity	Overrepresentation of European populations in genetic databases; misclassification in admixed cohorts.	Global genomic initiatives targeting underrepresented populations.
Clinical Implementation	Lack of physician education, alert fatigue in EHR systems, and absence of standardized CDS tools.	Integration of intuitive CDS alerts, specialized pharmacist training programs.
Economic	High initial cost of comprehensive panel testing and variable reimbursement policies by insurers.	Health economic models demonstrating long-term cost savings via averted ADRs.
Ethical & Privacy	Concerns regarding genetic data storage, secondary findings, and potential genetic discrimination.	Robust genomic privacy laws, informed consent protocols, anonymized databases.

A major technical limitation involves the architectural complexity of specific loci. The CYP2D6 locus, for instance, is highly homologous to pseudogenes (CYP2D7, CYP2D8) and is susceptible to complex structural rearrangements, including gene duplications, deletions, and hybrid alleles. Traditional PCR and microarray techniques frequently mischaracterize these structures, necessitating advanced NGS or targeted long-read sequencing methodologies for accurate resolution (Nofziger et al., 2020).

Furthermore, the genetic diversity observed across global populations necessitates cautionary application of testing platforms designed primarily around variants frequent in European populations. An allele common in one ethnic group may be rare or absent in another, emphasizing the critical need for inclusive genomic research to prevent the exacerbation of health disparities. Clinically, the integration of pharmacogenetic data must account for phenoconversion—whereby non-genetic factors such as age, organ dysfunction, drug-drug interactions (e.g., concomitant administration of a strong CYP inhibitor), and diet modify the genetic phenotype into a different clinical phenotype (Shah & Smith, 2015).

8. Future Perspectives: Precision Medicine, Artificial Intelligence, and Advanced Molecular Diagnostics

The trajectory of molecular pharmacogenetics is fundamentally shifting from single-gene, reactive methodologies toward comprehensive, preemptive, and multi-omic paradigms. Table 8 delineates emerging technologies shaping this landscape.

Table 8. Emerging Technologies and Future Directions in Molecular Pharmacogenetics

Emerging Technology	Application in Pharmacogenetics	Future Impact on Precision Medicine
Long-Read Sequencing	Resolving complex genomic loci (CYP2D6, HLA) and accurate phasing of alleles.	Elimination of ambiguous phenotypes caused by pseudogenes and structural variations.
Artificial Intelligence (AI)	Predictive modeling combining genomic, clinical, and environmental data.	Highly individualized, real-time dynamic dosing algorithms.
Pharmacotranscriptomics	Measuring real-time mRNA expression levels rather than static DNA variants.	Accounts for epigenetic changes and transient states of metabolic induction/inhibition.
Multi-Gene Panel Testing	Preemptive screening of dozens of pharmacogenes in a single assay.	A lifetime resource in the EHR guiding all future pharmacological interventions.
CRISPR-Cas Base Editing	In vitro modeling of novel variants (VUS) to determine metabolic impact.	Rapid functional classification of uncharacterized genetic variations discovered via WGS.

Long-read sequencing technologies, such as those developed by Pacific Biosciences (PacBio) and Oxford Nanopore Technologies, promise to resolve the complex structural variations that evade short-read NGS. By sequencing intact, extensive DNA fragments, these platforms can accurately determine the cis/trans orientation (phasing) of multiple SNPs on a single chromosome and effortlessly span highly homologous pseudogene regions. Furthermore, the integration of Artificial Intelligence (AI) and Machine Learning (ML) stands to revolutionize the interpretation of

pharmacogenomic data. AI algorithms are uniquely equipped to synthesize massive multi-omic datasets—incorporating genomics, transcriptomics, metabolomics, and electronic health records—to predict drug responses with a precision previously unattainable. These models can dynamically adjust to account for phenoconversion and complex polygenic interactions that govern systemic drug metabolism (Khera et al., 2018).

9. Discussion

This review underscores that molecular biotechnology is the pivotal force enabling pharmacogenetics to fulfill the aspirations of precision medicine. The transition from simplistic genotype-phenotype correlations to sophisticated, algorithm-driven dosing reflects deep advancements in molecular diagnostic methodologies. While early pharmacogenetic milestones relied heavily on low-throughput PCR diagnostics, contemporary applications are characterized by preemptive, microarray, and NGS-based multi-gene panels capable of informing a lifetime of clinical decision-making.

However, as demonstrated by the critical analysis of current literature, translating analytical validity into clinical utility remains complex. Organizations like CPIC and DPWG have been instrumental in establishing evidence-based algorithms, yet the uptake by healthcare systems is heterogeneous. The fundamental discrepancy lies in the integration gap: the molecular data generated must be contextually interpreted within the clinical ecosystem, adjusting for interacting medications and patient-specific physiological constraints. Furthermore, addressing the lack of genomic diversity in foundational research is an ethical and scientific imperative to ensure that the benefits of precision medicine are equitably distributed.

10. Conclusion

Pharmacogenetics represents a paradigm shift in therapeutic medicine, leveraging molecular biotechnology to predict drug response based on intrinsic genetic variation. The identification and functional characterization of variants in genes such as CYP2D6, CYP2C19, TPMT, and the HLA complex have provided irrefutable evidence of their utility in avoiding fatal adverse drug reactions and ensuring therapeutic efficacy. Advancements in molecular techniques, particularly next-generation sequencing, have dramatically improved the resolution and accessibility of genetic testing. However, the successful integration of pharmacogenetics into routine clinical practice requires overcoming significant bioinformatic, educational, and economic barriers. Future endeavors must focus on leveraging artificial intelligence, adopting long-read sequencing technologies, and expanding research across diverse global populations. Ultimately, the maturation of molecular pharmacogenetics holds the unprecedented potential to transform clinical pharmacology into a truly individualized, safe, and preemptive science.

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АРПАНЫҢ САБАҚ ТАТ АУРУЫНА ТӨЗІМДІЛІГІН АНЫҚТАУДА МОРФОЛОГИЯЛЫҚ ЖӘНЕ ФИТОПАТОЛОГИЯЛЫҚ КӨРСЕТКІШТЕРДІҢ МАҢЫЗЫ

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1. АННОТАЦИЯ ЖӘНЕ ТҮЙІН СӨЗДЕР

Зерттеу жұмысында арпа (*Hordeum vulgare* L.) генотиптерінің сабақ тат ауруына (*Puccinia graminis* Pers. f. sp. *secalis* / *tritici*) төзімділігін айқындаудағы морфологиялық-анатомиялық белгілер мен фитопатологиялық көрсеткіштердің кешенді маңызы қарастырылған. Зерттеу Абай атындағы Қазақ ұлттық педагогикалық университетінің Биология кафедрасының зертханалық базасында және провокациялық инфекциялық фонда жүргізілді. Мақалада арпаның 10 сорты мен селекциялық желісінің (Арна, Сауле, Сырашы, Қарабалықты 150, Астана 2000, Ілек 16, Нұр, Ғасыр, Желі-102, Желі-204) эпидермис кутикуласының қалыңдығы, балауыз жабынының тығыздығы, устьицалар саны, паренхима қабырғасының склеренхиматоздану дәрежесі сияқты анатомиялық-морфологиялық параметрлері мен аурудың даму қарқындылығы (Cobb шкаласы), инфекция типі (Stakman шкаласы) және ауру дамуының интегралдық көрсеткіші (AUDPC) арасындағы байланыстар зерттелді. Корреляциялық талдау нәтижесінде сабақ эпидермисінің кутикула қалыңдығы ($r = -0.84$, $p < 0.01$) мен балауыз жабынының тығыздығы ($r = -0.79$, $p < 0.01$) сабақ татының өршуіне және AUDPC мәніне кері пропорционал күшті байланыста екендігі дәлелденді. Селекциялық тәжірибеге төзімділіктің экспресс-диагностикасы ретінде морфо-анатомиялық маркерлерді пайдалану бойынша ұсыныстар дайындалды.

Түйін сөздер: Арпа (*Hordeum vulgare* L.), сабақ аты (*Puccinia graminis*), морфологиялық көрсеткіштер, фитопатологиялық бағалау, AUDPC, кутикула, устьица тығыздығы, төзімділік селекциясы. **Ключевые слова:** Ячмень (*Hordeum vulgare* L.), стеблевая ржавчина (*Puccinia graminis*), морфологические показатели, фитопатологическая оценка, AUDPC, кутикула, плотность устьиц, селекция на устойчивость. **Keywords:** Barley (*Hordeum vulgare* L.), stem rust (*Puccinia graminis*), morphological traits, phytopathological evaluation, AUDPC, cuticle, stomatal density, resistance breeding.

2. КІРІСПЕ

Ғаламдық климаттың өзгеруі, агроэкологиялық жүйелердің дисбалансы және биотикалық стресс факторларының артуы заманауи ауыл шаруашылығы ғылымының алдына азық-түлік қауіпсіздігін қамтамасыз ету бойынша күрделі міндеттер қойып отыр. Қазақстан Республикасының агроөнеркәсіптік кешенінде дәнді дақылдар өндірісі ерекше стратегиялық

орын алады. Осы орайда, арпа (*Hordeum vulgare* L.) – азықтық, техникалық, азық-түліктік және экспорттық маңызы жоғары, құрғақшылыққа салыстырмалы түрде төзімді негізгі дақылдардың бірі болып табылады.

Арпаның өнімділігі мен дән сапасын төмендететін ең қауіпті фитопатологиялық факторлардың бірі – сабақ таты ауруы. Сабақ татының негізгі қоздырғыштары – облигатты биотопты саңырауқұлақтар *Puccinia graminis* Pers. f. sp. *secalis* және *Puccinia graminis* f. sp. *tritici*. Бұл саңырауқұлақ биомикробиологиялық тұрғыдан өте серпінді, генетикалық рекомбинацияға бейім және агрессивті нәсілдерді жылдам қалыптастыра алатын патоген. Ауру өсімдіктің вегетативті және генеративті органдарын, әсіресе сабағын, жапырақ қынабын, кейде масақ қабыршақтарын зақымдайды. Сабақта урединиопустулалардың жаппай дамуы өткізгіш шоқтардың (ксилема мен флоэма) анатомиялық тұтастығын бұзып, су мен минералды элементтердің, сондай-ақ ассимиляттардың тасымалдануын нашарлатады. Осының салдарынан өсімдікте транспирация реттелуі бұзылып, құрғап кету процесі жеделдейді, нәтижесінде дән толыспай, сирек, өнімділігі мен технологиялық сапасы төмен болып қалады. Эпифитотиялық жылдары сабақ татынан келетін өнім шығыны 30%-дан 70%-ға дейін жетеді, ал патогеннің өте агрессивті нәсілдері таралған жағдайда егістік толығымен жойылуы мүмкін.

Сабақ тат ауруымен күресудің ең экологиялық қауіпсіз, экономикалық тұрғыдан тиімді және ұзақ мерзімді жолы – генетикалық иммунитеті жоғары, иммунологиялық бақыланған төзімді сорттарды селекциялап, өндіріске енгізу. Алайда, патогеннің генотиптік құрамының үнемі өзгеріп отыруы және жаңа вирулентті нәсілдердің пайда болуы (мысалы, Ug99 нәсілдер тобы және оның вариациялары) өсімдіктердің физиологиялық және генетикалық төзімділік жүйесін үнемі бақылап отыруды талап етеді.

Өсімдіктің патогендерге төзімділігі күрделі фенотиптік және физиологиялық-биохимиялық реакциялар жиынтығынан тұрады. Төзімділіктің алғашқы және маңызды бөгеті – өсімдіктердің сыртқы морфологиялық және ішкі анатомиялық құрылысы болып табылады (пассивті немесе структуралық төзімділік). Сабақ пен жапырақ эпидермисінің сыртқы балауыз жабыны, кутикуланың қалыңдығы, устьицалардың тығыздығы мен құрылысы, паренхималық және склеренхималық ұлпалардың даму дәрежесі саңырауқұлақ урединиоспораларының өнуіне, апрессорийлердің түзілуіне және устьицалар арқылы паренхима ішіне енуіне механикалық бөгет жасайды.

Осыған байланысты, арпаның сабақ тат ауруына төзімділігін анықтауда тек фитопатологиялық бағалаумен (инфекция типі, зақымдану қарқындылығы) шектелмей, морфологиялық-анатомиялық индикаторларды кешенді түрде зерттеу селекциялық материалды ерте кезеңде скринингтен өткізуге мүмкіндік береді.

Зерттеудің мақсаты: Арпа генотиптерінің сабақ тат ауруына (*Puccinia graminis*) төзімділігін бағалауда морфологиялық-анатомиялық белгілер мен фитопатологиялық көрсеткіштердің байланысын кешенді түрде анықтау және төзімділік маркерлерін негіздеу.

Зерттеудің міндеттері:

1. Жинақталған арпа сорттары мен селекциялық желілерінің сабақ татының инфекциялық фон жағдайындағы фитопатологиялық реакциясын (инфекция типі, аурудың өршу қарқындылығы, AUDPC) бағалау.
2. Арпа генотиптерінің сабақ анатомиясы мен морфологиясының негізгі көрсеткіштерін (кутикула қалыңдығы, устьица тығыздығы, балауыз жабыны, склеренхима қабаты) микроскопиялық әдістер арқылы анықтау.
3. Морфо-анатомиялық параметрлер мен фитопатологиялық төзімділік индекстері арасындағы Пирсон корреляциялық байланысын есептеу.
4. Арпа селекциясы үшін механикалық төзімділік индикаторы ретінде пайдалануға болатын негізгі морфологиялық белгілерді анықтау және ұсыныстар дайындау.

3. ӘДЕБИЕТТЕРГЕ ШОЛУ

Арпаның (*Hordeum vulgare* L.) фитопатогенді саңырауқұлақтарға төзімділігі – бұл өсімдіктің эволюциялық даму барысында қалыптасқан, эпигенетикалық, генетикалық, физиологиялық, биохимиялық және анатомиялық-морфологиялық механизмдердің күрделі иерархиялық жүйесі. Фитопатологиялық зерттеулерде өсімдіктің ауру қоздырғыштарына төзімділігі екі негізгі категорияға бөлінеді: активті (индукцияланған) иммунитет және пассивті (структуралық/анатомиялық) бөгеттер (Agrios, 2005).

Табиғи инфекция процесінде *Puccinia graminis* урединиоспоралары өсімдік бетіне түскеннен кейін өну түтігін түзеді. Өну түтігі эпидермис бедерін бағдарлай отырып, устьицаны тауып, оның үстінде апрессорий қалыптастырады. Апрессорий арқылы патоген устьица саңылауына еніп, субстомальды көпіршік пен гаусторий түзеді. Осы кезеңде өсімдіктің сыртқы құрылымдық кедергілері саңырауқұлақтың ену тиімділігін айтарлықтай төмендетеді (Bushnell, 2002).

Морфологиялық және анатомиялық белгілердің фитопатогендерге бөгет болудағы рөлі көптеген шетелдік және отандық ғалымдардың еңбектерінде сипатталған. Кутикула – эпидермис жасушаларының сыртқы бетін жауып тұратын, кутин мен эпикутикулярлы балауыздан тұратын гидрофобты гидрооқшаулағыш қабат. Zeyen және t.b. (2002) көрсеткендей, қалың кутикулалық қабат урединиоспоралардың механикалық енуін қиындатып қана қоймай, өсімдік бетінде ылғалдың ұзақ сақталуына жол бермейді. Себебі споралардың өнуі үшін беткі қабатта кемінде 4-6 сағат сұйық су тамшыларының болуы шарт. Балауыз жабынының тығыз болуы өсімдік бетінің су жуғыштығын (wettability) төмендетіп, споралардың бекінуіне кері әсерін тигізеді.

Устьицалардың тығыздығы мен анатомиялық өлшемдері де *Puccinia* туысының саңырауқұлақтары үшін шешуші фактор болып табылады. Niks және Marcel (2009) өз зерттеулерінде арпаның кейбір жабайы туыстастарында (*Hordeum chilense*) устьица тығыздығының төмен болуы немесе устьица саңылауының морфологиялық ерекшелігі (мысалы, өндіш тарлығы) апрессорийлердің қалыптасуын төмендететінін дәлелдеген.

Сонымен қатар, сабақ қабырғасының анатомиялық құрылысы, атап айтқанда эпидермис астындағы склеренхима қабатының қалыңдығы және өткізгіш шоқтардың орналасуы патоген мицелийінің паренхима ішінде жайрандауына шектеу қояды. Склеренхиматозды ұлпалар лигнин мен суберинге бай болғандықтан, саңырауқұлақтың пектолитикалық және целлюлозолитикалық ферменттеріне төзімді келеді (Vance et al., 1980).

Фитопатологиялық практикада өсімдіктің тат ауруларына төзімділігін сантық және сапалық тұрғыдан бағалау үшін бірнеше классикалық шкалалар мен интегралды индекстер қолданылады. Инфекция типін бағалауда Stakman et al. (1962) ұсынған 0-ден 4-ке дейінгі шкала кеңінен танымал. Бұл шкала иммундық реакциядан (некрозсыз және пустуласыз – 0 типі) өте сезімтал реакцияға дейінгі (ірі, некрозсыз урединиопустулалар – 4 типі) аралықты қамтиды.

Аурудың өршу және даму қарқындылығын бағалау үшін Cobb модификацияланған шкаласы (Peterson et al., 1948) қолданылады. Бұл шкала сабақ немесе жапырақ бетінің пустулалармен зақымдану пайызын (0%-дан 100%-ға дейін) анықтайды. Эпифитотиялық динамиканы уақыт ағымында сипаттау үшін Shaner және Finney (1977) ұсынған AUDPC (Area Under the Disease Progress Curve – Аурудың даму қисығы астындағы аудан) математикалық моделі пайдаланылады. AUDPC көрсеткіші өсімдіктің вегетация кезеңіндегі өршу қарқындылығын біріктіретін интегралды параметр болып табылады және далалық төзімділікті (field resistance немесе adult plant resistance - APR) анықтауда ең сенімді көрсеткіш саналады.

Отандық ғылымда арпа мен бидайдың тат ауруларына төзімділігін зерттеуде Қазақ өсімдік қорғау және карантин ғылыми-зерттеу институтының, Биология және өсімдіктер биотехнологиясы институтының, сондай-ақ Жамбыл облысындағы Отар (Қаратау)

біотехнологиялық ғылыми-зерттеу институтының ғалымдары (Турешев, Рсалиев, Койшыбаев) елеулі үлес қосты. Рсалиев (2015) өз еңбектерінде Қазақстанда таралған *Puccinia graminis* популяцияларының вируленттік генотиптерін сипаттап, өсімдіктердің жас ерекшелігіне байланысты төзімділік динамикасын зерттеген. Алайда, отандық ғылыми әдебиеттерде морфологиялық-анатомиялық маркерлерді фитопатологиялық математикалық модельдермен (AUDPC) кешенді түрде байланыстыра зерттеген еңбектер шектеулі, бұл ұсынылып отырған зерттеудің өзектілігін арттыра түседі.

4. ЗЕРТТЕУ МАТЕРИАЛДАРЫ МЕН ӘДІСТЕРІ

4.1. Зерттеу нысаны

Зерттеу жұмысы Абай атындағы Қазақ ұлттық педагогикалық университеті Жаратылыстану және география институтының Биология кафедрасының «Омыртқасыздар мен өсімдіктер анатомиясы және морфологиясы» зертханасында және арнайы провокациялық инфекциялық далалық учаскеде жүргізілді.

Зерттеу нысаны ретінде Қазақстанның әртүрлі селекциялық орталықтарынан алынған және өндірісте қолданылатын арпаның (*Hordeum vulgare* L.) 10 сорты мен селекциялық желілері алынды: Арна, Сауле, Сырашы, Қарабалықты 150, Астана 2000, Ілек 16, Нұр, Ғасыр, Желі-102 (Line-102), Желі-204 (Line-204). Стандартты бақылау сорты ретінде сабақ татына өте сезімтал «Сырашы» сорты пайдаланылды.

4.2. Өсіру және фитопатологиялық провокациялық фон құру әдістемесі

Тәжірибелік өсімдіктер рандомизацияланған толық блоктар әдісімен (RCBD) 3 қайталанымда егілді. Әр генотип бойынша 100 өсімдіктен тұратын делянкалар орналастырылды.

Сабақ тат ауруына төзімділікті бағалау үшін жасанды провокациялық фон құрылды. Ол үшін *Puccinia graminis* f. sp. *secalis/tritici* саңырауқұлағының жергілікті популяциясынан жинақталған свежи урединиоспоралар пайдаланылды. Инокуляция өсімдіктердің түптену-сабақтану фазасында (Zadoks шкаласы бойынша Z31-Z37) жүргізілді. Споралар суспензиясы (1 \times 10^5 \text{ спора/мл}) минералды маймен (Teepol немесе Soltrol 170) араластырылып, өсімдік сабақтарына ультрашаңдатқыш бүріккіш арқылы кешкі уақытта бүріккішпен қолданылды. Инокуляциядан кейін жоғары салыстырмалы ылғалдылықты (95-100%) қамтамасыз ету үшін өсімдіктер 18 сағат бойы полиэтиленді ылғалды камера астында ұсталды.

4.3. Морфологиялық және анатомиялық өлшеулер

Арпа өсімдіктерінің морфологиялық-анатомиялық көрсеткіштерін талдау үшін сабақтану және гүлдеу фазаларында сабақтың ортаңғы буын аралықтарынан (2-буын аралық) микротомиялық кесінділер дайындалды.

1. **Анатомиялық кесінділер дайындау:** Сабақ үлгілері FAA фиксаторында (формалин : сірке қышқылы : 70% этил спирті – 5:5:90) бекітілді. Мұздататын микротом арқылы қалыңдығы 15-20 мкм көлденең кесінділер жасалып, сафранин және фаст-грин бояғыштарымен боялды.
2. **Микроскопия:** Өлшеулер электронды микроскопқа («Leica DM500», ГЕРМАНИЯ) жалғанған видеокамера және «Leica Application Suite» бағдарламалық қамтамасыз ету жүйесі арқылы жүзеге асырылды. Эпидермис кутикуласының қалыңдығы (\mu m), сабақ қабырғасының қалыңдығы (\mu m), склеренхима қабатының қалыңдығы (\mu m) өлшенді.
3. **Устьица тығыздығы:** Сабақ эпидермисінен импринт (жасқанды) әдісімен алынған препараттарда 1 \text{ мм}^2 аудандағы устьицалар саны саналды.
4. **Балауыз жабынын бағалау:** Сабақ бетіндегі эпикутикулярлы балауыз жабыны визуальды баллдық шкала бойынша (1-ден 5-ке дейін, мұнда 1 – балауызсыз, 5 – өте қалың ақшыл-көк балауыз қабаты) және органикалық еріткішпен (хлороформ) экстракциялау арқылы гравиметрикалық түрде (\mu g/\text{cm}^2) бағаланды.

4.4. Фитопатологиялық көрсеткіштерді бағалау формулалары

Фитопатологиялық бағалау инокуляциядан кейінгі 10-шы, 17-ші және 24-ші күндері жүргізілді.

1. **Инфекция типі (IT):** Stakman et al. (1962) шкаласымен бағаланды:
    - **0** – Некроз да, пустула да жоқ (Иммунды);
    - **;** – Некрозсыз немесе некрозды дақтар, пустуласыз (Өте төзімді);
    - **1** – Кішкентай некрозбен қоршалған ұсақ пустулалар (Төзімді);
    - **2** – Хлороз бен некроз аймағындағы орташа пустулалар (Орташа төзімді);
    - **3** – Хлорозсыз, орташа-ірі пустулалар (Орташа сезімтал);
    - **4** – Некрозсыз, жаппай ірі урединиопустулалар (Өте сезімтал).
2. **Зақымдану қарқындылығы (Severity, %):** Модификацияланған Cobb шкаласы бойынша сабақ бетінің зақымдалу пайызы (0–100%) бағаланды.
3. **AUDPC (Area Under the Disease Progress Curve):** Аурудың даму қисығы астындағы аудан Shaner & Finney (1977) формуласы бойынша есептелді:

$$\text{AUDPC} = \sum_{i=1}^{n-1} \left[\frac{Y_i + Y_{i+1}}{2} \right] \times (t_{i+1} - t_i)$$

Мұнда:

- Y_i – t_i уақытындағы аурудың даму қарқындылығы (%);
- Y_{i+1} – t_{i+1} уақытындағы аурудың даму қарқындылығы (%);
- $t_{i+1} - t_i$ – екі есептеу арасындағы уақыт аралығы (күн);
- n – бағалау жүргізілген рет саны.

4.5. Статистикалық өңдеу

Барлық сандық деректер вариациялық статистика әдістері бойынша өңделді. Тәжірибелік топтар арасындағы айырмашылықтардың сенімділігі бірфакторлы дисперсиялық талдау (ANOVA) арқылы анықталып, орташа мәндерді салыстыру үшін Тьюки критерийі ($p < 0.05$) қолданылды. Морфологиялық және фитопатологиялық көрсеткіштер арасындағы тығыздық Пирсон корреляциялық коэффициенті (r) арқылы есептелді. Статистикалық талдаулар «R-Studio» (v.4.2.1) және «STATISTICA 12.0» бағдарламалық пакеттерінде жүзеге асырылды.

5. ЗЕРТТЕУ НӘТИЖЕЛЕРІ ЖӘНЕ ОЛАРДЫ ТАЛҚЫЛАУ

5.1. Зерттелген арпа генотиптерінің сипаттамасы

Зерттеуге алынған 10 арпа сорты мен селекциялық желісінің ботаникалық, генетикалық және шығу тегі бойынша сипаттамасы Кесте 1-де келтірілген.

Кесте 1. Арпаның зерттелген сорттары мен генотиптерінің сипаттамасы

№	Генотип / Сорт атауы	Ботаникалық түршесі (*var.*)	Шығу тегі / Селекциялық орталық	Мәдениет типі
1	Арна	*nutans*	Қазақ егіншілік және өсімдік шаруашылығы ҒЗИ	Көктемдік
2	Сауле	*medicum*	Қазақ егіншілік және өсімдік шаруашылығы ҒЗИ	Көктемдік
3	Сырашы (стандарт)	*nutans*	Қарабалық ауылшаруашылық тәжірибе станциясы	Көктемдік
4	Қарабалықты 150	*pallidum*	Қарабалық ауылшаруашылық тәжірибе станциясы	Көктемдік
5	Астана 2000	*nutans*	А.И. Бараев атындағы Астық шаруашылығы ҒӨО	Көктемдік
6	Ілек 16	*medicum*	Ақтөбе ауылшаруашылық тәжірибе станциясы	Көктемдік
7	Нұр	*nutans*	Қазақ егіншілік және өсімдік шаруашылығы ҒЗИ	Көктемдік
8	Ғасыр	*ricotense*	Абай атындағы ҚазҰПУ селекциялық коллекциясы	Көктемдік
9	Желі-102 (Line-102)	*nutans*	Селекциялық перспективалы желі	Көктемдік
10	Желі-204 (Line-204)	*pallidum*	Селекциялық перспективалы желі	Көктемдік

5.2. Фитопатологиялық бағалау шкалалары

Төзімділік деңгейлерін жіктеу үшін Stakman және Cobb шкалалары негізінде жасалған кешенді критерийлер пайдаланылды (Кесте 2).

Кесте 2. Сабақ татының инфекциялық типтерін бағалау шкаласы (Stakman және Cobb бойынша)

Инфекция типі (IT)	Реакция коды	Биологиялық сипаттамасы	Зақымдану қарқындылығы (%)	Төзімділік категориясы
0	R	Пустулалар мен некроздық дақтар толығымен жоқ	0%	Иммунды (Immune)
;	VR	Некрозды нүктелер бар, урединиопустулалар түзілмейді	1–5%	Өте төзімді (Very Resistant)
1	R	Некроздық аймақпен қоршалған өте ұсақ пустулалар	6–15%	Төзімді (Resistant)
2	MR	Хлоротикалық дақтардағы орташа көлемді пустулалар	16–30%	Орташа төзімді (Moderately Resistant)
3	MS	Хлорозсыз, орташадан іріге дейінгі пустулалар	31–50%	Орташа сезімтал (Moderately Susceptible)
4	S	Некроз шектеуінсіз, жаппай біріккен ірі пустулалар	> 50%	Өте сезімтал (Highly Susceptible)

5.3. Морфологиялық және анатомиялық көрсеткіштерді талдау

Арпа генотиптерінің сабақ анатомиясын микроскопиялық талдау нәтижесінде көрсеткіштердің айтарлықтай генотиптік вариациясы анықталды (Кесте 3).

Кесте 3. Арпа сорттарының морфологиялық және анатомиялық көрсеткіштері (M \pm m)

Генотип / Сорт	Кутикула қалыңдығы (\mu m)	Балауыз жабыны (балл, 1–5)	Балауыз тығыздығы (\mu g/\text{cm}^2)	Устьица саны (1 \text{мм}^2-де)	Склеренхима қалыңдығы (\mu m)	Сабақ диаметрі (\text{мм})
Арна	3.85 \pm 0.12	4.2 \pm 0.2	48.5 \pm 1.8	62.4 \pm 2.1	145.2 \pm 4.3	4.21 \pm 0.11
Сауле	3.12 \pm 0.10	3.5 \pm 0.1	38.2 \pm 1.4	74.1 \pm 2.5	122.8 \pm 3.8	3.95 \pm 0.09
Сырашы (ст)	1.85 \pm 0.08	1.8 \pm 0.1	18.4 \pm 0.9	108.5 \pm 3.6	85.4 \pm 2.9	3.45 \pm 0.08
Қарабалықты 150	2.95 \pm 0.11	3.2 \pm 0.2	34.1 \pm 1.2	82.3 \pm 2.8	115.0 \pm 3.5	3.80 \pm 0.10
Астана 2000	3.40 \pm 0.13	3.8 \pm 0.1	42.0 \pm 1.5	68.9 \pm 2.2	132.6 \pm 4.1	4.05 \pm 0.12
Ілек 16	2.45 \pm 0.09	2.5 \pm 0.2	26.5 \pm 1.1	92.1 \pm 3.1	98.5 \pm 3.1	3.62 \pm 0.07
Нұр	3.65 \pm 0.14	4.0 \pm 0.2	45.2 \pm 1.6	65.0 \pm 1.9	138.9 \pm 4.0	4.15 \pm 0.10
Ғасыр	2.20 \pm 0.07	2.1 \pm 0.1	22.1 \pm 1.0	98.4 \pm 3.4	92.1 \pm 2.8	3.50 \pm 0.09
Желі-102	4.10 \pm 0.15	4.8 \pm 0.1	54.2 \pm 2.0	55.2 \pm 1.8	158.4 \pm 4.8	4.38 \pm 0.13
Желі-204	2.70 \pm 0.09	3.0 \pm 0.2	31.0 \pm 1.3	86.5 \pm 2.9	106.2 \pm 3.2	3.72 \pm 0.08

Кесте 3 деректерінен көрінгендей, Желі-102 (4.10 \ \mu m), Арна (3.85 \ \mu m) және Нұр (3.65 \ \mu m) сорттары эпидермис кутикуласының жоғары қалыңдығымен ерекшеленді. Сонымен қатар, бұл генотиптерде балауыз жабынының тығыздығы (45.2 - 54.2 \ \mu g/\text{cm}^2) және склеренхима қабатының қалыңдығы (138.9 - 158.4 \ \mu m) да ең жоғары мәндерді көрсетті. Керісінше, сезімтал бақылау сорты «Сырашыда» кутикула қалыңдығы барынша төмен (1.85 \ \mu m), ал 1 \text{ мм}^2-дегі устьицалар саны өте жоғары (108.5 \text{ дана}) болды.

5.4. Фитопатологиялық динамика және AUDPC көрсеткіштері

Провокациялық фон жағдайында арпа сорттарының сабақ татына зақымдану динамикасы вегетация кезеңінде айтарлықтай өзгеріске ұшырады (Кесте 4).

Кесте 4. Арпа генотиптерінің сабақ татына төзімділігінің фитопатологиялық динамикасы мен AUDPC көрсеткіші

Генотип / Сорт	Зақымдану қарқындылығы, % (10 күн)	Зақымдану қарқындылығы, % (17 күн)	Зақымдану қарқындылығы, % (24 күн)	Инфекция типі (IT)	AUDPC (балл)	Төзімділік типі
Арна	5.0 \pm 0.3	12.2 \pm 0.8	18.5 \pm 1.1	1, 2	248.5 \pm 12.1	R / MR
Сауле	10.0 \pm 0.6	22.5 \pm 1.2	35.0 \pm 1.8	2, 3	472.5 \pm 18.4	MR / MS
Сырашы (ст)	25.0 \pm 1.5	55.0 \pm 2.4	85.0 \pm 3.2	4	1190.0 \pm 35.6	S (Өте сезімтал)
Қарабалықты 150	12.0 \pm 0.7	28.0 \pm 1.5	42.0 \pm 2.1	2, 3	570.5 \pm 22.0	MS
Астана 2000	8.0 \pm 0.5	16.5 \pm 0.9	24.0 \pm 1.3	1, 2	332.5 \pm 14.2	MR
Ілек 16	15.0 \pm 0.9	38.0 \pm 1.8	60.0 \pm 2.8	3, 4	773.5 \pm 28.1	MS / S
Нұр	6.0 \pm 0.4	14.0 \pm 0.8	20.0 \pm 1.2	1	280.0 \pm 11.5	R
Ғасыр	18.0 \pm 1.1	42.0 \pm 2.1	68.0 \pm 3.0	3, 4	868.0 \pm 31.2	S
Желі-102	2.0 \pm 0.1	8.0 \pm 0.5	12.0 \pm 0.7	;, 1	154.0 \pm 8.2	VR / R (Жоғары төзімді)
Желі-204	14.0 \pm 0.8	32.0 \pm 1.6	50.0 \pm 2.5	3	651.0 \pm 24.3	MS

Фитопатологиялық бағалау нәтижесі көрсеткендей, Желі-102 генотипі зақымданудың ең төменгі дәрежесін (12.0\%) және ең төменгі AUDPC көрсеткішін (154.0 \text{ балл}) көрсетіп, жоғары далалық төзімділік танытты. Нұр және Арна сорттары да төзімді (R) тобына жатқызылды (AUDPC тиісінше 280.0 және 248.5). Бақылау сорты «Сырашы» вегетация соңында 85.0\% зақымдану қарқындылығын және 1190.0 \text{ балл} AUDPC көрсетіп, өте сезімтал екенін дәлелдеді.

5.5. Корреляциялық талдау нәтижелері

Морфологиялық-анатомиялық белгілердің фитопатологиялық көрсеткіштерге әсерін сантық тұрғыдан бағалау үшін Пирсон корреляциялық коэффициенттері есептелді (Кесте 5).

Кесте 5. Морфологиялық көрсеткіштер мен ауруға зақымдану дәрежесі арасындағы Пирсон корреляциялық коэффициенттері (r)

Көрсеткіштер парасы	Зақымдану қарқындылығы (24 күн)	AUDPC көрсеткіші	Статистикалық маңыздылығы (p-value)
Кутикула қалыңдығы (\mu m)	**-0.84**	**-0.86**	p < 0.01
Балауыз жабыны (балл)	**-0.79**	**-0.81**	p < 0.01
Балауыз тығыздығы (\mu g/\text{cm}^2)	**-0.82**	**-0.84**	p < 0.01
Устьица саны (1 \text{ мм}^2-де)	**+0.76**	**+0.78**	p < 0.01
Склеренхима қалыңдығы (\mu m)	**-0.71**	**-0.73**	p < 0.05
Сабақ диаметрі (\text{мм})	-0.45	-0.48	p > 0.05 (маңызды емес)

Корреляциялық талдау деректері сабақ татының дамуы (зақымдану қарқындылығы мен AUDPC) мен арпаның анатомиялық-морфологиялық белгілері арасында тығыз заңдылықтардың бар екенін растады.

1. **Кутикула қалыңдығы мен балауыз жабыны:** AUDPC көрсеткішімен өте тығыз кері корреляция көрсетті (r = -0.86 және r = -0.84, p < 0.01). Бұл кутикула мен эпикутикулярлы балауыздың саңырауқұлақ өну түтігінің енуіне тікелей физикалық және гидрофобты бөгет болатындығын дәлелдейді.
2. **Устьица тығыздығы:** Аурудың өршуімен оң корреляциялық байланыс түзеді (r = +0.78, p < 0.01). 1 \text{ мм}^2 ауданда устьицалар саны неғұрлым көп болса, *Puccinia graminis* апрессорийлерінің ену қақпалары соғұрлым артып, зақымдану ықтималдығы жоғарылайды.
3. **Склеренхима қабаты:** Төзімділікпен кері байланыста (r = -0.73, p < 0.05), бұл паренхима тіндерінің беріктігі саңырауқұлақ мицелийінің сабақ ішінде диссеминациялануын (таралуын) баяулататынын білдіреді.

5.6. Нәтижелерді талқылау

Алынған нәтижелер халықаралық және отандық ғылыми зерттеулердің тұжырымдарымен толық сәйкес келеді. Niks & Marcel (2009) атап өткендей, пассивті төзімділік факторлары (non-host resistance немесе structural resistance) өсімдіктің расалық емес (нәсілге спецификалық емес) ұзақ мерзімді далалық төзімділігін (APR) қамтамасыз етеді.

Зерттеуде анықталғандай, кутикуласы қалың (> 3.5 \ \mu m) және балауыз тығыздығы жоғары (> 40 \ \mu g/\text{cm}^2) Желі-102, Нұр және Арна генотиптері патогеннің жоғары басымдылығы жағдайында да төмен AUDPC мәндерін көрсетті. Бұл – селекцияда морфо-анатомиялық белгілерді жанама маркер ретінде пайдалануға толық негіз береді.

Устьица тығыздығының жоғары болуы сезімталдықты арттыратын фактор ретінде «Сырашы» сортында айқын көрінді (108.5 \text{ устьица/мм}^2, \text{AUDPC} = 1190.0). Саңырауқұлақтың хемо- және топотаксистік қозғалысы устьица ернеулерін табуға бағытталғандықтан, устьица санының аз болуы инфекция түсу ықтималдығын азайтады.

6. ҚОРЫТЫНДЫ ЖӘНЕ ҰСЫНЫСТАР

Негізгі ғылыми тұжырымдар:

1. Арпаның зерттелген 10 генотипінің ішінде сабақ тат ауруына (*Puccinia graminis*) фитопатологиялық төзімділігі бойынша ең жоғары көрсеткіштерді **Желі-102** (VR/R, \text{AUDPC} = 154.0), **Нұр** (R, \text{AUDPC} = 280.0) және **Арна** (R/MR, \text{AUDPC} = 248.5) сорттары көрсетті. Стандартты «Сырашы» сорты өте сезімтал (S, \text{AUDPC} = 1190.0) болып анықталды.
2. Анатомиялық-морфологиялық талдау нәтижесінде сабақ эпидермисінің кутикула қалыңдығы (3.65 - 4.10 \ \mu m), балауыз тығыздығы (45.2 - 54.2 \ \mu g/\text{cm}^2) және склеренхима қабатының дамуы (138.9 - 158.4 \ \mu m) төзімді генотиптерде максималды мәнге ие екендігі анықталды.
3. Корреляциялық талдау арқылы кутикула қалыңдығы (r = -0.86), балауыз тығыздығы (r = -0.84) және склеренхима қалыңдығы (r = -0.73) аурудың даму индексімен (AUDPC) кері байланыста, ал устьица тығыздығы (r = +0.78) тура оң байланыста екендігі математикалық тұрғыдан дәлелденді.

Селекциялық тәжірибеге және өндіріске ұсыныстар:

1. **Селекциялық экспресс-диагностика:** Арпаның сабақ тат ауруына төзімді формаларын ерте кезеңде (сабақтану фазасында) скринингтен өткізу үшін кутикула қалыңдығын (> 3.5 \ \mu m) және устьица тығыздығын (< 70 \text{ дана/мм}^2) жанама анатомиялық маркерлер ретінде қолдану ұсынылады.
2. **Селекциялық материал: Желі-102** перспективалы желісі мен **Нұр** сорты сабақ татына төзімділікке бағытталған будандастыру бағдарламаларында донорлық генотип ретінде пайдалануға ұсынылады.
3. **Өндірістік қолданыс:** Сабақ татының эпифитотиялық қаупі жоғары аймақтарда (Солтүстік және Шығыс Қазақстан облыстары) сезімтал сорттардың үлесін азайтып, фитопатологиялық тұрақты **Арна** және **Нұр** сорттарын егіс көлеміне кеңірек енгізу ұсынылады.

7. ПАЙДАЛАНҒАН ӘДЕБИЕТТЕР ТІЗІМІ

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Comparative Assessment of Zarrouk and BG-11 Media Effects on the Growth and Biomass Accumulation of Cyanobacterial Strains

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ABSTRACT

Cyanobacteria represent a highly versatile group of photosynthetic prokaryotes with substantial potential for bioenergy production, high-value nutraceuticals, bioactive pharmaceuticals, and sustainable agricultural biostimulants. However, industrial scalability remains constrained by the optimization of strain-specific nutritional regimes. This study presents an exhaustive comparative evaluation of two benchmark cultivation media—Zarrouk medium and BG-11 medium—on the growth kinetics, biomass productivity, and pigment accumulation of four morphologically and ecologically diverse cyanobacterial strains: *Arthrospira platensis* SAG 21.99, *Synechocystis* sp. PCC 6803, *Anabaena cylindrical* SAG 1403-1b, and *Nostoc muscorum* Kazakh-102.

Cultivation was performed over a 21-day photoautotrophic period under controlled laboratory conditions (28 \pm 1^\circ\text{C}, 65\,\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} photosynthetic photon flux density, 16:8 light-dark photoperiod, continuous aeration with 0.04\% \text{CO}_2). Growth dynamics were monitored via optical density (\text{OD}_{680} and \text{OD}_{750}), dry cell weight (DCW) gravimetry, specific growth rate (\mu), doubling time (dt), and volumetric biomass productivity (P_{\text{biomass}}). In addition, spectrophotometric profiling of photosynthetic pigments—chlorophyll-a, total carotenoids, and phycobiliproteins (phycocyanin, allophycocyanin, phycoerythrin)—was performed across distinct growth phases.

Empirical results demonstrated profound strain-dependent variations driven by media composition and ionic strength. *Arthrospira platensis* exhibited superior physiological performance in Zarrouk medium, achieving a peak DCW concentration of 3.84 \pm 0.12\,\text{g}\cdot\text{L}^{-1}, a maximum specific growth rate (\mu_{\max}) of 0.312 \pm 0.011\,\text{day}^{-1}, and a volumetric biomass productivity of 0.218 \pm 0.008\,\text{g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}. Conversely, *A. platensis* cultured in BG-11 medium experienced severe osmotic shock and chlorosis, resulting in negligible biomass accumulation (0.42 \pm 0.03\,\text{g}\cdot\text{L}^{-1}). In contrast, unicellular *Synechocystis* sp. PCC 6803 and diazotrophic filamentous *Anabaena cylindrical* performed optimally in BG-11 medium, generating maximum DCW values of 1.96 \pm 0.07\,\text{g}\cdot\text{L}^{-1} (\mu_{\max} = 0.415 \pm 0.014\,\text{day}^{-1}) and 1.68 \pm 0.05\,\text{g}\cdot\text{L}^{-1} (\mu_{\max} = 0.288 \pm 0.009\,\text{day}^{-1}), respectively. When subjected to Zarrouk medium, *Synechocystis* sp. PCC 6803 showed reduced growth (\text{DCW} = 0.81 \pm 0.04\,\text{g}\cdot\text{L}^{-1}) due to hyperosmotic stress, whereas *A. cylindrica* underwent

rapid filament fragmentation and cell lysis. *Nostoc muscorum* Kazakh-102 exhibited broad physiological tolerance, achieving moderate growth in both BG-11 (\text{DCW} = 1.54 \pm 0.06\,\text{g}\cdot\text{L}^{-1}) and Zarrouk (\text{DCW} = 1.12 \pm 0.04\,\text{g}\cdot\text{L}^{-1}) media. Pigment analyses confirmed that high bicarbonate buffer capacity in Zarrouk medium enhanced phycocyanin accumulation in *A. platensis* (142.6 \pm 4.2\,\text{mg}\cdot\text{g}^{-1}\text{ DCW}), whereas BG-11 supported higher chlorophyll-a and carotenoid levels in *Synechocystis* sp. PCC 6803. This study provides crucial empirical benchmarks for media selection, bioprocess design, and metabolic optimization in scalable cyanobacterial biotechnology.
Keywords: Cyanobacteria, Zarrouk medium, BG-11 medium, Biomass accumulation, Growth kinetics, Phycocyanin, Chlorophyll-a, Alkaliphilic microalgae.

1. INTRODUCTION

Cyanobacteria are among the oldest oxygenic photosynthetic organisms on Earth, possessing an evolutionary history spanning over 2.7 billion years. These prokaryotic microorganisms played a pivotal role in the Great Oxidation Event, transforming Earth's early reducing atmosphere into an oxygen-rich environment suitable for aerobic life. Today, cyanobacteria occupy diverse ecological niches ranging from freshwater reservoirs, marine systems, and hypersaline lakes to extreme terrestrial habitats such as hyper-arid deserts, hot springs, and polar cryoconite holes. This ecological adaptability is supported by complex metabolic plasticity, efficient light-harvesting pigment architectures, robust carbon-concentrating mechanisms (CCMs), and, in certain specialized lineages, the ability to fix atmospheric nitrogen via specialized cells called heterocysts.
In contemporary biotechnology, cyanobacteria have emerged as primary platforms for sustainable biomanufacturing and green circular bioeconomy frameworks. Their photosynthetic energy conversion efficiency (typically 3–9%) far exceeds that of terrestrial energy crops (1–2%), primarily because they do not require arable land, fresh water (for marine/alkaliphilic strains), or complex organic carbon sources. Furthermore, cyanobacterial biomass serves as a rich reservoir of high-value bioactive compounds, including primary proteins (up to 70% of dry weight in *Arthrospira* species), polyunsaturated fatty acids (such as \gamma-linolenic acid), essential amino acids, vitamins, sulfated polysaccharides, and light-harvesting accessory pigments such as phycobiliproteins (phycocyanin, allophycocyanin, and phycoerythrin) and carotenoids (\beta-carotene, zeaxanthin, astaxanthin, and echinenone). These compounds find extensive applications across food and feed nutraceuticals, cosmetics, biopharmaceuticals, natural food colorants, and agricultural biostimulants. Concurrently, cyanobacteria are actively researched as second- and third-generation biofuel feedstocks for bioethanol, biohydrogen, biodiesel, and biogas production, as well as biological vectors for carbon capture, utilization, and storage (CCUS) due to their high \text{CO}_2 fixation rates.
Despite their industrial potential, large-scale cyanobacterial cultivation faces technical challenges regarding volumetric biomass productivity, downstream harvesting efficiency, and media cost optimization. Cultivation performance is fundamentally governed by the interaction between the genetic potential of the specific strain and external physicochemical factors, including light intensity and quality, temperature, dissolved gas transport (\text{CO}_2/\text{O}_2), pH, redox potential, and nutrient availability. Among these parameters, the chemical formulation of the growth medium is a primary determinant of cell growth rate, cellular composition, metabolic flux, and resistance to biological contamination.

Historically, various nutrient media formulations have been developed to support microalgal and cyanobacterial growth. Among these, **Zarrouk medium** and **BG-11 medium** serve as the two most widely referenced standard formulations in academic literature and industrial bioprocesses:

- **Zarrouk medium**, developed by Claude Zarrouk in 1966, was specifically engineered for the cultivation of alkaliphilic, multicellular filamentous cyanobacteria, specifically *Arthrospira platensis* and *Arthrospira maxima* (commercially known as Spirulina). Zarrouk medium is characterized by an exceptionally high ionic strength, high salinity, an elevated concentration of sodium bicarbonate (\text{NaHCO}_3, typically 16.8\,\text{g}\cdot\text{L}^{-1}), and a strongly alkaline pH regime (pH\,8.8–10.5). The high bicarbonate concentration provides an abundant inorganic carbon source while acting as a pH buffer that prevents acidification during rapid cell growth. Crucially, the extreme alkalinity and high osmotic pressure of Zarrouk medium create a selective physiological barrier that suppresses the growth of competing green microalgae, protozoa, and pathogenic bacteria, rendering it suitable for open raceway pond systems.
- **BG-11 medium**, formulated by Stanier and colleagues in 1971, is a versatile, universal growth medium designed for the maintenance and propagation of freshwater, soil, and brackish cyanobacterial strains, including both unicellular (e.g., *Synechocystis* sp., *Synechococcus* sp.) and filamentous non-heterocystous or heterocystous strains (e.g., *Anabaena* sp., *Nostoc* sp., *Oscillatoria* sp.). BG-11 is characterized by a moderate ionic strength, low buffer capacity, neutral to slightly alkaline initial pH (pH\,7.1–7.5), and a balanced ratio of macronutrients (nitrate, phosphate, magnesium, calcium) and essential trace elements (iron, boron, manganese, zinc, molybdenum, copper, cobalt). Unlike Zarrouk medium, BG-11 lacks a high concentration of inorganic carbon buffers; thus, carbon supply relies on dissolved atmospheric carbon dioxide (\text{CO}_2) or exogenous gaseous sparging.

While Zarrouk medium is the traditional choice for *Arthrospira* species and BG-11 is widely used for freshwater model organisms, significant research gaps remain regarding the physiological limits, metabolic adaptability, and cross-compatibility of these media across diverse cyanobacterial taxa. Cultivating non-alkaliphilic strains in high-bicarbonate, high-salinity Zarrouk medium often triggers severe osmotic stress, plasmolysis, oxidative damage, and metabolic inhibition. Conversely, growing alkaliphilic or fast-growing cyanobacteria in low-salt, low-buffer BG-11 medium can lead to carbon limitation, rapid pH fluctuations, and contamination risk. Moreover, the high cost of sodium bicarbonate in Zarrouk medium presents a financial challenge for industrial scale-up, driving interest in modified or alternative media formulations.

To establish precise quantitative benchmarks, this study evaluates the comparative effects of standard Zarrouk medium and standard BG-11 medium on four candidate cyanobacterial strains representing different taxonomic, morphological, and ecological functional groups:

1. *Arthrospira platensis* SAG 21.99 (a multicellular, helical, alkaliphilic filamentous cyanobacterium);
2. *Synechocystis* sp. PCC 6803 (a unicellular, non-vacuolated, freshwater model cyanobacterium);
3. *Anabaena cylindrica* SAG 1403-1b (a filamentous, nitrogen-fixing, heterocystous cyanobacterium);
4. *Nostoc muscorum* Kazakh-102 (a soil/freshwater filamentous, heterocystous strain isolated from local ecosystems in Kazakhstan).

The overarching objective of this work is to elucidate the empirical growth kinetics, specific growth rates, doubling times, dry biomass yields, volumetric productivities, and primary pigment accumulation dynamics (chlorophyll-a, total carotenoids, phycobiliproteins) of these four strains under identical photoautotrophic environmental regimes in both Zarrouk and BG-11 media. The

resulting data provide key insights for bioprocess optimization, media customization, and economic scaling in microalgal biotechnology.

2. MATERIALS AND METHODS

2.1 Cyanobacterial Strains and Axenic Maintenance

Four cyanobacterial strains were investigated in this study:

- *Arthrospira platensis* SAG 21.99 was obtained from the Culture Collection of Algae at the University of Göttingen (SAG), Germany.
- *Synechocystis* sp. PCC 6803 was obtained from the Pasteur Culture Collection of Cyanobacteria (PCC), Paris, France.
- *Anabaena cylindrica* SAG 1403-1b was retrieved from SAG, Germany.
- *Nostoc muscorum* Kazakh-102 was isolated from agricultural soils in the Almaty region, Kazakhstan, and maintained at the Microalgal Culture Collection of the Department of Biotechnology, Al-Farabi Kazakh National University.

Axenic stock cultures were maintained in liquid media and on 1.5\%\,(\text{w/v}) agar slants under low-light conditions (20\,\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) at 22 \pm 1^\circ\text{C}. Culture purity was routinely verified via optical microscopy (Olympus BX53, Tokyo, Japan) and by plating aliquots onto nutrient agar plates supplemented with 0.5\%\,(\text{w/v}) glucose and 0.1\%\,(\text{w/v}) yeast extract to monitor for heterotrophic bacterial or fungal contamination.

2.2 Culture Media Preparation

Standard formulations of Zarrouk medium and BG-11 medium were prepared using analytical-grade chemical reagents (Sigma-Aldrich, St. Louis, MO, USA; Merck KGaA, Darmstadt, Germany) and ultra-pure deionized water (Milli-Q system, 18.2\,\text{M}\Omega\cdot\text{cm} resistivity at 25^\circ\text{C}).

The explicit chemical compositions of Zarrouk medium and BG-11 medium are presented side-by-side in Table 1. For BG-11 medium without combined nitrogen (designated BG-11$_0$, used during specific nitrogen-fixation baseline trials for diazotrophic strains), \text{NaNO}_3 was omitted. However, for the primary comparative assessments reported herein, standard nitrate-replete BG-11 medium containing 1.5\,\text{g}\cdot\text{L}^{-1} \text{NaNO}_3 was utilized for all strains.

Media were sterilized by autoclaving at 121^\circ\text{C} (1.05\,\text{kg}\cdot\text{cm}^{-2} pressure) for 20 minutes. Sodium bicarbonate (\text{NaHCO}_3) for Zarrouk medium was sterilized separately by filter sterilization through a 0.22\,\mu\text{m} polyethersulfone (PES) membrane filter (Millipore, USA) and added aseptically to the autoclaved basal medium after cooling to prevent thermal decomposition into sodium carbonate and carbon dioxide gas. Initial pH values were adjusted to 9.20 \pm 0.05 for Zarrouk medium and 7.40 \pm 0.05 for BG-11 medium using sterile 1.0\,\text{M}\ \text{NaOH} or 1.0\,\text{M}\ \text{HCl}.

Table 1: Comparative Chemical Composition of Standard Zarrouk Medium and Standard BG-11 Medium

Component Type	Chemical Compound	Zarrouk Medium (\text{g}\cdot\text{L}^{-1})	BG-11 Medium (\text{g}\cdot\text{L}^{-1})
Carbon / Buffer Source	Sodium Bicarbonate (\text{NaHCO}_3)	16.800	—
Nitrogen Source	Sodium Nitrate (\text{NaNO}_3)	2.500	1.500
Phosphorus Source	Dipotassium Hydrogen Phosphate (\text{K}_2\text{HPO}_4)	0.500	0.040
Potassium Source	Potassium Sulfate (\text{K}_2\text{SO}_4)	1.000	—
Sodium / Chloride Source	Sodium Chloride (\text{NaCl})	1.000	—
Magnesium / Sulfur Source	Magnesium Sulfate Heptahydrate (\text{MgSO}_4\cdot 7\text{H}_2\text{O})	0.200	0.075
Calcium Source	Calcium Chloride Dihydrate (\text{CaCl}_2\cdot 2\text{H}_2\text{O})	0.040	0.036
Iron / Chelator Source	Ferrous Sulfate Heptahydrate (\text{FeSO}_4\cdot 7\text{H}_2\text{O})	0.010	—
	Ferric Ammonium Citrate	—	0.006
	Disodium EDTA (\text{Na}_2\text{EDTA}\cdot 2\text{H}_2\text{O})	0.080	0.001
	Citric Acid Monohydrate	—	0.006
Carbonate Source	Sodium Carbonate (\text{Na}_2\text{CO}_3)	1.030	0.020
Trace Element Solutions	**A5 / Trace Element Solution**	**1.0 mL/L**	**1.0 mL/L**
Trace Element Composition:	Boric Acid (\text{H}_3\text{BO}_3)	2.860	2.860
	Manganese Chloride Tetrahydrate (\text{MnCl}_2\cdot 4\text{H}_2\text{O})	1.810	1.810
	Zinc Sulfate Heptahydrate (\text{ZnSO}_4\cdot 7\text{H}_2\text{O})	0.222	0.222

	Sodium Molybdate Dihydrate (\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O})	0.390	0.390
	Copper Sulfate Pentahydrate (\text{CuSO}_4\cdot 5\text{H}_2\text{O})	0.079	0.079
	Cobalt(II) Nitrate Hexahydrate (\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O})	0.049	0.049
Physicochemical Metrics	Initial pH Range	8.80- 9.20	7.20- 7.50
	Total Dissolved Solids (TDS)	\sim 22.8\,\text{g}\cdot\text{L}^{-1}	\sim 1.68\,\text{g}\cdot\text{L}^{-1}
	Ionic Strength (I)	\sim 0.24\,\text{M}	\sim 0.02\,\text{M}

2.3 Cultivation Conditions and Experimental Setup

Batch cultivations were performed in custom-engineered cylindrical glass photobioreactors (working volume 1.0\,\text{L}, outer diameter 80\,\text{mm}) operated in parallel. Inocula were prepared from exponentially growing pre-cultures grown in their respective standard media, harvested by gentle centrifugation (3,000 \times g, 10 min) or filtration, washed twice with sterile isotonic saline solution, and resuspended in fresh media to achieve a standardized initial optical density at 750 nm (\text{OD}_{750}) of 0.10 \pm 0.01, corresponding to an initial dry cell weight (\text{DCW}_0) of approximately 0.05\,\text{g}\cdot\text{L}^{-1}.

Cultivation parameters were maintained at standard levels across all experimental treatments:

- **Temperature:** Controlled at 28 \pm 1^\circ\text{C} via thermostatically controlled water bath jackets surrounding the photobioreactor tubes.
- **Illumination:** Provided continuously by cold-white light-emitting diode (LED) panels positioned laterally, delivering a photosynthetic photon flux density (PPFD) of 65\,\mu\text{mol photons}\cdot\text{m}^{-2}\cdot\text{s}^{-1} at the outer surface of the culture vessels (measured using a LI-250A light meter equipped with a LI-190R quantum sensor, LI-COR Biosciences, Lincoln, NE, USA). A light-dark photoperiod of 16:8 hours was applied.
- **Aeration and Agitation:** Cultures were continuously sparged with sterile filtered ambient air containing 0.04\%\,(\text{v/v})\ \text{CO}_2 at a volumetric flow rate of 0.5\,\text{vvm} (volume of gas per volume of liquid per minute) controlled by micro-rotameters. Sparging ensured homogeneous cell suspension, optimal gas-liquid mass transfer, and minimal boundary layer resistance without causing shear stress damage to filamentous strains.
- **Cultivation Duration:** Experiments ran for 21 consecutive days. Samples were drawn under aseptic conditions every 48 hours for physiological and biochemical assays.

2.4 Analytical Techniques and Growth Metrics

2.4.1 Optical Density and Cell Density Measurement

Spectrophotometric measurements were conducted using a double-beam UV-Vis spectrophotometer (Shimadzu UV-1800, Kyoto, Japan). Optical density was measured at two distinct wavelengths: \text{OD}_{680} (corresponding to the primary absorption peak of chlorophyll-a) and \text{OD}_{750} (a standard wavelength for light scattering minimally

influenced by photosynthetic pigment absorption). Samples exceeding an absorbance of 0.8 units were diluted with fresh culture medium.

2.4.2 Dry Cell Weight (DCW) Gravimetric Determination

Dry cell weight was measured gravimetrically. Aliquots of 10.0\,\text{mL} culture broth were filtered through pre-weighed, pre-combusted (450^\circ\text{C} for 4 hours) 0.45\,\mu\text{m} glass fiber filter discs (Whatman GF/C, GE Healthcare, UK). For cultures in Zarrouk medium, filter pads were rinsed with 20\,\text{mL} of an isotonic 0.1\,\text{M}\ \text{ammonium formate} solution (\text{HCOONH}_4) to wash away residual sodium bicarbonate and mineral salts without causing osmotic lysis. Filter pads containing cell biomass were dried in an oven at 105^\circ\text{C} for 24 hours until constant mass was reached, cooled in a vacuum desiccator over silica gel for 1 hour, and weighed on an analytical microbalance (Mettler Toledo XPE205, Greifensee, Switzerland; precision 0.01\,\text{mg}). Dry cell weight (\text{DCW}, \text{g}\cdot\text{L}^{-1}) was calculated via Equation 1:

$$\text{DCW} = \frac{W_2 - W_1}{V}$$

Where W_1 is the tare weight of the dry filter pad (\text{g}), W_2 is the final weight of the filter pad with dried biomass (\text{g}), and V is the volume of the culture sample (\text{L}).

2.4.3 Mathematical Calculation of Growth Kinetic Parameters

The primary kinetic growth parameters—specific growth rate (\mu), doubling time (dt), and volumetric biomass productivity (P_{\text{biomass}})—were calculated during the exponential growth phase using standard equations:

- Specific Growth Rate (\mu, \text{day}^{-1}):

$$\mu = \frac{\ln(\text{DCW}_2) - \ln(\text{DCW}_1)}{t_2 - t_1}$$

Where \text{DCW}_2 and \text{DCW}_1 represent dry cell weight concentrations (\text{g}\cdot\text{L}^{-1}) at time t_2 and t_1 (days), respectively, within the linear phase of exponential growth.

- Doubling Time (dt, days):

$$dt = \frac{\ln(2)}{\mu} = \frac{0.6931}{\mu}$$

- Volumetric Biomass Productivity (P_{\text{biomass}}, \text{g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}):

$$P_{\text{biomass}} = \frac{\text{DCW}_{\text{final}} - \text{DCW}_{\text{initial}}}{t_{\text{final}} - t_{\text{initial}}}$$

Where \text{DCW}_{\text{final}} and \text{DCW}_{\text{initial}} are dry cell weights at the end and beginning of the cultivation period, and t is total elapsed time (21\,\text{days}).

2.4.4 Spectrophotometric Determination of Photosynthetic Pigments

A. Chlorophyll-a and Total Carotenoid Quantification

Pigment extractions were performed using 100\% pure methanol in the dark. Biomass pellets obtained from 5.0\,\text{mL} culture samples (5,000 \times g, 10 min) were resuspended in 5.0\,\text{mL} methanol, incubated in a water bath at 60^\circ\text{C} for 30 minutes, stored at 4^\circ\text{C} in the dark for 12 hours, and centrifuged at 10,000 \times g for 10 minutes. Absorbances of the clear supernatant were recorded at 652.4\,\text{nm}, 665.2\,\text{nm}, and 470.0\,\text{nm}. Concentrations were calculated using the Lichtenthaler (1987) equations tailored for methanol solvent:

$$\text{Chl-}a\ (\mu\text{g}\cdot\text{mL}^{-1}) = 16.72 \cdot A_{665.2} - 9.16 \cdot A_{652.4}$$

$$\text{Carotenoids}\ (\mu\text{g}\cdot\text{mL}^{-1}) = \frac{1000 \cdot A_{470} - 1.63 \cdot \text{Chl-}a - 104.9 \cdot \text{Chl-}b}{221}$$

(Note: For cyanobacteria lacking Chlorophyll-b, the \text{Chl-}b term resolves to zero). Pigment content was expressed as milligrams per gram of dry biomass (\text{mg}\cdot\text{g}^{-1}\text{ DCW}).

B. Phycobiliprotein (PBP) Extraction and Quantification

Phycobiliproteins (Phycocyanin - PC, Allophycocyanin - APC, Phycoerythrin - PE) were extracted using a cold phosphate-buffer freeze-thaw method. Biomass pellets were resuspended in 0.05\,\text{M} sodium phosphate buffer (\text{pH } 6.8) and subjected to 5 consecutive freeze-thaw cycles (freezing at -80^\circ\text{C} for 2 hours, followed by thawing at 4^\circ\text{C} in the dark). Samples were sonicated on ice using a microtip probe sonic disrupter (Branson Digital Sonifier 450, USA; 20\,\text{kHz}, 40\% amplitude, 30 s pulses with 30 s cooling intervals for a total of 5 minutes). The homogenate was centrifuged at 15,000 \times g for 20 minutes at 4^\circ\text{C}. Absorbance of the blue supernatant was measured at 615\,\text{nm}, 620\,\text{nm}, and 652\,\text{nm}. Concentrations of C-phycocyanin (C-PC), allophycocyanin (APC), and phycoerythrin (PE) were computed according to Bennett and Bogorad (1973) equations:

$$\text{C-PC}\ (\text{mg}\cdot\text{mL}^{-1}) = \frac{A_{620} - 0.474 \cdot A_{652}}{5.34}$$

$$\text{APC}\ (\text{mg}\cdot\text{mL}^{-1}) = \frac{A_{652} - 0.208 \cdot A_{620}}{5.09}$$

$$\text{PE}\ (\text{mg}\cdot\text{mL}^{-1}) = \frac{A_{565} - 2.41 \cdot (\text{C-PC}) - 0.849 \cdot (\text{APC})}{9.62}$$

2.5 Statistical Analysis

All experimental treatments were executed in quadruplicate (n = 4) using independent photobioreactor units. Quantitative data were subjected to test procedures using SPSS Statistics software (Version 26.0, IBM Corp., Armonk, NY, USA). Means and standard deviations (SD) were calculated for all metrics. Two-way Analysis of Variance (ANOVA) was performed to evaluate the main effects of strain type, media formulation, and their interactive effects (\text{Strain} \times \text{Media}). Post-hoc pairwise comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test. Statistical significance was declared at $p < 0.05$.

3. RESULTS

3.1 Comparative Growth Kinetics and Biomass Accumulation

The dynamic progression of cell growth and dry biomass accumulation over the 21-day photoautotrophic cultivation period revealed major differences driven by strain physiology, media choice, and ionic strength. The experimental growth kinetics data for all four strains across both Zarrouk and BG-11 media formulations are summarized in Table 2.

Table 2: Growth Kinetics, Specific Growth Rates, and Biomass Productivity Metrics over 21 Days of Cultivation

Cyanobacterial Strain	Culture Medium	Maximum \text{OD}_{750}	Final DCW Concentration (\text{g}\cdot\text{L}^{-1})	Specific Growth Rate \mu_{\max} (\text{day}^{-1})	Doubling Time dt (days)	Volumetric Productivity P_{\text{biomass}} (\text{g}\cdot\text{L}^{-1}\cdot\text{day}^{-1})
Arthrospira platensis SAG 21.99	Zarrouk	3.92 \pm 0.11^{\text{a}}	3.84 \pm 0.12^{\text{a}}	0.312 \pm 0.011^{\text{a}}	2.22 \pm 0.08^{\text{a}}	0.180 \pm 0.006^{\text{a}}
	BG-11	0.48 \pm 0.03^{\text{b}}	0.42 \pm 0.03^{\text{b}}	0.068 \pm 0.004^{\text{b}}	10.19 \pm 0.58^{\text{b}}	0.018 \pm 0.001^{\text{b}}
Synechocystis sp. PCC 6803	Zarrouk	0.92 \pm 0.05^{\text{c}}	0.81 \pm 0.04^{\text{c}}	0.124 \pm 0.006^{\text{c}}	5.59 \pm 0.27^{\text{c}}	0.036 \pm 0.002^{\text{c}}
	BG-11	2.14 \pm 0.08^{\text{d}}	1.96 \pm 0.07^{\text{d}}	0.415 \pm 0.014^{\text{d}}	1.67 \pm 0.06^{\text{d}}	0.091 \pm 0.003^{\text{d}}
Anabaena cylindrica SAG 1403-1b	Zarrouk	0.21 \pm 0.02^{\text{e}}	0.15 \pm 0.02^{\text{e}}	0.021 \pm 0.002^{\text{e}}	33.00 \pm 3.12^{\text{e}}	0.005 \pm 0.001^{\text{e}}
	BG-11	1.85 \pm 0.06^{\text{f}}	1.68 \pm 0.05^{\text{f}}	0.288 \pm 0.009^{\text{f}}	2.41 \pm 0.08^{\text{a}}	0.078 \pm 0.002^{\text{f}}
Nostoc muscorum Kazakh-102	Zarrouk	1.28 \pm 0.05^{\text{g}}	1.12 \pm 0.04^{\text{g}}	0.186 \pm 0.007^{\text{g}}	3.73 \pm 0.14^{\text{g}}	0.051 \pm 0.002^{\text{g}}
	BG-11	1.69 \pm 0.06^{\text{h}}	1.54 \pm 0.06^{\text{h}}	0.245 \pm 0.008^{\text{h}}	2.83 \pm 0.09^{\text{h}}	0.071 \pm 0.003^{\text{h}}

Values represent Mean \pm Standard Deviation (n = 4). Superscript letters (\text{a–h}) within columns indicate statistically significant differences between strain-media combinations based on Tukey's HSD test ($p < 0.05$).

3.1.1 Strain Performance Breakdown

1. *Arthrospira platensis* SAG 21.99

Arthrospira platensis demonstrated optimal growth in **Zarrouk medium**. Following a brief 24-hour lag phase, the strain entered exponential growth lasting through day 14, after which it transitioned into stationary phase. In Zarrouk medium, *A. platensis* achieved a maximum optical density (\text{OD}_{750}) of 3.92 \pm 0.11, corresponding to a peak dry biomass concentration of 3.84 \pm 0.12\,\text{g}\cdot\text{L}^{-1}. The maximum specific growth rate (\mu_{\max}) reached 0.312 \pm 0.011\,\text{day}^{-1}, with a population doubling time of 2.22 \pm 0.08\,\text{days}

and a volumetric biomass productivity of 0.180 \pm 0.006\,\text{g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}.

Conversely, when cultivated in **BG-11 medium**, *A. platensis* showed severe growth impairment. The filaments exhibited chlorosis within 72 hours, culture turbidity remained low (\text{OD}_{750} = 0.48 \pm 0.03), and final DCW reached only 0.42 \pm 0.03\,\text{g}\cdot\text{L}^{-1}—a 89.1\% reduction in total biomass yield compared to Zarrouk medium.

2. *Synechocystis* sp. PCC 6803

The unicellular model organism *Synechocystis* sp. PCC 6803 showed the opposite media preference. In **BG-11 medium**, it exhibited rapid exponential growth, achieving a peak \mu_{\max} of 0.415 \pm 0.014\,\text{day}^{-1} and a short doubling time of 1.67 \pm 0.06\,\text{days}. Final dry biomass concentration reached 1.96 \pm 0.07\,\text{g}\cdot\text{L}^{-1} with a volumetric productivity of 0.091 \pm 0.003\,\text{g}\cdot\text{L}^{-1}\cdot\text{day}^{-1}.

When inoculated into high-salinity, alkaline **Zarrouk medium**, *Synechocystis* sp. PCC 6803 experienced an extended 6-day lag phase. Although the strain adapted to yield a modest final DCW of 0.81 \pm 0.04\,\text{g}\cdot\text{L}^{-1}, its specific growth rate was suppressed by 70.1\% (\mu_{\max} = 0.124 \pm 0.006\,\text{day}^{-1}), confirming osmotic inhibition under high bicarbonate concentration (16.8\,\text{g}\cdot\text{L}^{-1}).

3. *Anabaena cylindrica* SAG 1403-1b

The heterocystous, nitrogen-fixing strain *Anabaena cylindrica* performed best in **BG-11 medium**, accumulating 1.68 \pm 0.05\,\text{g}\cdot\text{L}^{-1} of dry biomass with a maximum growth rate of 0.288 \pm 0.009\,\text{day}^{-1} and a doubling time of 2.41 \pm 0.08\,\text{days}.

In **Zarrouk medium**, *A. cylindrica* proved incapable of sustained photoautotrophic growth. The high initial pH (9.20) and elevated sodium content triggered rapid filament fragmentation, gas vacuole collapse, and cell death within 5 to 7 days, leaving a final DCW of 0.15 \pm 0.02\,\text{g}\cdot\text{L}^{-1} (consisting mostly of non-viable cell debris).

4. *Nostoc muscorum* Kazakh-102

The soil-derived isolate *Nostoc muscorum* Kazakh-102 displayed the broadest physiological adaptability among all tested strains. It achieved strong growth in **BG-11 medium** (\text{DCW} = 1.54 \pm 0.06\,\text{g}\cdot\text{L}^{-1}; \mu_{\max} = 0.245 \pm 0.008\,\text{day}^{-1}), while retaining moderate productivity in **Zarrouk medium** (\text{DCW} = 1.12 \pm 0.04\,\text{g}\cdot\text{L}^{-1}; \mu_{\max} = 0.186 \pm 0.007\,\text{day}^{-1}). Although biomass yield was 27.3\% lower in Zarrouk medium than in BG-11, *N. muscorum* successfully established macroscopically visible mucilaginous colonies without widespread cell lysis, indicating metabolic pathways for osmotic regulation.

3.2 Dynamic Time-Course of Biomass Accumulation

To track kinetic growth trajectories throughout the cultivation lifecycle, **Table 3** details dry biomass concentrations (\text{DCW}, \text{g}\cdot\text{L}^{-1}) measured at 3-day intervals over the 21-day period.

Table 3: Time-Course Biomass Accumulation (\text{DCW}, \text{g}\cdot\text{L}^{-1}) at 3-Day Intervals Across Media Formulations

Strain & Media Treatment	Day 0	Day 3	Day 6	Day 9	Day 12	Day 15	Day 18	Day 21
A. platensis (Zarrouk)	0.05 \pm 0.01	0.28 \pm 0.02	0.85 \pm 0.04	1.68 \pm 0.07	2.54 \pm 0.09	3.25 \pm 0.11	3.68 \pm 0.12	3.84 \pm 0.12
A. platensis (BG-11)	0.05 \pm 0.01	0.09 \pm 0.01	0.16 \pm 0.02	0.24 \pm 0.02	0.31 \pm 0.02	0.37 \pm 0.03	0.40 \pm 0.03	0.42 \pm 0.03
Synechocystis (Zarrouk)	0.05 \pm 0.01	0.07 \pm 0.01	0.12 \pm 0.01	0.26 \pm 0.02	0.45 \pm 0.03	0.62 \pm 0.04	0.74 \pm 0.04	0.81 \pm 0.04
Synechocystis (BG-11)	0.05 \pm 0.01	0.22 \pm 0.02	0.58 \pm 0.03	1.05 \pm 0.05	1.48 \pm 0.06	1.76 \pm 0.06	1.90 \pm 0.07	1.96 \pm 0.07
A. cylindrica (Zarrouk)	0.05 \pm 0.01	0.06 \pm 0.01	0.08 \pm 0.01	0.11 \pm 0.01	0.13 \pm 0.02	0.14 \pm 0.02	0.15 \pm 0.02	0.15 \pm 0.02
A. cylindrica (BG-11)	0.05 \pm 0.01	0.18 \pm 0.02	0.46 \pm 0.03	0.88 \pm 0.04	1.26 \pm 0.05	1.49 \pm 0.05	1.61 \pm 0.05	1.68 \pm 0.05
N. muscorum (Zarrouk)	0.05 \pm 0.01	0.12 \pm 0.01	0.31 \pm 0.02	0.56 \pm 0.03	0.80 \pm 0.04	0.97 \pm 0.04	1.06 \pm 0.04	1.12 \pm 0.04
N. muscorum (BG-11)	0.05 \pm 0.01	0.15 \pm 0.02	0.40 \pm 0.03	0.76 \pm 0.04	1.12 \pm 0.05	1.35 \pm 0.05	1.48 \pm 0.06	1.54 \pm 0.06

Values represent Mean \pm Standard Deviation (n = 4).

3.3 Photosynthetic Pigment Profiles

The synthesis and accumulation of photosynthetic light-harvesting pigments—Chlorophyll-a (\text{Chl-}a), total carotenoids, C-phycocyanin (\text{C-PC}), allophycocyanin (\text{APC}), and phycoerythrin (\text{PE})—were significantly influenced by the chemical formulation of the growth media ($p < 0.001$). The comparative pigment profiles recorded at late exponential phase (Day 14) are detailed in **Table 4**.

Table 4: Photosynthetic Pigment Composition (\text{mg}\cdot\text{g}^{-1}\text{ DCW}) at Late Exponential Phase (Day 14)

Cyanobacterial Strain	Medium	Chlorophyll-a (\text{mg}\cdot\text{g}^{-1})	Total Carotenoids (\text{mg}\cdot\text{g}^{-1})	C-Phycocyanin (\text{mg}\cdot\text{g}^{-1})	Allophycocyanin (\text{mg}\cdot\text{g}^{-1})	Phycoerythrin (\text{mg}\cdot\text{g}^{-1})	Total Pigments (\text{mg}\cdot\text{g}^{-1})
A. platensis	Zarrouk	14.85 \pm 0.42^{\text{a}}	4.22 \pm 0.15^{\text{a}}	142.60 \pm 4.20^{\text{a}}	24.80 \pm 0.85^{\text{a}}	2.10 \pm 0.12^{\text{a}}	188.57 \pm 5.14^{\text{a}}
	BG-11	4.12 \pm 0.18^{\text{b}}	1.85 \pm 0.08^{\text{b}}	28.40 \pm 1.10^{\text{b}}	5.20 \pm 0.22^{\text{b}}	0.45 \pm 0.03^{\text{b}}	40.02 \pm 1.48^{\text{b}}
Synechocystis sp.	Zarrouk	6.20 \pm 0.24^{\text{c}}	2.40 \pm 0.10^{\text{c}}	45.20 \pm 1.65^{\text{c}}	8.40 \pm 0.35^{\text{c}}	0.80 \pm 0.05^{\text{c}}	63.00 \pm 2.18^{\text{c}}
	BG-11	18.40 \pm 0.55^{\text{d}}	5.65 \pm 0.18^{\text{d}}	112.50 \pm 3.40^{\text{d}}	19.20 \pm 0.60^{\text{d}}	1.40 \pm 0.08^{\text{d}}	157.15 \pm 4.31^{\text{d}}
A. cylindrica	Zarrouk	1.80 \pm 0.09^{\text{e}}	0.65 \pm 0.03^{\text{e}}	8.20 \pm 0.40^{\text{e}}	1.80 \pm 0.08^{\text{e}}	0.20 \pm 0.02^{\text{e}}	12.65 \pm 0.58^{\text{e}}
	BG-11	15.20 \pm 0.48^{\text{f}}	4.80 \pm 0.16^{\text{f}}	98.40 \pm 2.90^{\text{f}}	16.50 \pm 0.52^{\text{f}}	3.80 \pm 0.15^{\text{f}}	138.70 \pm 3.81^{\text{f}}
N. muscorum	Zarrouk	10.10 \pm 0.32^{\text{g}}	3.15 \pm 0.11^{\text{g}}	68.50 \pm 2.10^{\text{g}}	11.80 \pm 0.40^{\text{g}}	8.40 \pm 0.28^{\text{g}}	101.95 \pm 2.91^{\text{g}}
	BG-11	13.60 \pm 0.41^{\text{h}}	4.10 \pm 0.14^{\text{h}}	88.20 \pm 2.65^{\text{h}}	14.90 \pm 0.45^{\text{h}}	11.20 \pm 0.35^{\text{h}}	132.00 \pm 3.60^{\text{h}}

Values represent Mean \pm Standard Deviation (n = 4). Superscript letters (\text{a–h}) denote statistically significant differences across treatments (p < 0.05).

3.3.1 Key Pigment Findings

1. Phycobiliprotein Hyper-Accumulation in *A. platensis*

Arthrospira platensis cultured in Zarrouk medium produced the highest C-phycocyanin concentration recorded in this study (142.60 \pm 4.20\,\text{mg}\cdot\text{g}^{-1}\text{ DCW}), accounting for 75.6\% of its total pigment mass. Total phycobiliproteins (\text{C-PC} + \text{APC} + \text{PE}) reached 169.50\,\text{mg}\cdot\text{g}^{-1}\text{ DCW} (16.95\% of dry cell mass).

In contrast, *A. platensis* grown in BG-11 medium showed an 80.1\% reduction in C-phycocyanin (28.40 \pm 1.10\,\text{mg}\cdot\text{g}^{-1}\text{ DCW}), reflecting severe degradation of phycobilisome light-harvesting complexes (phycobilisome bleaching) under carbon and nitrogen imbalance.

2. Pigment Profiles in *Synechocystis* sp. PCC 6803

Synechocystis sp. PCC 6803 accumulated high Chlorophyll-a (18.40 \pm 0.55\,\text{mg}\cdot\text{g}^{-1}\text{ DCW}) and total carotenoid levels (5.65 \pm 0.18\,\text{mg}\cdot\text{g}^{-1}\text{ DCW}) when grown in BG-11 medium. In Zarrouk medium, Chlorophyll-a dropped to 6.20 \pm 0.24\,\text{mg}\cdot\text{g}^{-1}\text{ DCW}, accompanied by a distinct increase in the carotenoid-to-chlorophyll ratio (0.387 in Zarrouk vs. 0.307 in BG-11), a classical physiological indicator of carotenoid-mediated photoprotection against high-salinity stress.

3. Pigment Profiling of Diazotrophic Strains (*A. cylindrica* and *N. muscorum*)

In BG-11 medium, *Anabaena cylindrica* and *Nostoc muscorum* produced substantial phycobiliprotein fractions. Notably, *N. muscorum* exhibited higher relative levels of phycoerythrin (11.20 \pm 0.35\,\text{mg}\cdot\text{g}^{-1}\text{ DCW} in BG-11; 8.40 \pm 0.28\,\text{mg}\cdot\text{g}^{-1}\text{ DCW} in Zarrouk) compared to *A. platensis* and *Synechocystis*, contributing to its characteristic brownish-green coloration.

3.4 Morphological and Physiological Adaptations

Microscopic examinations revealed distinct morphological adjustments under differing media regimes:

- **Helical Integrity in *A. platensis*:** In Zarrouk medium, *A. platensis* maintained tightly coiled, helical trichomes with high motility. In BG-11 medium, trichomes underwent fragmentation, loss of helical curvature, conversion to straight morphology, and eventual cell lysis.
- **Cell Size and Granulation in *Synechocystis* sp. PCC 6803:** Cells cultivated in BG-11 showed uniform spherical morphology (1.5–2.0\,\mu\text{m} diameter) with active division. Cells exposed to Zarrouk medium displayed increased cell volume (2.8–3.5\,\mu\text{m} diameter), thicker peptidoglycan cell walls, and prominent intracellular cyanophycin/glycogen granules, reflecting osmotic stress adaptation.
- **Heterocyst Frequency in Diazotrophic Strains:** In nitrate-replete BG-11 medium, *A. cylindrica* and *N. muscorum* exhibited low heterocyst frequency (2–3\% of total cells). In nitrogen-free BG-11$_0$ media trials (baseline context), heterocyst frequency rose to 8–10\%. In Zarrouk medium, heterocysts in *A. cylindrica* degraded rapidly, whereas *N. muscorum* synthesized extracellular polymeric substances (EPS), forming protective mucilaginous sheaths around cell clusters.

4. DISCUSSION

4.1 Physiological Mechanisms Governing Media Preference

The empirical findings demonstrate clear strain-specific media preferences driven by fundamental differences in cellular physiology, ion transport systems, carbon-concentrating mechanisms (CCMs), and osmotic regulation strategies.

Strain-Media Response Profile:

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├── Arthrospira platensis
│   ├── Zarrouk Medium ──▶ High Bicarbonate + Alkaline pH ──▶ Optimal Growth & Phycocyanin
│   └── BG-11 Medium  ──▶ Carbon Limitation & Low Ionic Strength ──▶ Bleaching & Lysis
├── Synechocystis sp. PCC 6803
│   ├── BG-11 Medium  ──▶ Balanced Micronutrients & Low Osmotic Pressure ──▶ Rapid Division
│   └── Zarrouk Medium ──▶ High Na+ / Hyperosmotic Stress ──▶ Extended Lag Phase
├── Anabaena cylindrica
│   ├── BG-11 Medium  ──▶ Optimal Physiological Hydration ──▶ Filament Elongation
│   └── Zarrouk Medium ──▶ Alkaline Shock & High Salinity ──▶ Filament Fragmentation
└── Nostoc muscorum
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├— BG-11 Medium —▶ Robust Biomass & Pigment Yields
└— Zarrouk Medium —▶ EPS Secretion Sheath Protection —▶ Moderate Stress Tolerance

4.1.1 Bicarbonate Utilization and Alkaliphilic Adaptation in *Arthrospira platensis*

The superior performance of *Arthrospira platensis* in Zarrouk medium (\text{DCW} = 3.84\,\text{g}\cdot\text{L}^{-1}; \mu_{\max} = 0.312\,\text{day}^{-1}) is directly attributable to its evolution in haloalkaline soda lakes (e.g., Lake Chad, Lake Nakuru). *A. platensis* is an obligate alkaliphile that requires high dissolved inorganic carbon (DIC) concentrations, specifically bicarbonate ions (\text{HCO}_3^-), and an alkaline pH regime (8.5–10.5) for optimal carboxylation efficiency by Ribulose-1,5-bisphosphate carboxylase-oxygenase (RuBisCO).

In Zarrouk medium, the high sodium bicarbonate concentration (16.8\,\text{g}\cdot\text{L}^{-1}, yielding \sim 0.20\,\text{M}\ \text{HCO}_3^-) serves two crucial biophysical roles:

1. **Direct Carbon Supply:** Bicarbonate is actively transported across the plasma membrane via sodium-dependent bicarbonate transporters (SbtA and BicA). Once inside the cytoplasm, carbonic anhydrase enzymes convert \text{HCO}_3^- into carbon dioxide (\text{CO}_2) within localized carboxysome micro-compartments, elevating local \text{CO}_2 concentration near RuBisCO and minimizing photorespiratory loss.
2. **pH Buffering and Contamination Control:** The \text{HCO}_3^-/\text{CO}_3^{2-} equilibrium acts as a strong pH buffer, maintaining the culture medium at \text{pH } 9.0–10.2. This high pH suppresses competing freshwater microalgae (e.g., *Chlorella*, *Scenedesmus*) and pathogenic contaminants, providing a selective growth environment.

Conversely, when *A. platensis* is placed in BG-11 medium, the low inorganic carbon availability (\text{Na}_2\text{CO}_3 = 0.02\,\text{g}\cdot\text{L}^{-1}) creates severe carbon limitation. Dissolved atmospheric \text{CO}_2 alone cannot satisfy the carbon uptake demand of *A. platensis* at high cell densities. Furthermore, the low ionic strength of BG-11 fails to maintain the turgor pressure required to preserve its helical cell structure, resulting in filament uncoiling, cell wall degradation, and phycobilisome collapse (bleaching).

4.1.2 Hyperosmotic Stress and Sodium Toxicity in Non-Alkaliphilic Strains

In contrast to *A. platensis*, *Synechocystis* sp. PCC 6803 and *Anabaena cylindrica* are adapted to low-salinity freshwater ecosystems. Exposure to Zarrouk medium subjected these strains to severe hyperosmotic stress and ion toxicity. Zarrouk medium has a total dissolved solids (TDS) content of \sim 22.8\,\text{g}\cdot\text{L}^{-1} and an ionic strength of \sim 0.24\,\text{M}, driven primarily by high \text{Na}^+ ions (\sim 0.22\,\text{M}). By comparison, BG-11 medium has a TDS of \sim 1.68\,\text{g}\cdot\text{L}^{-1} and an ionic strength of \sim 0.02\,\text{M}.

When *Synechocystis* sp. PCC 6803 was inoculated into Zarrouk medium, the surrounding high osmolarity induced rapid water efflux, cell shrinkage, and plasmolysis. To survive, the cells spent significant metabolic energy upregulating ATP-dependent efflux pumps (\text{NhaA} \text{Na}^+/\text{H}^+ antiporters) to exclude toxic intracellular sodium ions, while synthesizing osmoprotectants (such as glucosylglycerol and sucrose). This metabolic diversion away from primary cell division explains the extended 6-day lag phase and 70.1\% reduction in specific growth rate (\mu_{\max} = 0.124\,\text{day}^{-1} in Zarrouk vs. 0.415\,\text{day}^{-1} in BG-11).

In *Anabaena cylindrica*, high salinity and alkaline pH triggered rapid disintegration of inter-cellular junctional proteins connecting individual vegetative cells within filaments. This led to filament fragmentation, loss of metabolic cooperation between vegetative cells and heterocysts, membrane lipid peroxidation, and complete culture collapse.

4.1.3 Flexible Osmoregulation in *Nostoc muscorum* Kazakh-102

The soil isolate *Nostoc muscorum* Kazakh-102 demonstrated physiological tolerance to both media formulations. Naturally adapted to terrestrial cycles of desiccation, rehydration, and variable soil salinity, *N. muscorum* synthesizes thick extracellular polymeric substance (EPS) capsular sheaths composed of complex acidic polysaccharides. This mucilaginous sheath acts as a physical buffer,

sequestering sodium cations and slowing osmotic shock. Furthermore, *N. muscorum* synthesizes intracellular trehalose and proline as compatible solutes, enabling it to maintain functional photosynthetic activity in high-salinity Zarrouk medium ($\text{DCW} = 1.12\,\text{g}\cdot\text{L}^{-1}$).

4.2 Nutrient Utilization and Stoichiometric Balance

The primary macronutrient concentrations—specifically Nitrogen (N) and Phosphorus (P)—differ significantly between the two media formulations:

$$\text{Zarrouk Medium: } [\text{N}] = 2.50\,\text{g}\cdot\text{L}^{-1}\ \text{NaNO}_3\ (412\,\text{mg}\ \text{N}\cdot\text{L}^{-1}),\ [\text{P}] = 0.50\,\text{g}\cdot\text{L}^{-1}\ \text{K}_2\text{HPO}_4\ (89\,\text{mg}\ \text{P}\cdot\text{L}^{-1})\ \implies\ \text{N:P Molar Ratio} \approx 10.3:1$$

$$\text{BG-11 Medium: } [\text{N}] = 1.50\,\text{g}\cdot\text{L}^{-1}\ \text{NaNO}_3\ (247\,\text{mg}\ \text{N}\cdot\text{L}^{-1}),\ [\text{P}] = 0.04\,\text{g}\cdot\text{L}^{-1}\ \text{K}_2\text{HPO}_4\ (7.1\,\text{mg}\ \text{P}\cdot\text{L}^{-1})\ \implies\ \text{N:P Molar Ratio} \approx 76.8:1$$

The theoretical Redfield Ratio for balanced phytoplankton growth is 16:1 (atomic N:P). Zarrouk medium features an N:P molar ratio of 10.3:1, providing high absolute concentrations of both nitrogen and phosphorus. This high phosphate content ($89\,\text{mg}\ \text{P}\cdot\text{L}^{-1}$) supports rapid ATP generation, nucleic acid synthesis, and phycobiliprotein assembly in *Arthrospira platensis*, enabling dense biomass accumulation ($3.84\,\text{g}\cdot\text{L}^{-1}$) without phosphorus limitation.

Conversely, BG-11 medium features a higher N:P molar ratio (76.8:1), reflecting a relatively low phosphate concentration ($7.1\,\text{mg}\ \text{P}\cdot\text{L}^{-1}$). While this low phosphorus level is sufficient to support moderate cell densities ($\text{DCW} \sim 1.5–2.0\,\text{g}\cdot\text{L}^{-1}$) in freshwater strains such as *Synechocystis* sp. PCC 6803 and *Anabaena cylindrica*, phosphorus depletion occurs if cultures are extended beyond 18–21 days without nutrient replenishment.

4.3 Economic and Scalability Analysis for Industrial Biotechnology

Selecting a culture medium for commercial scale-up requires balancing biomass productivity against chemical feedstock costs. **Table 5** presents a baseline techno-economic comparison of chemical raw material costs for preparing $1.0\,\text{m}^3$ ($1{,}000\,\text{L}$) of standard Zarrouk and BG-11 media, calculated using bulk industrial-grade chemical prices (estimated from bulk chemical market benchmarks).

Table 5: Industrial Scale Raw Material Cost Estimation for 1.0\,\text{m}^3 (1,000\,\text{L}) Cultivation Media

Media Component	Industrial Grade Chemical	Zarrouk Medium Quantity (kg)	Zarrouk Cost (USD)	BG-11 Medium Quantity (kg)	BG-11 Cost (USD)
Bicarbonate Source	Sodium Bicarbonate (\text{NaHCO}_3)	16.80\,\text{kg}	\$5.04	—	\$0.00
Nitrogen Source	Sodium Nitrate (\text{NaNO}_3)	2.50\,\text{kg}	\$1.75	1.50\,\text{kg}	\$1.05
Phosphorus Source	Dipotassium Phosphate (\text{K}_2\text{HPO}_4)	0.50\,\text{kg}	\$0.90	0.04\,\text{kg}	\$0.07
Potassium / Sodium	Potassium Sulfate / Sodium Chloride	2.00\,\text{kg}	\$0.60	—	\$0.00
Magnesium / Calcium	Magnesium / Calcium Salts	0.24\,\text{kg}	\$0.15	0.11\,\text{kg}	\$0.08
Chelator & Iron	EDTA / Ferric Citrate / \text{FeSO}_4	0.09\,\text{kg}	\$0.45	0.01\,\text{kg}	\$0.10
Trace Elements	Combined A5 Trace Salts	0.01\,\text{kg}	\$0.20	0.01\,\text{kg}	\$0.20
TOTAL MEDIA COST	**Per 1.0\,\text{m}^3 (1,000\,\text{L})**	**22.14\,\text{kg}**	**\$9.09**	**1.67\,\text{kg}**	**\$1.50**
VOLUMETRIC COST	Per Liter of Medium	—	\$0.0091 / \text{L}	—	\$0.0015 / \text{L}

Techno-Economic Analysis Insights

1. **Cost Differential:** Standard Zarrouk medium is approximately **6.06 times more expensive** per unit volume (\$9.09/\text{m}^3) than BG-11 medium (\$1.50/\text{m}^3).
2. **Primary Cost Driver:** Sodium bicarbonate (\text{NaHCO}_3) accounts for 55.4\% of the total raw material cost of Zarrouk medium.
3. **Biomass Production Cost Normalized:**
    - For *A. platensis* in Zarrouk medium (\text{Yield} = 3.84\,\text{kg}\cdot\text{m}^{-3}): Media cost per kg dry biomass = \$9.09 / 3.84\,\text{kg} = \mathbf{\$2.37\ \text{per kg DCW}}.
    - For *Synechocystis* sp. PCC 6803 in BG-11 medium (\text{Yield} = 1.96\,\text{kg}\cdot\text{m}^{-3}): Media cost per kg dry biomass = \$1.50 / 1.96\,\text{kg} = \mathbf{\$0.77\ \text{per kg DCW}}.

This economic reality highlights a primary commercial challenge: while Zarrouk medium supports high growth rates and contamination control for *A. platensis*, its high salt content increases production costs. As a result, industrial *Spirulina* producers often investigate modified media formulations that reduce \text{NaHCO}_3 content (e.g., integrating gaseous \text{CO}_2 injection systems paired with lower carbonate buffer concentrations) to lower input costs while maintaining alkaline pH regimes.

5. CONCLUSION

This study presents a comparative evaluation of Zarrouk and BG-11 growth media across four morphologically and ecologically distinct cyanobacterial strains (*Arthrospira platensis* SAG 21.99, *Synechocystis* sp. PCC 6803, *Anabaena cylindrica* SAG 1403-1b, and *Nostoc muscorum* Kazakh-102). The key empirical findings and practical recommendations are summarized as follows:

1. Strict Media Specificity for Obligate Strains:
    - *Arthrospira platensis* requires the high-bicarbonate, high-salinity, and strongly alkaline environment of Zarrouk medium to achieve high performance (\text{DCW} = 3.84 \pm 0.12\,\text{g}\cdot\text{L}^{-1}, \mu_{\max} = 0.312 \pm 0.011\,\text{day}^{-1}, Phycocyanin = 142.60 \pm 4.20\,\text{mg}\cdot\text{g}^{-1}). BG-11 medium fails to support viable growth, causing cell lysis and loss of helical structure.
    - Unicellular *Synechocystis* sp. PCC 6803 and heterocystous *Anabaena cylindrica* perform optimally in lower-salinity BG-11 medium (\text{DCW} = 1.96\,\text{g}\cdot\text{L}^{-1} and 1.68\,\text{g}\cdot\text{L}^{-1}, respectively). Inoculating these strains into Zarrouk medium induces severe osmotic shock, ion toxicity, extended lag phases, or culture death.
2. Ecological Adaptability of Soil Isolates:
    - *Nostoc muscorum* Kazakh-102 exhibits broad osmotolerance, achieving viable biomass accumulation in both BG-11 (\text{DCW} = 1.54\,\text{g}\cdot\text{L}^{-1}) and Zarrouk (\text{DCW} = 1.12\,\text{g}\cdot\text{L}^{-1}) media. This physiological flexibility is attributed to protective extracellular polymeric substance (EPS) capsular sheaths and compatible solute synthesis.
3. Photosynthetic Pigment Modulation:
    - Zarrouk medium maximizes phycobiliprotein (specifically C-phycocyanin) production in alkaliphilic strains, whereas BG-11 supports higher per-cell chlorophyll-a and carotenoid accumulation in freshwater strains. Carotenoid-to-chlorophyll ratios increase under non-optimal high-salinity conditions, serving as an indicator of physiological photoprotection.
4. Practical Recommendations for Cyanobacterial Biotechnology:
    - For Commercial Phycocyanin and High-Protein *Spirulina* Production: Zarrouk medium remains the benchmark formulation due to its high productivity and built-in protection against biological contamination. However, to improve process economics, future research should focus on partial bicarbonate substitution combined with automated \text{CO}_2 pH-stat gas sparging.
    - For Freshwater Biofuel Feedstock and Genetics Platforms (*Synechocystis*, *Anabaena*): BG-11 medium is the recommended formulation, providing an optimal ionic balance that minimizes osmotic stress while supporting high specific growth rates.

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UNUSUAL PATTERNS OF HUMAN GROWTH AND AGING

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1. Abstract and scope

Unusual patterns of human growth and aging challenge the assumption that chronological age, physical appearance, developmental stage, and biological aging move together in a uniform way. Some children develop features associated with old age unusually early; some individuals grow very little because of endocrine, genetic, nutritional, or systemic disease; and a small number of rare developmental conditions preserve an infant-like appearance or produce profound impairment of maturation. These phenomena are often described informally as “not aging,” “remaining a baby,” or “aging in reverse,” but these phrases can conceal important biological differences.

This review examines documented clinical patterns relevant to those descriptions: Hutchinson–Gilford progeria syndrome, Werner syndrome, severe growth disorders, disorders of thyroid or growth-hormone signaling, and rare neurodevelopmental conditions involving profound developmental impairment. It also considers the distinction between visible appearance and underlying physiological aging. Case descriptions are presented as representative patterns from published literature, not as claims that a specific unidentified person has been diagnosed. No single case can establish a universal mechanism.

The central hypothesis is that apparently anomalous aging is best understood as a set of partially independent biological processes—somatic growth, sexual maturation, tissue maintenance, cellular senescence, cognition, and organ-specific decline—that may become uncoupled in rare conditions. This framework predicts that a person may appear young while having age-related organ changes or appear prematurely old while retaining many functions usually associated with youth.

The evidence base is uneven. Rare disorders are often represented by case reports, small cohorts, or registries, and unusual descriptions circulating outside medical literature may lack verified diagnoses. Accordingly, the article distinguishes established findings from plausible interpretations and explicitly identifies unanswered questions. It is a narrative scientific review, not a systematic review or clinical guideline. Diagnosis of a child with poor growth or arrested development requires individualized medical assessment; neither appearance nor a single laboratory value is sufficient to determine the cause.

Keywords: biological aging; growth failure; progeria; developmental delay; endocrine disorders; genomic instability; rare disease.

2. What does “aging” mean?

Aging is not one measurable event. Chronological age counts time since birth, whereas biological aging refers to changes in molecular damage, tissue function, physiological reserve, and vulnerability to disease. Development is a separate process: infants acquire motor, language, social, and cognitive abilities through interacting genetic, neurological, endocrine, nutritional, and environmental influences. Linear growth describes changes in height and skeletal size, while puberty involves a distinct sequence of hormonal and reproductive changes. These processes are related but not interchangeable.

A person who remains very short is not necessarily biologically young. Growth can be limited by inadequate nutrition, chronic illness, skeletal dysplasia, endocrine deficiency, or genetic variants affecting growth pathways. Conversely, a person with a youthful face may have ordinary internal aging, and a child with progeria may show premature vascular and connective-tissue pathology while retaining normal cognitive development. “Aging” therefore must be specified: which tissue, function, or biomarker is changing, and compared with what reference population?

Modern geroscience describes several interacting processes, including genomic instability, epigenetic alteration, loss of proteostasis, mitochondrial dysfunction, cellular senescence, altered nutrient sensing, stem-cell exhaustion, and chronic inflammation (López-Otín et al., 2013). No single marker captures the whole organism. Epigenetic clocks estimate aspects of biological age from DNA methylation, but they are not definitive diagnostic tests for every rare developmental condition, and results may differ by tissue and method.

A rigorous investigation of an apparent “non-aging” case should document height, weight, head circumference, skeletal maturation, pubertal stage, developmental milestones, organ function, imaging, genetics, and longitudinal change. Repeated measurements matter more than a single photograph or observation. A child whose size changes little over several years may have severe growth failure, but the reason could be entirely different from the reason for an infant-like facial appearance.

The key conceptual point is that growth arrest is not age arrest. The organism continues to experience time, cellular turnover, exposures, and disease even when outward growth is limited. Likewise, premature aging syndromes do not reproduce every aspect of ordinary aging. They are better understood as segmental disorders that disproportionately affect selected biological systems (Fig. 1).

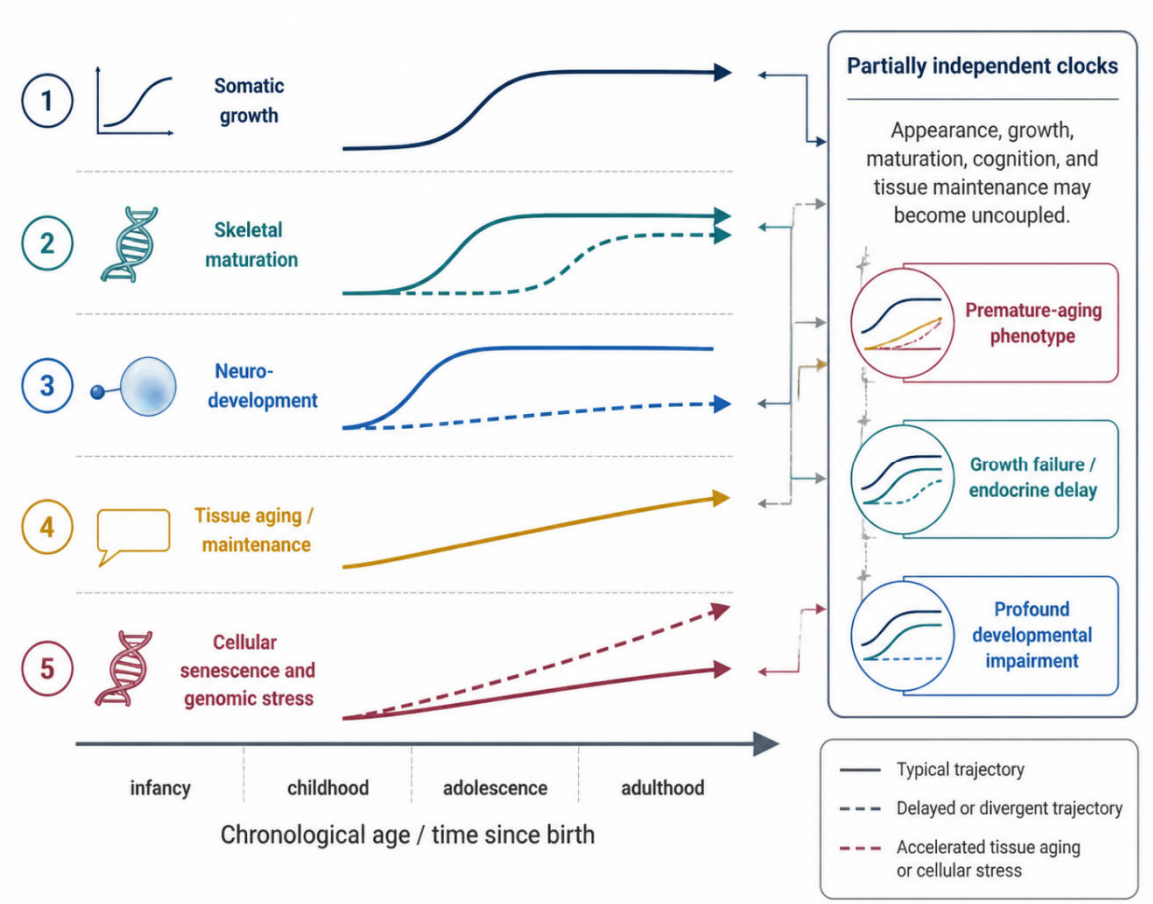


Figure 1. Conceptual framework illustrating the partial independence of chronological age and biological trajectories. Somatic growth, skeletal maturation, neurodevelopment, tissue maintenance, and cellular senescence/genomic stress may progress at different rates and become uncoupled. Solid lines represent typical trajectories, dashed lines represent delayed or divergent trajectories, and burgundy lines represent accelerated tissue aging or cellular stress. The schematic illustrates patterns associated with premature-aging phenotypes, growth failure or endocrine delay, and profound developmental impairment. These relationships are conceptual and are not intended to establish a diagnosis in any individual.

3. Evidence standards and case interpretation

Claims that a person “stayed a baby” require unusually careful verification. A scientifically useful case report needs a clear chronology, objective anthropometric measurements, clinical examination, relevant laboratory tests, imaging when appropriate, and ideally molecular diagnosis. The report should distinguish a person’s actual developmental status from their appearance in photographs, clothing, or family descriptions. A face that appears infant-like does not prove that the brain, skeleton, hormones, or internal organs have remained in an infant state (Gagnier et al., 2013).

Case reports are valuable when a condition is exceptionally rare, but they have limits. They can identify a phenotype and generate hypotheses, yet they cannot by themselves establish prevalence, prognosis, or causation. Referral bias may make severe cases more visible, and unusual cases are more likely to be published than ordinary or ambiguous ones. Historical reports may lack modern genetic testing, standardized growth charts, or complete follow-up. For these reasons, an old description should not be retroactively assigned a modern diagnosis without adequate evidence.

For the purposes of this review, findings are grouped into three levels. First, established mechanisms are supported by repeated clinical observations and molecular evidence, as in many

cases of Hutchinson–Gilford progeria. Second, supported but incomplete explanations are consistent with existing data but do not account for every feature. Third, speculative hypotheses are testable proposals that should not be mistaken for clinical facts. Each hypothesis should identify observations that would support or weaken it.

Ethical issues also matter. Rare patients can be identifiable even when names are omitted. Descriptions should avoid sensationalism, stigmatizing language, or treating a person as a curiosity. “Atypical growth” or “profound developmental impairment” is more precise than “frozen baby.” Reports should protect privacy and acknowledge the person’s agency and family context.

A further distinction is needed between verified clinical cases and internet anecdotes. Viral stories may omit age, diagnosis, medical records, or later outcomes. A responsible review can discuss the general medical possibilities behind such descriptions, but cannot claim to explain a particular person without reliable case information. This restraint is not a weakness: it is part of scientific accuracy. Where the evidence is missing, the correct conclusion is that the case remains unverified (Fig. 2).

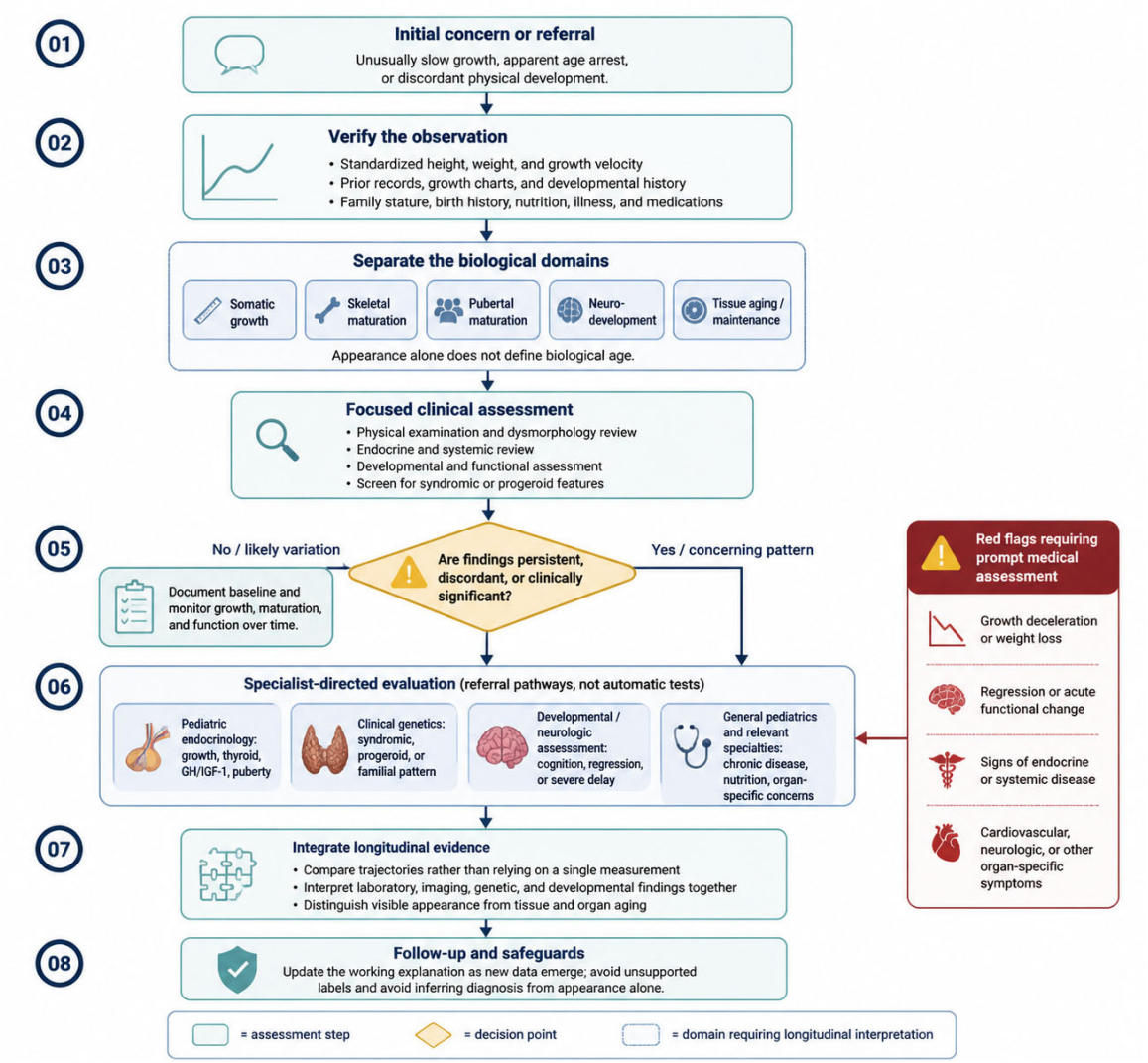


Figure 2. Proposed clinical workflow for the evaluation of unusually slow growth or apparent age arrest

The proposed workflow comprises eight sequential stages: initial clinical concern or referral; verification of growth and developmental observations using standardized anthropometric measurements, longitudinal growth records, and relevant medical history; separation of biological domains, including somatic growth, skeletal maturation, pubertal maturation, neurodevelopment, and tissue maintenance; focused clinical assessment; evaluation of the persistence, discordance,

and clinical significance of the findings; specialist-directed assessment; integration of longitudinal clinical, laboratory, imaging, genetic, and developmental data; and continued follow-up with appropriate clinical safeguards. Findings consistent with likely biological variation are documented and monitored over time, whereas persistent or clinically concerning patterns prompt referral to pediatric endocrinology, clinical genetics, developmental or neurologic services, or other relevant specialties. The workflow emphasizes that physical appearance alone is insufficient to define biological age or establish a diagnosis. Red flags requiring prompt medical evaluation include growth deceleration or weight loss, developmental regression or acute functional deterioration, signs of endocrine or systemic disease, and cardiovascular, neurologic, or other organ-specific symptoms. Rounded rectangles represent assessment steps, the diamond represents the clinical decision point, and the dashed-outline box represents a biological domain requiring longitudinal interpretation. GH, growth hormone; IGF-1, insulin-like growth factor 1.

4. Hutchinson–Gilford progeria syndrome

Hutchinson–Gilford progeria syndrome (HGPS) is among the best-characterized examples of premature aging in childhood. Affected children often appear typical at birth, then develop poor weight gain, growth deficiency, loss of subcutaneous fat, hair loss, tight or sclerodermatous skin, joint limitations, and distinctive facial features. Severe cardiovascular disease is a major cause of morbidity and early mortality. Despite these physical changes, cognitive development is generally preserved (Hennekam, 2006; Gordon et al., 2008).

Most classic cases are associated with a de novo variant in LMNA, which encodes lamin A, a structural protein important to the nuclear envelope. The common variant promotes production of progerin, an abnormal protein that remains abnormally farnesylated and disrupts nuclear structure and cellular function. Studies have implicated altered gene regulation, DNA damage responses, telomere biology, and vascular smooth-muscle-cell dysfunction, although the full chain from mutation to every clinical feature is not completely resolved (Gordon et al., 2014; Harhous et al., 2019).

HGPS does not mean that a child has become old in every respect. Rather, selected tissues develop pathologies that resemble aspects of aging, particularly vascular disease and changes in connective tissue. Children with HGPS are not cognitively equivalent to elderly adults, and the syndrome does not reproduce the usual sequence of adult aging. It is a segmental progeroid condition.

This syndrome helps clarify the question posed by reports of children who “age strangely.” The best-documented dramatic deviation is often acceleration of some aging-related processes, not a complete pause or reversal of time. Clinical monitoring focuses on cardiovascular health, growth, nutrition, joint function, and other complications. Lonafarnib has been shown to improve outcomes, but treatment does not remove all disease risk (Gordon et al., 2018).

An unresolved question is why tissues differ so much in vulnerability. Vascular smooth muscle, bone, skin, and adipose tissue are affected in characteristic ways, while other systems are relatively spared. Understanding this selectivity may reveal how nuclear architecture interacts with mechanical stress, gene expression, and tissue-specific repair. HGPS is therefore informative for aging research, but it should not be treated as a miniature or accelerated version of normal aging.

5. Werner syndrome and adult-onset progeroid features

Werner syndrome is a rare autosomal recessive disorder in which signs associated with aging typically emerge after puberty rather than in infancy. Individuals may fail to experience the normal adolescent growth spurt and later develop premature graying and thinning of hair, skin atrophy, cataracts, diabetes, osteoporosis, infertility, characteristic ulcers, and increased risk of certain cancers. The syndrome is often described as segmental progeria because multiple tissues show

early degenerative changes without reproducing all aspects of ordinary aging (Oshima et al., 2017).

The underlying cause is usually pathogenic variation in WRN, which encodes a RecQ-family helicase involved in DNA replication, repair, recombination, and maintenance of chromosome stability. When WRN function is lost, cells can accumulate genomic instability and show abnormalities in replication and repair. These mechanisms connect Werner syndrome to broader theories of aging in which long-term maintenance of the genome is essential to tissue function.

The clinical pattern differs from HGPS. Werner syndrome is often not obvious during early childhood; the lack of a pubertal growth spurt may be an early clue, while skin and metabolic features emerge later. This distinction matters when interpreting stories of a child who never grows: some conditions affect growth from infancy, while others become apparent around adolescence. The same outward label—"stunted growth"—can refer to very different developmental trajectories.

Werner syndrome also illustrates that premature aging is not simply accelerated passage through every life stage. Cognitive development may be broadly typical, while selected tissues experience early pathology. Its mechanisms have helped researchers investigate the role of DNA maintenance in age-related disease, but the syndrome alone cannot explain all causes of ordinary aging.

Important unanswered questions include why specific tissues are particularly vulnerable, how modifier genes and environmental exposures affect severity, and why individuals with similar variants may differ in complications. Because the disorder is rare, many studies involve small cohorts. International registries and standardized longitudinal assessments are needed to improve estimates of natural history and treatment effects. The broader lesson is that aging-like changes can arise through identifiable molecular pathways, yet their distribution across organs remains complex.

6. When a child remains unusually small: growth failure

A child who remains close to infant size may have severe growth failure, but this is not equivalent to remaining biologically an infant. Clinicians evaluate growth through serial measurements of length or height, weight, head circumference, growth velocity, and position on age- and sex-appropriate growth charts. A single measurement is less informative than the pattern over months or years. Birth history, parental heights, nutrition, chronic disease, medications, and developmental milestones all influence interpretation.

Potential causes include insufficient energy intake, malabsorption, chronic inflammatory disease, kidney or heart disease, hypothyroidism, growth hormone deficiency, genetic syndromes, and skeletal disorders. Some children have proportionate short stature, while others have differences in limb length, trunk size, or head growth. The pattern can help guide testing, but no one physical feature is diagnostic (de Onis and Branca, 2016).

Severe growth failure can coexist with cognitive disability, but the two are not necessarily causally linked. Some endocrine conditions affect height while leaving cognition largely intact if recognized and treated. Conversely, certain genetic or neurological conditions affect development more broadly. It is therefore important not to infer a child's intellectual abilities from size or appearance.

A useful hypothesis is that reports of "remaining a baby" may combine several different clinical categories: marked short stature, delayed bone age, delayed puberty, a congenital syndrome with distinctive facial features, and profound developmental impairment. The hypothesis predicts that objective records will separate cases that look similar in photographs. It can be tested by comparing growth trajectories, skeletal age, hormone results, genetic findings, and adaptive functioning.

Growth hormone should not be assumed to be the solution. Treatment is appropriate for selected diagnoses and requires specialist assessment; it does not correct every genetic or systemic cause of short stature. Likewise, growth hormone testing and interpretation are technically complex.

The relevant scientific question is not simply why a child is small, but which biological process is limiting growth and whether other systems are affected. If a real child shows stalled growth, urgent medical evaluation is more appropriate than trying to diagnose the condition from an anecdote (Grimberg et al., 2016) (Fig. 3).

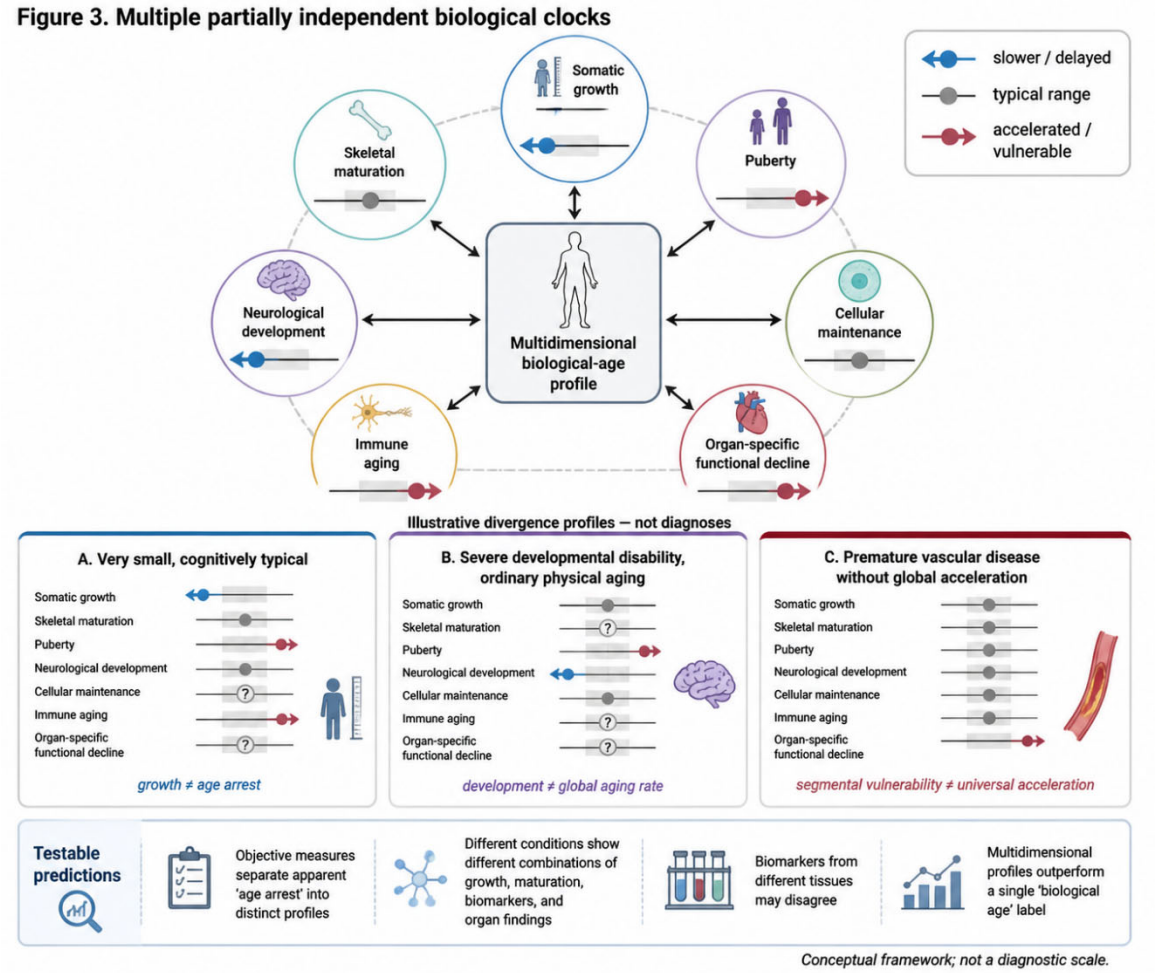


Figure 3. Multiple partially independent biological clocks. Conceptual model illustrating that somatic growth, skeletal maturation, puberty, neurological development, cellular maintenance, immune aging, and organ-specific functional decline are related but partially independent processes. The central multidimensional biological-age profile emphasizes that these domains may interact without progressing at the same rate. Blue markers indicate slower or delayed trajectories, gray markers indicate values within a typical range, and burgundy markers indicate accelerated or vulnerable trajectories. The lower panels show illustrative divergence profiles rather than diagnostic categories: (A) markedly reduced somatic growth with relatively typical cognitive or neurological development; (B) severe developmental impairment with otherwise ordinary physical aging; and (C) premature vascular or organ-specific disease without generalized acceleration of all aging processes. The framework predicts that objective assessment may distinguish apparently similar reports of "age arrest" into different combinations of growth velocity, skeletal age, pubertal development, endocrine function, developmental functioning, tissue-specific biomarkers, and organ pathology. It further predicts that biomarkers obtained from different tissues may provide discordant estimates and that multidimensional profiles may be more informative than a single biological-age measure. This figure presents an organizing hypothesis and is not intended to function as a diagnostic scale.

7. Endocrine mechanisms: thyroid, growth hormone, and IGF-1

Endocrine signaling coordinates growth and maturation. Thyroid hormones are essential for normal brain development and skeletal growth, while growth hormone (GH) and insulin-like growth factor 1 (IGF-1) contribute to linear growth, tissue metabolism, and changes during childhood and puberty. Severe untreated congenital hypothyroidism can impair growth and neurodevelopment; early screening and treatment substantially reduce preventable harm (Rastogi and LaFranchi, 2010). GH deficiency can slow linear growth, but its clinical effects vary with age of onset, severity, and the condition of other pituitary hormones (Rosenfeld and Hwa, 2009).

GH and IGF-1 signaling also appear in research on aging. In animal models, reduced signaling in some pathways can extend lifespan and improve resistance to selected age-related diseases. Human evidence is more complicated: people with GH deficiency or resistance do not uniformly live longer, and protection from some diseases does not imply global slowing of biological aging (Junnila et al., 2013; Bartke and Darcy, 2017). These findings should not be used to suggest that inducing hormone deficiency is a safe anti-aging strategy.

Laron syndrome, a form of GH insensitivity commonly associated with GHR variants, can cause severe short stature despite circulating GH. This illustrates why hormone concentration alone does not describe the whole pathway: the receptor and downstream signaling matter. Some cohorts have reported low rates of certain diseases, including cancer and diabetes, but the relationship between altered IGF-1 signaling and human lifespan remains unsettled (Laron, 2004; Guevara-Aguirre et al., 2011).

One hypothesis is that some extreme growth phenotypes arise from a developmental pathway being selectively disrupted while other maintenance systems remain relatively functional. If so, a person could be very small without showing the broad cellular pathology of a progeroid syndrome. This can be tested by comparing endocrine profiles, organ health, molecular markers, and longitudinal outcomes across diagnoses.

Unanswered questions include how local tissue signaling differs from blood hormone levels, how childhood growth pathways affect adult health, and whether any molecular signature reliably predicts the balance between disease protection and adverse effects. These are research questions, not grounds for hormone treatment in otherwise healthy people.

8. Delayed skeletal maturation and puberty

Skeletal maturation is commonly estimated from radiographs of the hand and wrist. Bone age can be delayed relative to chronological age in constitutional delay, endocrine disorders, chronic disease, undernutrition, and some genetic conditions. A delayed bone age may indicate that skeletal development is proceeding more slowly, but it does not mean that the entire organism has stopped aging. The brain, immune system, and internal organs do not necessarily share the same developmental timetable.

Constitutional delay of growth and puberty is one relatively common pattern. Children may be shorter than peers for a period and enter puberty later, then continue growing for longer and often approach a height consistent with family background. This is different from permanent growth arrest. The diagnosis depends on clinical history, growth velocity, family pattern, physical examination, and exclusion of relevant disease (Palmert and Dunkel, 2012).

Other conditions can cause persistent delays. Hypothyroidism, inadequate nutrition, chronic inflammation, hypogonadism, and some genetic disorders can affect bone age and pubertal progression. In certain syndromes, delayed puberty occurs alongside short stature and developmental differences. Distinguishing these possibilities matters because some causes are treatable and some require long-term monitoring.

A testable hypothesis is that reports of children who “never grow up” sometimes reflect an observer’s focus on delayed skeletal or sexual maturation rather than a true cessation of all

biological development. Longitudinal data should show whether height, bone age, hormones, and developmental milestones remain static together or diverge. The latter would support a model of asynchronous maturation.

There are limitations to bone-age assessment: readings have inter-observer variability, reference standards may not fit every population equally well, and skeletal age is only one component of development. It should not be interpreted in isolation. The unanswered scientific question is how to integrate multiple developmental clocks into a reliable profile for rare and complex cases. A more comprehensive model would combine skeletal maturation, endocrine function, molecular markers, and functional development, while acknowledging that no current measurement captures “biological age” in its entirety.

9. Profound developmental impairment and infant-like appearance

Some rare neurological and genetic conditions involve profound developmental impairment, limited speech, severe motor disability, or distinctive facial and behavioral features. A person may consequently appear much younger than their chronological age to an unfamiliar observer. This appearance can be intensified by short stature, limited mobility, dependence on caregivers, or atypical skeletal development. However, infant-like appearance is not evidence that a person has literally remained at an infant developmental stage in every biological system.

Developmental disorders are heterogeneous. Some primarily affect motor function; others affect cognition, communication, growth, or several domains together. Even where learning is profoundly limited, individuals may continue to undergo physical maturation, experience puberty, develop medical complications, and age. Their support needs may remain high across the lifespan, but this should not be confused with arrested aging (Moeschler and Shevell, 2014).

A careful clinical description separates chronological age, physical growth, cognitive and adaptive functioning, communication, pubertal development, and medical comorbidities. These domains may diverge. For example, a person might have severe intellectual disability with relatively typical physical growth, or marked short stature with relatively preserved cognition. The term “developmental age” can be misleading if used as though it were a single biological quantity.

A hypothesis relevant to informal reports is that a perceived “permanent baby” phenotype often reflects the combination of appearance and functional dependence rather than an absence of aging. The hypothesis can be evaluated through medical records and longitudinal assessment, not photographs alone. If a case also has unusual skin, bone, vascular, or metabolic findings, a separate diagnosis affecting biological aging should be investigated rather than assumed.

Ethical communication is essential. People with disabilities should not be reduced to their resemblance to infants, and the language used should not obscure adult rights, preferences, or dignity. Research remains limited for many ultra-rare developmental syndromes, particularly regarding adult outcomes and age-related disease. Better natural-history studies are needed to learn whether specific syndromes alter typical aging trajectories, or whether apparent differences are primarily consequences of disability, treatment, mobility, and associated illness.

10. Atypical cases and how to interpret them

Published case literature contains people with unusual combinations of short stature, delayed maturation, distinctive appearance, and developmental disability. These cases are scientifically useful when they are documented well enough to establish what is actually unusual. However, a dramatic description is not itself a diagnosis. The review cannot responsibly attribute a particular viral or unnamed story to a disease without records or a reliable published report.

Three broad case patterns illustrate the reasoning. In the first, a child has profound growth failure from infancy, low weight, and progressive loss of body fat. This pattern raises questions about systemic disease, endocrine disorders, genetic syndromes, and progeroid conditions; serial growth records and examination of multiple organ systems are essential. In the second, a child is very small but has stable health, delayed bone age, and later pubertal progression. This may be more

consistent with delayed maturation or a growth-related condition than with aging arrest. In the third, an older individual has an infant-like face or limited adaptive functioning, yet shows ordinary physical aging. Here, appearance and developmental disability may explain the impression without a biological pause.

These are illustrative clinical patterns, not three invented patient histories. A real case report should include age, sex where clinically relevant, family history, growth measurements, developmental milestones, endocrine testing, imaging, genetics, and follow-up. Negative findings matter too: they can help distinguish syndromes that share visible traits.

The working hypothesis is that a subset of purported "aging anomalies" reflects a mismatch between the observer's intuitive age judgment and the patient's actual developmental biology. Another subset reflects genuine pathological uncoupling among growth, maturation, and tissue aging. These explanations are compatible rather than mutually exclusive.

The most important unanswered issue is how often each pattern occurs outside specialist clinics. Because extraordinary stories attract attention, there may be strong selection bias toward dramatic examples. Population-based registries, standardized terminology, and careful follow-up would help distinguish rare biological phenomena from misclassification. Until that evidence exists, conclusions should remain proportional to the quality of documentation.

11. Cellular senescence and tissue-specific aging

Cellular senescence is a state in which cells stop dividing in response to stress or damage while remaining metabolically active. Senescent cells can release inflammatory and tissue-modifying factors, sometimes described as the senescence-associated secretory phenotype. Senescence can help suppress tumors and support wound healing, but persistent accumulation may contribute to tissue dysfunction. It is one of several mechanisms implicated in aging, not a complete explanation by itself (López-Otín et al., 2013; Campisi and d'Adda di Fagagna, 2007).

Progeroid syndromes have helped identify how defects in nuclear structure, DNA repair, and telomere maintenance can disrupt cell function. In HGPS, progerin alters nuclear architecture and affects several cellular processes. In Werner syndrome, loss of WRN function compromises genome maintenance. These disorders demonstrate that different molecular disruptions can converge on some similar outward features, such as skin changes, vascular disease, and altered growth, while still having distinct clinical patterns.

A theoretical possibility is that some rare developmental conditions preserve selected cellular functions while impairing growth or differentiation. For example, a pathway could be necessary for tissue expansion but less critical for short-term maintenance of certain mature cells. Such a model might help explain why reduced body size does not automatically imply accelerated aging. Yet it would be premature to infer cellular youth from small size or low hormone levels.

Testing this hypothesis requires direct evidence: cell samples from relevant tissues, molecular assays, longitudinal clinical outcomes, and comparisons with appropriate controls. Blood-based markers may not reflect the state of bone, brain, skin, or vascular tissue. Moreover, cell culture can alter cellular behavior, so findings should be validated in clinically relevant contexts.

A major unanswered question is whether there are human conditions that genuinely slow multiple components of biological aging while leaving development intact, rather than merely protecting against selected diseases. Evidence from animals and human genetic cohorts offers clues, but no simple biomarker currently establishes whole-body age arrest. A further challenge is separating primary effects of a mutation from secondary effects of poor nutrition, immobility, medication, and chronic disease. The most defensible approach treats cellular senescence as one mechanistic layer among many.

12. Telomeres, DNA repair, and genomic instability

Telomeres are repetitive DNA-protein structures at chromosome ends that help protect genetic material. In many dividing cells, telomeres shorten over time, although the rate depends on cell

type, replication history, inflammation, and other factors. Telomere biology is relevant to some aging processes, but telomere length is not a universal clock: different tissues and individuals show substantial variation, and long telomeres do not guarantee health or longevity (Shay and Wright, 2019).

DNA repair pathways preserve genomic integrity after damage from normal metabolism, replication errors, and environmental exposures. Werner syndrome provides a clear example of how disruption of a genome-maintenance protein can cause premature degenerative features. HGPS, though mechanistically distinct, also involves nuclear abnormalities and genome-related stress. Together, these syndromes support the proposition that maintaining DNA and chromosome organization is important for long-term tissue function (Oshima et al., 2017; Harhous et al., 2019).

Could unusually slow growth reflect a mechanism that also reduces cellular aging? This is an attractive but unproven hypothesis. Reduced cell proliferation could reduce some replication-associated stress in certain contexts, yet it could also impair tissue repair, immune function, and organ development. The consequences depend on which pathway is altered and at what stage of life. A simplistic equation—slower growth equals slower aging—does not fit the evidence.

A strong study would compare individuals with different growth disorders using multiple measures: telomere length in specified cell populations, DNA-damage markers, epigenetic age estimates, immune function, metabolic profiles, and longitudinal clinical outcomes. Researchers would need age-matched controls and careful adjustment for disease severity, medications, and nutrition. A single telomere result would not establish a generalized anti-aging state.

Important questions remain about the relationship between genomic instability and organ-specific disease. Why does a defect produce cataracts in one syndrome, severe vascular disease in another, or prominent skin changes in a third? How much is determined by tissue-specific gene expression, mechanical demand, stem-cell reserve, or environmental exposure? These questions are especially difficult in rare disorders because sample sizes are small. Collaborative registries and shared protocols may be essential to answer them.

13. Epigenetic clocks and the limits of biological-age measurement

Epigenetic clocks estimate age-related patterns from DNA methylation at selected genomic sites (Horvath, 2013). Other proposed measures include transcriptomic profiles, proteomic panels, inflammatory markers, immune-cell composition, and composite clinical indices. These tools have improved research into biological aging, but they answer different questions and should not be treated as interchangeable. A clock trained to predict chronological age in healthy adults may behave unexpectedly in a child with a rare genetic syndrome or in a tissue with unusual cell composition.

For a person described as “not aging,” the crucial issue is not whether one laboratory score is low. Researchers would need to determine whether the measure has been validated for the person’s age group, tissue, and disease. They would also need repeated samples over time and clinical outcomes. A lower predicted age on one assay could reflect disease-specific methylation patterns rather than slower aging across the body.

Children pose particular challenges because developmental changes are rapid and distinct from adult aging. A molecular signature associated with childhood maturation may not be directly comparable with a clock designed for adults. Similarly, progeroid syndromes may alter some biomarkers disproportionately. Such findings can be informative, but interpretation requires disease-specific validation.

A testable hypothesis is that rare conditions create divergent biological-age signals across tissues: a blood-based clock might suggest one trajectory, while vascular, skin, or skeletal measures indicate another. Multi-tissue sampling could test this prediction, although invasive sampling and

small patient populations present ethical and practical limits. Researchers should prioritize clinically meaningful questions and avoid testing that cannot improve understanding or care.

The unresolved question is whether a robust, validated panel can distinguish slowed development from slowed aging in rare pediatric conditions. Ideally, such a panel would include molecular markers, organ function, and longitudinal health outcomes. It would not reduce the person to a single numerical "age." Until validation improves, biological-age clocks should be treated as research instruments, not definitive tests for claims that a person has remained biologically young.

14. Nutrition, chronic illness, and environmental factors

Nutrition and general health strongly influence growth. Inadequate energy or protein intake, micronutrient deficiencies, malabsorption, chronic infection, and inflammatory disease can reduce weight gain and linear growth. These influences may be reversible, partly reversible, or associated with lasting effects depending on timing and severity. They do not generally imply that biological aging has stopped; rather, they may disrupt normal development while exposing tissues to illness and physiological stress (Black et al., 2013).

Environmental factors can also interact with genetic susceptibility. Prenatal growth restriction, premature birth, chronic stress, and some medications may influence developmental trajectories. The effect depends on the specific exposure, dose, timing, and the child's baseline health. A responsible case assessment therefore includes prenatal and birth history, feeding history, family context, medical conditions, and social determinants of health without assuming blame.

One hypothesis is that some historical reports of unusually small children reflect prolonged untreated disease or deprivation rather than a rare "anti-aging" mechanism. This is plausible in principle, but it cannot be applied to any particular case without evidence. Medical documentation, growth charts, and records of living conditions would be needed to evaluate it. The same caution applies in the opposite direction: not every unexplained case should be attributed to environment when a genetic cause may exist.

Researchers must also consider reverse causation. A child's underlying disorder may cause feeding difficulties and poor growth, so low weight is not necessarily the primary cause. In adults, chronic disease can make a person look older, while some treatments can change appearance without altering underlying aging. These complexities make observational associations difficult to interpret.

Unanswered questions include how early-life adversity interacts with rare genetic variants, whether growth recovery normalizes long-term biological markers, and which developmental effects persist after the original cause is treated. Longitudinal cohort studies are best suited to these questions. Clinically, poor growth deserves prompt evaluation because treatable causes can be missed when a striking appearance is assumed to represent a rare syndrome.

15. Could biological aging ever be broadly slowed?

Human aging research has identified genetic and environmental pathways that influence lifespan in model organisms. Alterations in insulin/IGF-1 signaling, nutrient sensing, stress responses, and cellular maintenance can affect longevity in animals. In humans, however, lifespan is shaped by many interacting genes, exposures, behaviors, social conditions, and medical interventions. A result in yeast, worms, flies, or mice cannot be directly assumed to apply to people.

Some human genetic conditions provide natural experiments. Reduced GH signaling has been associated with protection from selected diseases in certain cohorts, while not consistently demonstrating extended lifespan. Progeroid syndromes show the opposite pattern in selected tissues: severe pathology emerges early. These observations suggest that aging-related pathways can be modified, but they also demonstrate trade-offs. Growth, reproduction, metabolism, immune defense, cancer risk, and tissue repair share biological machinery.

A speculative hypothesis is that rare individuals may possess combinations of variants that preserve tissue maintenance while reducing specific age-related disease risks. Such a phenotype

would not necessarily involve remaining physically young or having a childlike appearance. It would require evidence of slower decline across multiple clinically meaningful domains, adjusted for chronological age and lifestyle. No claim of extraordinary biological youth should rest solely on appearance, short stature, or a single biomarker.

Research should distinguish lifespan from healthspan. Living longer with severe disability is not the same as delaying disease, and protection against cancer may not protect against cardiovascular or neurodegenerative disease. It is also important to consider sex differences, ancestry, socioeconomic conditions, and access to healthcare when interpreting longevity cohorts.

Major unanswered questions include which interventions can safely modify human aging, whether effects vary by life stage, and how to measure benefit over decades. There is currently no established intervention that reliably arrests human aging. Growth hormone and other hormonal treatments should not be used as general anti-aging therapies without an evidence-based indication; they can have meaningful adverse effects. The scientific goal is not to freeze people at a developmental stage, but to preserve health and function while respecting the complexity of human biology.

16. A unified hypothesis: multiple biological clocks

The evidence reviewed here supports a model of multiple partially independent biological clocks. These include somatic growth, skeletal maturation, puberty, neurological development, cellular maintenance, immune aging, and organ-specific functional decline. They interact, but they do not necessarily proceed at the same rate. This model can explain why a person may be very small but cognitively typical, have severe developmental disability but ordinary physical aging, or show premature vascular disease without a globally accelerated decline in every system.

The hypothesis generates several predictions. First, cases described as “remaining a baby” will separate into distinct profiles when objectively measured. Second, different conditions will show different combinations of growth velocity, bone age, endocrine function, cognitive and adaptive functioning, molecular biomarkers, and organ pathology. Third, within a single individual, biomarkers from different tissues may disagree. Fourth, clinical outcomes will be better predicted by a multidimensional profile than by a single label such as “biological age.”

A research program could recruit patients through rare-disease registries, define standardized phenotypes, and collect longitudinal data. Core measures might include height and weight trajectories, pubertal development, skeletal age where indicated, endocrine testing, developmental assessments, cardiovascular and metabolic measures, and genetic testing. Biomarkers should be selected according to the clinical question rather than collected indiscriminately. Comparison groups would need to include healthy participants and people with other growth or developmental conditions.

This framework does not imply that all mechanisms are known. It is an organizing hypothesis designed to prevent category errors. It also allows for genuine surprises: a future case might reveal a previously unknown mutation that uncouples growth from tissue maintenance, or a pathway that protects some organs while leaving others vulnerable. Such a discovery would require replication and functional validation.

The model’s principal limitation is complexity. Many measures are influenced by disease, treatment, nutrition, and environment, and rare cases may be too few for conventional statistical analysis. Nonetheless, the framework offers a testable alternative to the vague idea of “aging anomalies.” It turns a sensational question into specific scientific questions about which systems change, when they change, and why.

17. Research design for unexplained cases

A rigorous investigation of an unexplained growth or aging phenotype should begin with a detailed clinical timeline. Researchers should record birth measurements, serial height and weight, head

circumference where relevant, developmental milestones, pubertal history, medical illnesses, medications, and family history. Photographs may help document visible change with consent, but they cannot replace measurements or examination. Reports should state which information is unavailable.

The next stage is phenotype definition. Is the principal finding severe short stature, failure to thrive, delayed bone age, delayed puberty, unusual appearance, developmental impairment, or premature organ pathology? More than one may be present. A structured phenotype prevents investigators from grouping unlike cases merely because they share an informal description. Clinical geneticists, endocrinologists, pediatricians, neurologists, and aging researchers may need to collaborate.

Genetic testing can identify known disorders, but a negative result does not prove that the condition is non-genetic. Current tests may miss certain structural variants, regulatory changes, mosaicism, or variants in genes not yet associated with a phenotype. Conversely, a variant of uncertain significance should not be presented as causal without supporting evidence. Functional studies and segregation analysis may be needed (Moeschler and Shevell, 2014).

Longitudinal follow-up is essential to distinguish delay from permanent arrest. If a child's growth is slow but continues, the trajectory differs from a true plateau. Similarly, repeated organ-function measures can show whether a biomarker predicts meaningful decline. For rare conditions, international collaboration, shared definitions, and transparent data standards can improve statistical power.

Ethics should be built into study design. Consent and assent must reflect the participant's capacity and circumstances; privacy risks are high in rare disorders. Researchers should avoid unnecessary invasive procedures, especially when results will not alter care or materially advance knowledge. Families should be told the limits of research findings and the possibility of uncertain results.

The goal is not to prove a dramatic claim, but to characterize a phenotype accurately and test competing explanations. Publishing null findings and unsuccessful genetic investigations is valuable because it reduces duplication and helps define what remains unknown (Fig. 4).

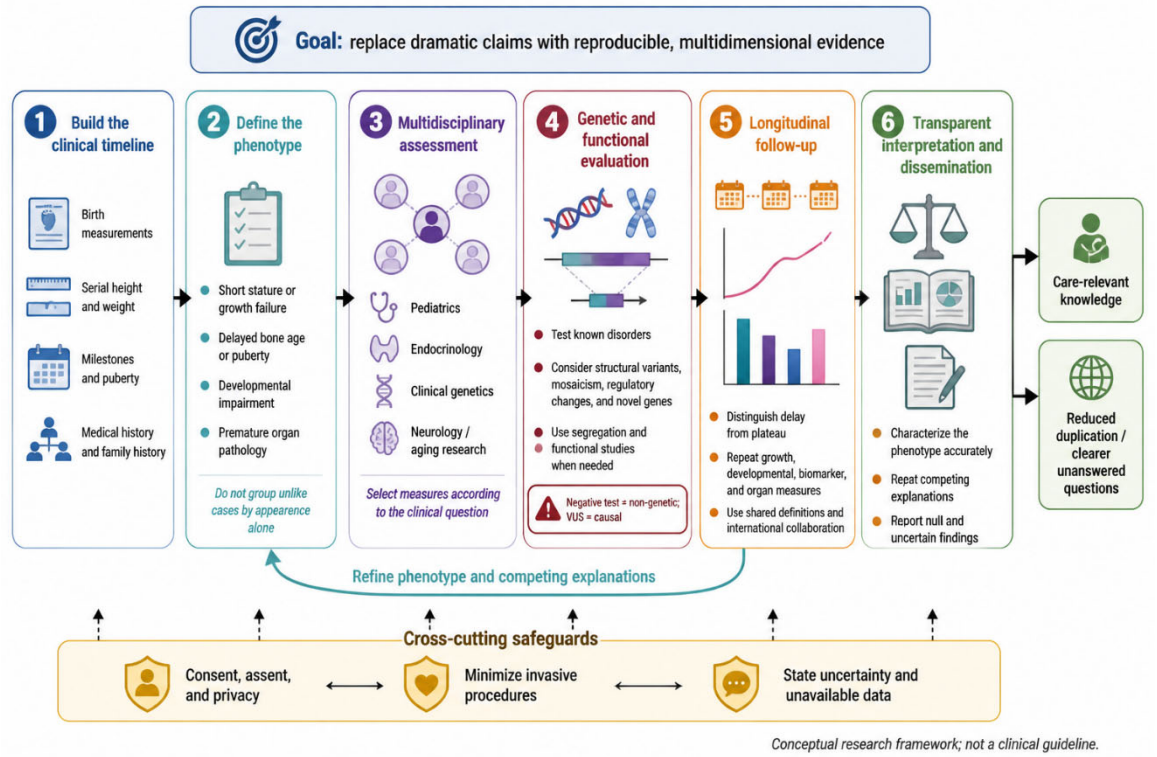


Figure 4. Research design for unexplained growth or aging phenotypes. Conceptual workflow for the rigorous investigation of unusual growth, developmental, or aging-related presentations. The process begins with construction of a detailed clinical timeline incorporating birth measurements,

serial growth data, developmental milestones, pubertal history, medical history, medications, and family history. The phenotype is then defined using explicit clinical domains, such as growth failure, delayed skeletal or pubertal maturation, developmental impairment, or premature organ pathology, rather than appearance alone. Multidisciplinary assessment supports selection of investigations according to the clinical question. Genetic evaluation should include known disorders while recognizing that negative testing does not exclude a genetic basis; structural variants, mosaicism, regulatory changes, and genes not yet associated with disease may remain undetected. Variants of uncertain significance should not be considered causal without supporting evidence. Longitudinal follow-up is required to distinguish developmental delay from permanent arrest and to relate biomarkers to clinically meaningful outcomes. The feedback loop indicates iterative refinement of the phenotype and competing explanations. Cross-cutting safeguards include consent and assent, privacy protection, minimization of invasive procedures, and explicit reporting of uncertainty and unavailable data. The framework aims to characterize phenotypes accurately, test competing explanations, and disseminate null or uncertain findings; it is not a clinical guideline.

References: Based on the supplied manuscript, “Unusual Patterns of Human Growth and Aging.”

18. Clinical implications and safeguards

The clinical implications depend on the underlying cause. A child with faltering growth may need nutritional support, endocrine evaluation, investigation for chronic disease, or genetic assessment. A child with a suspected progeroid syndrome may need coordinated monitoring for cardiovascular, skeletal, dermatological, and nutritional complications. A person with profound developmental disability may need lifelong communication support, accessible healthcare, and individualized screening for conditions that are difficult to recognize. These care pathways are not interchangeable.

Clinicians should avoid two opposite errors. The first is overdiagnosis: assigning a rare syndrome based on appearance or a dramatic family story without sufficient evidence. The second is underdiagnosis: dismissing severe growth failure as familial short stature or assuming that disability explains every new symptom. Serial measurements and a careful differential diagnosis help reduce both risks.

A claim that someone has “not aged” should prompt clarification rather than immediate acceptance or dismissal. Which feature has remained unchanged? Over what time interval? Are height, weight, bone age, cognition, puberty, and organ function all affected? Is the report based on medical records or visual impression? These questions turn an ambiguous statement into an assessable clinical description.

Families may encounter misleading claims about hormone treatments, supplements, or experimental anti-aging interventions. There is no established treatment that safely stops human aging, and therapies that affect growth pathways can have serious consequences. Treatment decisions should be made with qualified clinicians familiar with the specific diagnosis, not based on a generalized theory about aging.

The ethical principle is that unusual biology does not diminish personhood. Descriptions should emphasize the individual’s health, function, preferences, and quality of life rather than spectacle. Researchers and journalists should avoid publishing identifying details without appropriate consent.

An unresolved challenge is how to provide equitable specialist care for people with ultra-rare conditions, especially where genetic testing and multidisciplinary services are not readily available. International registries, telemedicine, and accessible diagnostic resources may help, but they do not eliminate disparities. Scientific understanding improves when affected individuals and families are treated as partners, not merely as sources of unusual data.

19. Unanswered questions and future directions

Several major questions remain open. First, how many reported cases of apparent age arrest represent verified disorders, and how many reflect incomplete information or observer misclassification? The answer requires better case documentation and registries that capture both positive and negative findings. Second, can biological-age measures be validated for children and rare syndromes, where normal developmental changes complicate interpretation? Third, why do related molecular pathways affect some organs much more than others?

Fourth, are there human genetic profiles that substantially slow multiple dimensions of biological aging without compromising growth, reproduction, immunity, or tissue repair? Current evidence supports pathway-specific effects more strongly than a universal slowing of aging. Fifth, how do early-life nutrition, chronic disease, and environmental exposures interact with rare variants? Sixth, can integrated multi-omics data meaningfully improve diagnosis or prognosis, or will complexity and small sample sizes limit clinical utility?

A promising direction is deep phenotyping: repeated, standardized assessment of growth, development, endocrine function, organ health, and molecular markers. The strongest studies will link these measures to outcomes that matter to patients, such as cardiovascular events, mobility, cognition, independence, and quality of life. Data sharing must be balanced with privacy protections, particularly for highly recognizable rare cases.

Another priority is to study people whose features do not fit established syndromes. Unsolved cases may reveal new biology, but they should be reported with explicit uncertainty. Whole-genome sequencing, transcriptomic studies, and functional experiments may help identify mechanisms, yet no single technique guarantees a diagnosis. Replication across unrelated individuals remains important.

The main hypothesis of this review—that growth, maturation, and aging are partially independent processes—can be tested. It predicts that apparent anomalies will be better classified through multidimensional profiles than by appearance alone. It also predicts that different diagnoses will produce distinct patterns of divergence across systems. If future evidence shows a coherent syndrome in which multiple aging processes are truly slowed, that would refine the model rather than validate every anecdote.

Scientific humility is especially important in rare-disease research. An unanswered question is not evidence for a supernatural or impossible explanation. It is a precise statement that current data do not yet distinguish among plausible mechanisms. The appropriate response is careful measurement, collaboration, and continued investigation.

20. Conclusion

Unusual growth and aging phenotypes are real, but the phrase “a person who stayed a baby” can refer to very different biological situations. Severe short stature, delayed skeletal maturation, endocrine disorders, profound developmental impairment, and premature-aging syndromes must be distinguished rather than grouped together. A person may remain small or appear young while continuing to age; another may show early aging-like pathology in selected tissues while retaining normal cognition and other functions.

Hutchinson–Gilford progeria syndrome and Werner syndrome demonstrate that specific genetic disruptions can produce premature degenerative features. Growth disorders involving thyroid, growth hormone, IGF-1, nutrition, or chronic disease illustrate that limited growth does not necessarily mean accelerated or slowed biological aging. Neurological and developmental conditions further show that appearance and functional ability are not reliable measures of an organism’s total biological state.

The central hypothesis is that human development and aging consist of multiple interacting but partially separable processes. This explains why a single outward feature cannot define a person’s biological age. It also suggests a practical research agenda: longitudinal measurements, precise

phenotyping, validated molecular tests, genetic investigation, and careful comparison across tissues and organ systems. Cases should be described without sensationalism and interpreted according to the strength of the evidence.

Important uncertainties remain. Researchers do not yet have a universal biological-age test; many rare cases lack molecular diagnoses; tissue-specific vulnerability is incompletely understood; and the long-term effects of altered growth pathways vary across conditions. It remains possible that future research will discover additional syndromes that uncouple growth, maturation, and maintenance in unexpected ways. Such discoveries would need reproducible clinical and molecular evidence.

The strongest conclusion is therefore both substantive and cautious: atypical growth and aging can reveal important biology, but there is no sound basis for assuming that a person who looks infant-like has literally stopped aging. Scientific explanations must be built from verified histories, clinical measurements, and testable mechanisms. Where the evidence is insufficient, the question should remain open rather than being filled with speculation. The goal is not merely to label unusual cases, but to understand how human development, tissue maintenance, and aging interact—and why they sometimes diverge.

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Large-Scale Genome Databases in Medicine: Resources, Applications, and Challenges

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Abstract
The completed sequencing of the human genome in the first decade of the twenty-first century shifted the central problem of medical genetics from the acquisition of sequence to the interpretation of sequence. Interpretation requires scale: a single human genome contains roughly four to five million variants relative to the reference assembly, and distinguishing the few hundred that are medically actionable from the millions that are benign cannot be accomplished by reasoning from first principles. Large databases of human genomes, exomes, variant interpretations, tumour sequences, and linked clinical records have therefore become the operative infrastructure of genomic medicine, performing the same function for sequence data that randomized trials perform for therapeutics. This review describes the principal classes of large genomic databases used in clinical and translational medicine and evaluates their design, scale, data types, access models, and medical applications. Population reference databases, exemplified by the 1000 Genomes Project, the Exome Aggregation Consortium, the Genome Aggregation Database, and the Trans-Omics for Precision Medicine programme, provide allele frequency and mutational constraint estimates that constitute the primary evidence for variant filtering. Clinical variant knowledge bases, including ClinVar, ClinGen, the Human Gene Mutation Database, OMIM, and locus-specific databases, aggregate curated interpretations and phenotype–gene relationships. Population biobanks with linked electronic health records, including UK Biobank, All of Us, FinnGen, the Million Veteran Program, BioBank Japan, the Estonian Biobank, the China Kadoorie Biobank, the Taiwan Biobank, and deCODE, enable genome-wide association, phenome-wide association, polygenic risk estimation, and pharmacogenomic discovery at a scale that supports clinical translation. Cancer genome resources, including The Cancer Genome Atlas, the International Cancer Genome Consortium, AACR Project GENIE, COSMIC, and cBioPortal, define the somatic mutational landscape that underpins molecular oncology. Functional genomic atlases such as GTEx, ENCODE, the Human Cell Atlas, and the Cancer Dependency Map supply the regulatory and cellular context in which non-coding variation acquires meaning. The review then examines the access and governance architectures that determine who can use these data, the clinical applications they currently support, and the structural limitations that constrain them, principally the profound ancestry bias of most databases, the unresolved problem of variants of uncertain significance, the variable quality of phenotype and variant annotation, and the ethical and economic fragility of long-term data stewardship. It concludes that the next phase of

development must prioritize globally representative sampling, machine-readable and evidence-graded interpretation, and sustainable public funding of openly accessible reference resources.

Keywords: genomic databases; biobanks; variant interpretation; allele frequency; precision medicine; genome-wide association; data sharing; clinical genomics

1. Introduction

Human genomic medicine is, in practical terms, a comparative discipline. Every clinical sequence is read against a background of other sequences: the reference assembly, population frequency catalogues, curated disease variant registries, tumour-matched normals, and increasingly the accumulated genomes of entire health systems. When a laboratory classifies a variant as pathogenic, it is implicitly asserting that the variant is rarer in the general population than the disease prevalence would permit, that it alters a residue or splice site that is conserved and constrained, that it has been observed in affected individuals, and that the gene in which it lies is intolerant of loss of function. Each of these assertions depends on a database. The databases are therefore not ancillary tools; they are the epistemic foundation on which a clinical genetic diagnosis rests [Richards et al., 2015].

The scale of the interpretive problem is best appreciated numerically. A typical exome contains approximately 20,000 to 25,000 single-nucleotide variants and small insertions or deletions relative to the reference; a whole genome contains four to five million. Of these, only a small minority have any plausible functional consequence, and fewer still are causally related to the phenotype under investigation. Early experience with clinical exome sequencing demonstrated that the technical capacity to generate sequence far outstripped the interpretive capacity to act on it, and that the rate-limiting resource was not sequencing chemistry but the accumulated knowledge against which candidate variants could be compared [Ashley, 2016; Shendure et al., 2019]. This recognition motivated a coordinated international investment in databases rather than in instruments, an investment that has produced resources spanning five orders of magnitude in size and addressing fundamentally different clinical questions [Claussnitzer et al., 2020].

The strategic logic of these investments is visible in the trajectory of the field's flagship programmes. The Human Genome Project and the International HapMap Project established the reference sequence and the first catalogue of common variation. The 1000 Genomes Project then produced a globally sampled haplotype reference that made imputation possible and thereby multiplied the effective sample size of every subsequent genetic study [Auton et al., 2015]. The Exome Aggregation Consortium and its successor, the Genome Aggregation Database, inverted the usual logic of case–control genetics by treating the healthy population as an enormous control series, allowing the frequency of a variant in ostensibly unaffected individuals to be quantified with unprecedented precision and enabling gene-level constraint metrics that now inform nearly every clinical interpretation [Lek et al., 2016; Karczewski et al., 2020]. In parallel, the clinical community constructed archives of interpreted variants, of which ClinVar is the largest and most authoritative, converting individual laboratory classifications into a shared public asset [Landrum et al., 2018]. Population biobanks then closed the loop by linking dense genomic data to longitudinal electronic health records, allowing genotype–phenotype relationships to be discovered and validated within the same cohort and enabling the return of clinically actionable findings to participants [Sudlow et al., 2015; Denny et al., 2019].

The purpose of this review is to describe these resources systematically and to evaluate them as medical infrastructure rather than as bioinformatic conveniences. The review proceeds in four parts. It first proposes a functional taxonomy of genomic databases according to the clinical question each is designed to answer. It then examines in detail the five principal classes of resource: population reference databases of human variation, clinical variant interpretation knowledge bases, population biobanks with linked health data, cancer genome databases, and functional genomic atlases. It next considers the access and governance architectures that

mediate use of these data, presents a comparative synthesis of scale and function, and reviews the clinical applications that are currently supported or in advanced translation, including rare disease diagnosis, molecular oncology, pharmacogenomics, polygenic risk prediction, and population-scale screening. Finally, it analyses the structural limitations of the current resource ecology, with particular attention to ancestry bias, the burden of variants of uncertain significance, annotation quality, privacy and consent, and the sustainability of public data infrastructure, before identifying the priorities that should govern the next decade of development.

2. A functional taxonomy of genomic data resources

Genomic databases are frequently discussed as a single category, but they answer different questions and fail in different ways. A clinically useful taxonomy distinguishes at least six functions.

The first function is frequency estimation. Given a variant, what is its allele frequency in the general population, stratified by ancestry and by sex, and is that frequency compatible with the prevalence of the disease it is claimed to cause? Resources serving this function require breadth of sampling rather than depth of phenotyping, and their value is limited principally by the underrepresentation of non-European ancestries.

The second function is constraint and consequence annotation. Given a gene or a genomic interval, how tolerant is it of variation, and what is the predicted effect of a specific change on transcript, protein, or splicing? Constraint metrics derived from large population cohorts, together with regulatory annotation from functional atlases, serve this function and provide the prior probabilities that Bayesian variant classification requires.

The third function is curated interpretation. Given a variant, has any competent body classified it, on what evidence, and with what level of confidence and disagreement? This function is served by ClinVar, ClinGen expert panels, locus-specific databases, and commercial repositories, and its central problem is not scale but curation throughput and evidence transparency.

The fourth function is phenotype–gene mapping. Given a phenotype, which genes and variants are known to cause it? OMIM, Orphanet, and the developmental disorder cohorts serve this function and remain indispensable in the first stage of a diagnostic search.

The fifth function is discovery through genotype–phenotype linkage. Which variants, genes, and polygenic scores associate with which diseases, biomarkers, and drug responses in a population with real clinical outcomes? Population biobanks and disease-focused consortia serve this function and are distinguished by the depth of their longitudinal phenotyping rather than the size of their variant catalogues.

The sixth function is somatic and tumour-specific characterisation. Which somatic alterations drive a given malignancy, what is their prognostic significance, and which are therapeutically targetable? Cancer genome resources serve this function and are distinguished by the need to distinguish germline from somatic variation, by the absence of a stable "normal" baseline across tumours, and by the rapid obsolescence of therapeutic annotations as drug approvals change.

These six functions are complementary, and a mature health system requires all six. The recurrent policy error is to assume that a resource built for one function can substitute for another: a very large frequency database cannot diagnose a patient, and a curated clinical registry cannot estimate population allele frequency, because clinical registries are enriched for exactly the variants they contain. Understanding which function a database was designed to serve is the precondition for using it correctly (Fig. 1).

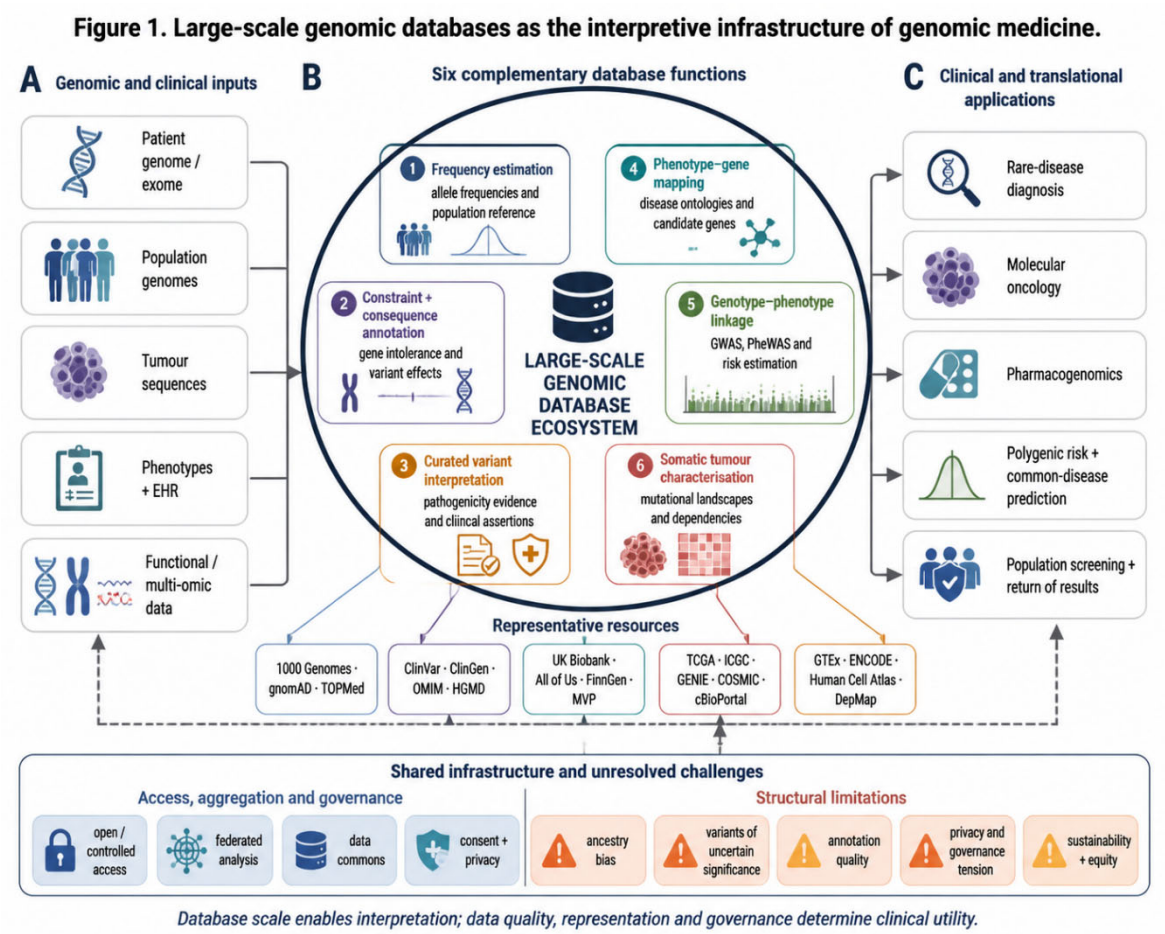


Figure 1. Large-scale genomic databases as the interpretive infrastructure of genomic medicine. (A) Genomic and clinical inputs include patient genome and exome sequences, population genomes, tumour sequences, phenotypic and electronic health record data, and functional or multi-omic measurements. (B) These data are integrated across six complementary database functions: frequency estimation; constraint and consequence annotation; curated variant interpretation; phenotype–gene mapping; genotype–phenotype linkage; and somatic tumour characterisation. Representative resources include the 1000 Genomes Project, the Genome Aggregation Database (gnomAD), and the Trans-Omics for Precision Medicine (TOPMed) programme; ClinVar, ClinGen, Online Mendelian Inheritance in Man (OMIM), and the Human Gene Mutation Database (HGMD); UK Biobank, the All of Us Research Program, FinnGen, and the Million Veteran Program (MVP); The Cancer Genome Atlas (TCGA), the International Cancer Genome Consortium (ICGC), AACR Project GENIE, COSMIC, and cBioPortal; and the Genotype-Tissue Expression (GTEx) project, Encyclopedia of DNA Elements (ENCODE), Human Cell Atlas, and Cancer Dependency Map (DepMap). (C) The resulting evidence supports rare-disease diagnosis, molecular oncology, pharmacogenomics, polygenic risk and common-disease prediction, and population screening with return of results. Access, aggregation, and governance mechanisms—including open or controlled access, federated analysis, data commons, consent, and privacy—span the entire ecosystem. Major structural limitations include ancestry bias, variants of uncertain significance, variable annotation quality, privacy and governance tensions, and challenges related to sustainability and equity. Arrows indicate the conceptual flow from genomic and clinical data acquisition through database-mediated interpretation to clinical and translational application.

3. Population reference databases of human variation

3.1 From dbSNP and HapMap to the 1000 Genomes Project

The systematic cataloguing of human variation began with dbSNP, established in 1998 as a public archive of short genetic variants, which grew from a few thousand submissions to hundreds of millions of records and became the identifier namespace on which almost all subsequent resources depend [Sherry et al., 2001]. The International HapMap Project then characterised common single-nucleotide polymorphisms in populations of African, European, and Asian ancestry, establishing the haplotype block structure of the genome and demonstrating that a limited set of markers could capture most common variation through linkage disequilibrium. HapMap made genome-wide association studies feasible, and its conceptual legacy is that the genome can be interrogated indirectly, through correlated markers, rather than base by base.

The 1000 Genomes Project, conducted between 2008 and 2015, replaced this marker-based approach with direct reconstruction of complete genomes at population scale. Its final phase reported the genomes of 2,504 individuals drawn from 26 populations across five continental groupings, combining low-coverage whole-genome sequencing, deep exome sequencing, and array genotyping, and identifying approximately 88 million variants, of which some 84.7 million were single-nucleotide variants and the remainder short insertions and deletions [Auton et al., 2015]. The resource achieved two things that were not previously available. First, it provided an empirically estimated haplotype reference panel in which variants absent from array designs could be imputed with high accuracy, effectively increasing the sample size of every subsequent association study by an order of magnitude at negligible cost. Second, it provided the first systematic global survey of rare variation, demonstrating that most variants are rare, that the majority of rare variants are population-specific, and that a substantial fraction of variants seen in any one population are absent from others. This last observation has direct clinical consequences: a variant that appears novel and therefore suspicious in a European patient may be common and benign in an African or East Asian population, a fact that only globally sampled reference panels can reveal.

3.2 The Exome Aggregation Consortium

The Exome Aggregation Consortium represented a change of purpose rather than merely of scale. By aggregating exome data from more than 60,000 individuals sequenced across numerous disease-specific studies, the consortium created a reference set in which the frequency of any candidate variant could be estimated in a population largely free of severe pediatric disease [Lek et al., 2016]. The intellectual contribution was the recognition that the aggregate of case cohorts, each enriched for a different disease, approximates a population sample for any variant not causally related to the diseases in question. The consortium reported that the average individual carries approximately 54 variants previously reported as disease-causing, a finding that reframed the interpretation of literature-derived pathogenicity claims and demonstrated that a substantial fraction of variants described as pathogenic in small studies are in fact common polymorphisms. The consortium also introduced the probability of loss-of-function intolerance, a gene-level metric comparing observed to expected counts of predicted truncating variants, which became the standard quantitative measure of gene constraint.

3.3 The Genome Aggregation Database

The Genome Aggregation Database (gnomAD) is the principal public reference for human variation and the most widely used genomic database in clinical interpretation. Its first major release aggregated 125,748 exomes and 15,708 genomes from 141,456 unrelated individuals across diverse ancestries, harmonised variant calling across contributing studies, and provided allele frequencies, quality metrics, and gene-level constraint scores, including the observed-to-expected ratio of loss-of-function variants and its upper bound, the loss-of-function observed/expected upper bound fraction, which is now routinely used to rank candidate genes [Karczewski et al.,

2020]. The accompanying constraint analysis classified genes by their tolerance of variation, identified genes in which loss of function is effectively unobserved, and provided a quantitative framework for distinguishing haploinsufficient disease genes from genes in which truncation is tolerated.

Subsequent releases expanded both scale and scope. gnomAD v4 encompasses 807,162 individuals, comprising 730,947 exomes and 76,215 genomes, an approximately fivefold expansion over the previous release, with substantially improved representation of African, Latino, East Asian, and South Asian ancestries, together with improved structural variant and copy-number variant calls. The genome-based release additionally enabled a mutational constraint map derived from 76,156 genomes, extending constraint analysis from the approximately 1.5 per cent of the genome that is protein-coding to the non-coding fraction, and identifying genomic regions depleted of variation that are likely to be functionally indispensable [Chen S et al., 2024]. For clinical laboratories, the practical consequences of these expansions are that allele frequencies can now be estimated in ancestry-matched subpopulations for many variants previously classifiable only as "rare", and that a growing fraction of candidate non-coding variants can be evaluated against an empirical expectation of variation.

The methodological caveats of aggregation resources are as important as their scale. Contributing cohorts are not a random sample of any population; they are enriched for individuals ascertained for disease, for particular ancestries, and for sequencing technologies of differing error profiles. Allele frequencies are therefore estimates with unquantified ascertainment bias, low-frequency variants are subject to substantial sampling error, and the absence of a variant from the database is not evidence that it is absent from the population, particularly for populations that are poorly represented. Clinical interpretation guidelines accordingly treat population frequency as one line of evidence, weighted by database representativeness, rather than as a decisive criterion [Richards et al., 2015].

3.4 TOPMed and the limits of aggregate reference panels

The Trans-Omics for Precision Medicine programme of the National Heart, Lung, and Blood Institute addressed a complementary problem: the deep characterisation of diverse populations with rich cardiovascular, pulmonary, and haematological phenotyping. Its first whole-genome sequencing release comprised 53,831 genomes from more than 80 contributing studies, detecting more than 400 million single-nucleotide and short insertion–deletion variants, the majority of which were rare and had not been previously catalogued [Taliun et al., 2021]. The programme demonstrated both the power and the limitation of large aggregate panels. The power lies in the density of rare variation: imputation into TOPMed substantially improves fine-mapping resolution and the detection of rare variant associations, particularly in ancestrally diverse cohorts. The limitation is one of interpretation: an ever-growing catalogue of rare variants increases the number of variants that any individual carries and that must be individually assessed, so that the marginal interpretive benefit of additional rare-variant discovery declines unless matched by improved functional annotation and frequency data from the same populations.

National and regional reference panels complement these international efforts. The Icelandic population has been characterised through whole-genome sequencing of a large fraction of the nation combined with extensive genealogical and phenotype data, enabling long-range haplotype phasing and the identification of variants with large effect that are rare elsewhere but common in the isolate [Gudbjartsson et al., 2015]. Similar logic motivates the sequencing of founder populations and of ancestrally distinct cohorts, which increase the power to detect allelic series and recessive conditions but also concentrate the risk of interpreting population-specific benign variants as pathogenic.

4. Clinical variant interpretation knowledge bases

4.1 ClinVar

ClinVar is the central public archive of interpretations of the relationship between human genomic variants and phenotypes. Established by the National Center for Biotechnology Information in 2013, it accepts submissions from clinical laboratories, research consortia, expert panels, and commercial entities, and releases the aggregated classifications together with the supporting evidence submitted for each record [Landrum et al., 2018]. Its design principle is deliberately archival rather than adjudicative: ClinVar does not decide whether a variant is pathogenic, but it makes visible who asserted what, on what date, and with what evidence, allowing users to observe concordance and discordance across submitters. The resource has grown from a few tens of thousands of records at launch to several million variant records with more than seven million submitted classifications from well over three thousand submitters in around one hundred countries, making it the largest repository of clinical variant interpretation in existence.

Three features of ClinVar are decisive for its medical utility. The first is the review-status metric, a graded indication of the strength of the evidence base for a classification, ranging from single-submitter assertions without criteria to classifications reviewed by expert panels and corroborated by practice guidelines. This metric allows a laboratory to distinguish a classification that reflects a single unpublished opinion from one that reflects systematic evidence review, and it is explicitly incorporated into the recommendation of the American College of Medical Genetics and Genomics and the Association for Molecular Pathology that population and curation databases be weighted by the quality of their evidence [Richards et al., 2015]. The second is the explicit preservation of conflicting interpretations, which serves a diagnostic function rather than merely an archival one: a variant with conflicting classifications signals genuine uncertainty and prompts independent review, whereas an artificially resolved consensus would conceal the disagreement. The third is the capacity for reanalysis. Because interpretations are time-stamped and versioned, a variant classified as uncertain in one year may be reclassified when new evidence accumulates, and laboratories that systematically re-examine their variant files against updated ClinVar releases have documented clinically consequential reclassification rates that justify periodic review as a standard of care.

The limitations of ClinVar follow from its archival design. Submission is voluntary, so coverage is uneven across genes and phenotypes, reflecting the testing volumes and research interests of contributing laboratories rather than the burden of disease. Classifications are not independent, because laboratories frequently cite one another, producing apparent consensus that reflects shared provenance rather than independent evidence. The evidence submitted is often sparse and unstructured, and the same variant may be submitted with different transcript references, different phenotype terms, and different criteria applied. Finally, historical submissions are not systematically withdrawn, so that outdated classifications persist in the archive and can be retrieved by users who do not examine submission dates. These properties mean that ClinVar is indispensable but not sufficient, and that its contents require active rather than passive interpretation.

4.2 ClinGen and the systematisation of evidence

The Clinical Genome Resource was established to address precisely the weaknesses of voluntary submission by creating an authoritative, evidence-based, and transparent process of gene–disease and variant–disease adjudication [Rehm et al., 2015]. Its model is expert-panel curation: variant curation expert panels, organised by gene or disease domain, apply the ACMG/AMP framework with gene-specific specifications, publish their criteria, and deposit classifications in ClinVar with the highest review status. The resource also maintains a gene–disease validity classification, grading the strength of evidence that a gene causes a given monogenic condition,

and a dosage sensitivity map that quantifies the pathogenicity of copy-number gains and losses for individual genes and genomic regions.

The medical significance of this systematisation is considerable. Gene–disease validity classification allows laboratories to avoid reporting variants in genes whose disease associations rest on single case reports and have not been replicated, a well-documented source of diagnostic error. Dosage sensitivity maps convert copy-number variant interpretation from a heuristic assessment of size and gene content into a structured evaluation against curated haploinsufficiency probabilities. The variant curation expert panels have resolved a substantial number of previously conflicting classifications, and their specifications for individual genes have made the ACMG/AMP criteria operational in contexts where the generic framework is ambiguous. The limitation of the model is throughput: expert curation is labour-intensive, cannot keep pace with variant discovery, and depends on sustained voluntary or grant-funded participation, so that coverage remains concentrated in genes of high clinical volume and well-organised clinical communities.

4.3 OMIM, Orphanet, and phenotype-driven resources

Phenotype-driven diagnosis begins with the question of which genes could plausibly explain a patient's presentation, and the resources that map phenotypes to genes are therefore as important as those that map variants to interpretations. Online Mendelian Inheritance in Man, established in the 1960s and available electronically since the 1980s, is the canonical compendium of Mendelian phenotypes and genes, comprising more than 25,000 entries with structured descriptions of clinical features, inheritance, molecular basis, and allelic variants, together with a phenotypic series that groups entries by locus [Amberger et al., 2019]. Its authority derives from expert editorial curation of the primary literature, and its characteristic weakness is that it is descriptive rather than probabilistic: an OMIM entry establishes that an association has been reported, not how strong the evidence is or how frequently the phenotype occurs.

Orphanet addresses the epidemiology and nosology of rare disease, providing a nomenclature of several thousand rare disorders with prevalence estimates, inheritance patterns, age of onset, and gene associations, together with an ontology that supports computational phenotyping [Nguengang Wakap et al., 2020]. The Human Phenotype Ontology provides the controlled vocabulary through which clinical descriptions are made computable, and its integration with OMIM, Orphanet, and DECIPHER enables phenotype-driven prioritisation of candidate genes, in which the semantic similarity between a patient's recorded phenotype terms and the phenotypes annotated to each gene is used to rank the exome [Köhler et al., 2021]. DECIPHER complements these resources by hosting de-identified phenotype and copy-number data from thousands of patients, providing the comparison against other affected individuals that is often decisive in the interpretation of rare structural variants [Firth et al., 2009]. Together these resources form the phenotype layer of genomic medicine, without which sequence data cannot be oriented toward a clinical question.

4.4 Locus-specific and commercial databases

Locus-specific databases, maintained by research communities for individual genes or diseases, remain the most detailed sources of variant-level information for their domains, frequently containing functional assays, segregation data, and founder effects that are not captured in general archives. Their strength is depth; their weakness is heterogeneity of format, accession, and curation standard, together with a well-recognised risk of attrition as funding cycles end. The Human Gene Mutation Database occupies an intermediate position, providing a comprehensive curated collection of published germline lesions underlying inherited disease, with more than 200,000 different gene lesions described in over 8,000 genes at the time of its principal description, and an accompanying professional edition with additional annotation [Stenson et al., 2017]. Its coverage is broader than that of clinical archives but its inclusion criteria are based on

publication rather than on evidence grading, so that it contains many variants whose disease attribution has since been questioned; this is the same ascertainment problem that the population databases were built to detect.

Commercial knowledge bases, maintained by diagnostic and informatics companies, integrate these public resources with proprietary curation, functional data, and clinical trial annotations, and are used operationally by many clinical laboratories. Their advantages are currency, integration, and support; their disadvantages are restricted access, limited transparency of curation criteria, and the collective inefficiency of duplicating curation that could be shared. The ongoing policy tension between open public curation and proprietary curation is one of the unresolved structural questions of genomic medicine, and it bears directly on the reproducibility of clinical interpretations across health systems (Fig. 2).

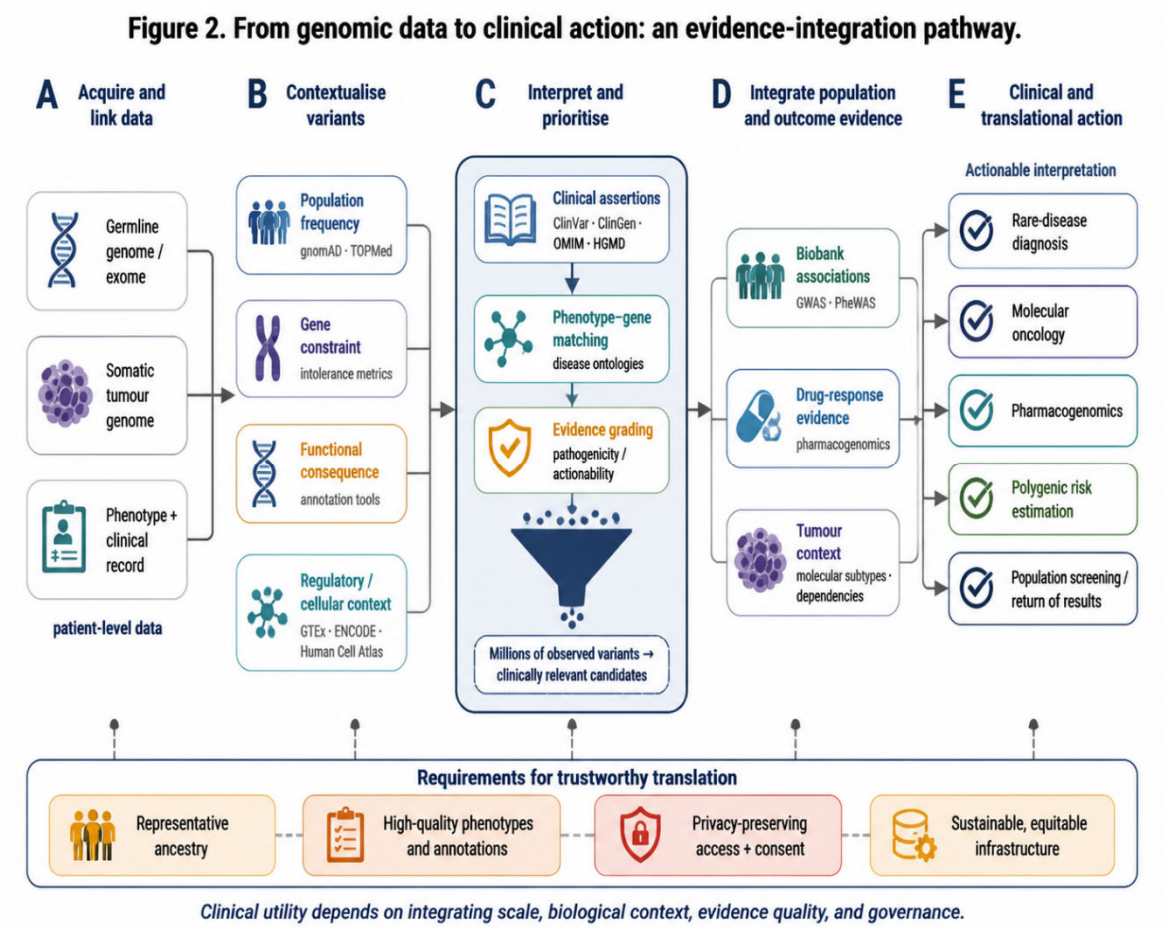


Figure 2. From genomic data to clinical action: an evidence-integration pathway. (A) Genomic medicine integrates germline genome or exome sequences, somatic tumour genomes, and phenotypic or clinical record data. (B) Observed variants are contextualized using population-frequency data, gene-constraint metrics, functional consequence annotations, and regulatory or cellular information. Representative resources include the Genome Aggregation Database (gnomAD), the Trans-Omics for Precision Medicine (TOPMed) programme, the Genotype-Tissue Expression (GTEx) project, the Encyclopedia of DNA Elements (ENCODE), and the Human Cell Atlas. (C) Evidence is integrated through clinical assertions, phenotype–gene matching, and evidence grading to prioritize variants with potential clinical relevance. Representative knowledge bases include ClinVar, ClinGen, Online Mendelian Inheritance in Man (OMIM), and the Human Gene Mutation Database (HGMD). (D) Population biobank associations, pharmacogenomic evidence, and tumour-specific molecular context further refine interpretation through genome-wide association studies, phenome-wide association studies, drug-response analyses, molecular subtyping, and dependency mapping. (E) The resulting evidence supports rare-disease diagnosis,

molecular oncology, pharmacogenomics, polygenic risk estimation, and population screening with return of results. Representative ancestry, high-quality phenotypic and variant annotations, privacy-preserving access and consent, and sustainable and equitable infrastructure are required throughout the pathway to support trustworthy clinical translation. Arrows indicate the conceptual progression from data acquisition and contextualization through variant prioritization, evidence integration, and actionable clinical interpretation.

5. Population biobanks with linked health records

5.1 The design logic of the genome-linked biobank

Population reference databases answer the question of what a variant does in general; biobanks answer the question of what it does in people whose health is observed over time. The distinctive design feature of the modern genomic biobank is not its size but its linkage: participants consent to the combination of genomic data, questionnaire and physical measurements, and longitudinal electronic health records, often supplemented by imaging, biomarkers, and linkage to death and disease registries. This architecture allows the same cohort to be used for genome-wide association, phenome-wide association across thousands of phenotypes defined from routine clinical coding, Mendelian randomisation, polygenic risk estimation with real outcomes, pharmacogenomic discovery, and the calibration of screening strategies. It also creates the ethical obligations that dominate biobank governance, since the return of individual findings, the management of incidental risk, and the maintenance of consent over decades all become empirical problems rather than hypothetical ones [Denny et al., 2019].

5.2 UK Biobank

UK Biobank is the most extensively used genomic resource in the world and functions as the de facto reference cohort for human genetics. It recruited approximately 500,000 participants aged 40 to 69 years across the United Kingdom between 2006 and 2010, collecting extensive baseline questionnaire data, physical measurements, biological samples, and consent for linkage to national health records, which has yielded longitudinal follow-up through hospital episode statistics, cancer and death registries, and primary care for a subset [Sudlow et al., 2015]. Genome-wide genotyping was completed for all participants and released with imputation to a combined reference panel, and this array plus imputation resource alone supported several thousand publications across every major disease area.

The resource has since been extended in three directions that matter clinically. Whole-exome sequencing of approximately 200,000 participants was released in 2022, and whole-genome sequencing of 490,640 participants was reported in 2025, providing a depth of rare-variant coverage that supports gene-based burden testing, the discovery of non-coding associations, and the identification of individuals carrying pathogenic variants in Mendelian disease genes [UK Biobank Whole-Genome Sequencing Consortium, 2025]. Deep phenotyping has been extended through multi-organ imaging in 100,000 participants, accelerometry, retinal imaging, cardiac magnetic resonance, and biochemical and proteomic profiling, with plasma proteomics measured in more than 50,000 participants across approximately 3,000 proteins, which has enabled proteome-wide association and the identification of protein biomarkers with causal support [Sun et al., 2023]. Linkage has been extended to primary care records, prescription data, and cancer registration, so that drug exposure and clinical outcome can be studied jointly with genotype.

The medical yield is substantial and specific. UK Biobank data established the population frequency and penetrance of pathogenic variants in the principal hereditary cancer and cardiac genes, showing that many clinically actionable variants are carried by a larger number of people than clinic-based estimates implied, and that penetrance in an unselected population is often lower than in family-based studies. It provided the empirical basis for polygenic risk scores across common diseases, demonstrating that individuals in the extremes of a score distribution can carry

risk comparable to that conferred by monogenic mutations. It has been used to quantify the heritability of hundreds of phenotypes, to identify modifiable risk factors through Mendelian randomisation, to characterise the long-term consequences of drug targets through cis-variant proxies, and to evaluate the clinical validity of biomarkers before trials are undertaken.

The limitations are equally instructive. Participants are volunteers, and the cohort is healthier, more educated, and less socioeconomically deprived than the general population, producing a healthy volunteer effect that biases prevalence and penetrance estimates. The cohort is overwhelmingly of European ancestry, which limits the portability of genetic effect estimates and the calibration of polygenic scores in other populations. Phenotypes derived from hospital coding are subject to ascertainment and coding variation, and the cohort is now ageing, so that younger-onset conditions are underrepresented. Finally, the resource is not a health system: it does not return comprehensive clinical-grade results, and its use for clinical decision-making requires independent validation in target populations (Fig. 3).

Figure 3. From genomic data to clinical action: evidence integration and longitudinal reanalysis.

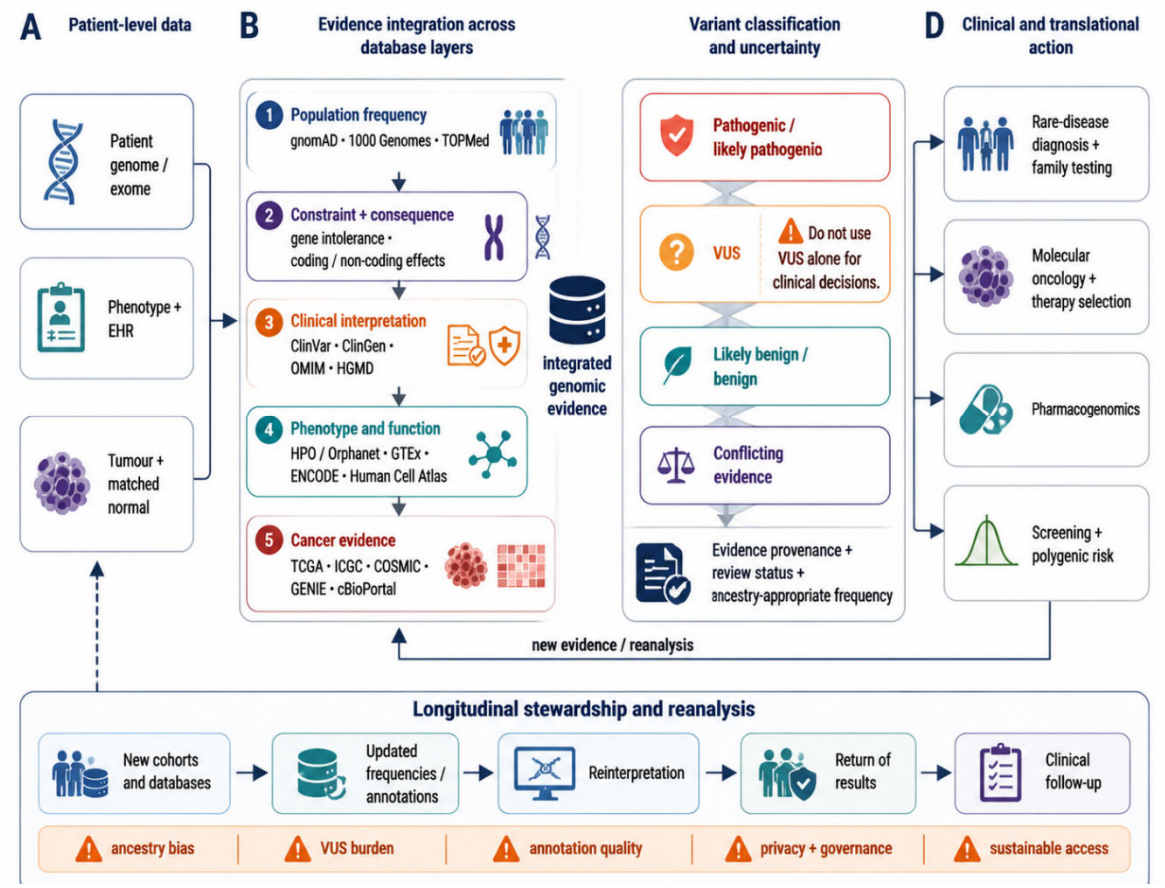


Figure 3. From genomic data to clinical action: evidence integration and longitudinal reanalysis. Conceptual framework illustrating how patient-level genomic, phenotypic, electronic health record, and tumour data are integrated with complementary genomic databases to support clinical interpretation. **(A)** Patient-level inputs include genome or exome sequences, phenotypic and electronic health record data, and tumour sequences with matched normal samples. **(B)** Evidence is assembled across population-frequency resources, constraint and consequence annotations, clinical variant databases, phenotype–gene and functional genomic resources, and cancer-genomic databases. **(C)** Integrated evidence supports classification as pathogenic or likely pathogenic, a variant of uncertain significance, likely benign or benign, or conflicting evidence. Classification should incorporate evidence provenance, review status, and ancestry-appropriate allele frequencies; variants of uncertain significance should not be used as the sole basis for clinical decision-making. **(D)** Interpreted findings may inform rare-disease diagnosis and family testing,

molecular oncology and treatment selection, pharmacogenomics, screening, and polygenic-risk assessment. The lower feedback loop depicts longitudinal stewardship, in which new cohorts and databases update allele frequencies and annotations, enabling variant reinterpretation, return of results, and clinical follow-up. Persistent challenges include ancestry bias, the burden of variants of uncertain significance, variable annotation quality, privacy and governance constraints, and the need for sustainable data access.

5.3 All of Us and the diversity imperative

The All of Us Research Program of the United States National Institutes of Health was designed explicitly to correct the ancestry bias of earlier cohorts. It aims to enrol at least one million participants with deliberate oversampling of groups historically underrepresented in biomedical research, and it released approximately 245,000 whole genome sequences, of which nearly half were from participants of non-European ancestry, together with survey data, electronic health records for a large subset, and physical measurements, delivered through a cloud-based research platform with tiered access controls [All of Us Research Program Genomics Investigators, 2024]. The programme reported that the genomic data revealed millions of variants not present in previous reference databases, that a substantial fraction of participants carried previously uncharacterised variants in medically actionable genes, and that the inclusion of diverse ancestries materially changed the interpretation of variants that would have been classified as rare or novel in European-only references. The programme also integrates pharmacogenomic variants relevant to drug metabolism, and it has established a return-of-results process for actionable findings, making it a test case for the ethics of large-scale genomic return in a diverse population.

5.4 FinnGen and the value of isolate populations

FinnGen integrates genomic data from approximately 500,000 Finnish biobank participants with decades of national health registry data, exploiting a population with a well-characterised bottleneck and founder effects, low genetic diversity, and comprehensive, linkable, universal health records [Kurki et al., 2023]. The resource has produced hundreds of novel genetic associations, several of which are enriched or exclusively detectable in the Finnish population because of the elevated frequency of otherwise rare alleles, and it has demonstrated the efficiency of registry-based phenotyping, in which disease endpoints are defined from national inpatient, outpatient, prescription, and cause-of-death registers rather than from research visits. FinnGen also illustrates the value of return of results at national scale: the programme has returned actionable genetic findings to participants through the public health system, and it has supported the development of a national pharmacogenomics implementation.

The Finnish experience reveals a general principle. Isolate populations increase statistical power for rare alleles with large effects and simplify haplotype inference, but they also generate associations that may not replicate elsewhere and that require careful distinction between founder effects, drift, and causal biology. For diagnostic laboratories, the practical implication is that a variant that is common in Finland may be pathogenic when found elsewhere, and that frequency comparisons must be ancestry-appropriate; for drug development, the implication is that targets validated in an isolate require replication in diverse cohorts before generalisation.

5.5 The Million Veteran Program

The Million Veteran Program has enrolled over one million veterans in the United States, linking genomic data to the Department of Veterans Affairs electronic health record, one of the most comprehensive longitudinal clinical data systems in existence, together with survey data on military exposures, lifestyle, and mental health [Gaziano et al., 2016]. Its distinguishing features are the size and depth of its clinical record, the availability of prescription and laboratory data at population scale, and the substantial representation of African American and Hispanic participants, which exceeds that of most cohorts of comparable size. The programme has supported large-scale genome-wide association and multi-trait analyses across psychiatric,

cardiovascular, metabolic, renal, and substance use phenotypes, and it has been used for pharmacogenomic discovery using prescription records as exposure and outcome, a design that exploits the natural experiment created by routine clinical care.

5.6 Asian and other national biobanks

BioBank Japan enrolled approximately 200,000 patients diagnosed with one of 47 target common diseases during its first recruitment period, later extended to more than 260,000 participants, and maintains DNA, serum, and clinical data that have supported genome-wide association studies in a Japanese population and the construction of a Japanese-specific reference panel for imputation [Nagai et al., 2017]. The Taiwan Biobank has genotyped more than 100,000 participants of Han Chinese ancestry with whole-genome sequencing of a subset, providing a population-specific reference for a population with distinctive ancestry and a high burden of certain cancers; the associated Taiwan Precision Medicine Initiative has extended recruitment beyond 500,000 participants with linked electronic medical records across multiple hospitals [Wei et al., 2021]. The China Kadoorie Biobank recruited 512,891 adults from ten geographically diverse regions between 2004 and 2008, with linkage to death and disease registries and a biobank of blood samples, and has provided some of the most informative evidence on the health effects of tobacco, alcohol, and diet in an East Asian population [Chen Z et al., 2011]. The Estonian Biobank, comprising more than 200,000 participants representing a substantial fraction of the adult population of a small country, has pioneered the return of genetic risk information through the national health system and the implementation of pharmacogenomic prescribing decision support [Leitsalu et al., 2015]. Beyond these, several programmes have been built specifically to address continental gaps. The GenomeAsia 100K project characterised variation across Asian populations, demonstrating substantial structure and the presence of variants of medical relevance that are absent from European-dominated references [GenomeAsia100K Consortium, 2019]. Sequencing initiatives in Africa, including the Human Heredity and Health in Africa consortium and several national programmes, have documented that African populations harbour the greatest human genetic diversity, that a large majority of variants observed in African individuals are not present in existing databases, and that the resulting interpretive uncertainty is both a scientific and an equity problem [Mulder et al., 2018]. The Human Pangenome Reference Consortium has begun to replace the single linear reference with a graph-based representation of multiple assembled genomes, which is expected to reduce reference bias in the alignment and variant calling of structurally diverse regions, but the clinical implications of pangenome-based pipelines are still being established [Liao et al., 2023].

5.7 deCODE and the Icelandic model

The Icelandic resource combines whole-genome sequencing of a large fraction of a small national population with an unusually complete genealogy and nationwide health data, and it has been the source of several landmark discoveries in medical genetics, including variants of large effect in lipid metabolism, cancer predisposition, and rare disease [Gudbjartsson et al., 2015]. Its productivity derives from three properties: the ability to impute variants into a much larger set of genotyped individuals using genealogy-based long-range phasing, giving effective sample sizes far larger than the number of sequenced individuals; the availability of national disease registers; and the stability of the population, which reduces confounding by population structure. Its limitations are those of all isolate resources, and its governance has been the subject of sustained ethical debate concerning consent, commercial involvement, and the protection of a population that is small enough for re-identification to be a realistic concern.

6. Cancer genome databases

6.1 The Cancer Genome Atlas

Cancer genomics required a different architecture from germline variation resources, because the object of study is the somatic alteration acquired by a tumour rather than the inherited variant shared by all cells of a person. The Cancer Genome Atlas, initiated in 2006 as a joint programme of the National Cancer Institute and the National Human Genome Research Institute, was designed to characterise the molecular landscape of human malignancy comprehensively across multiple data types. Its pan-cancer analysis reported the integrated characterisation of over 11,000 tumours from 33 cancer types, combining exome and whole-genome sequencing, RNA sequencing, DNA methylation arrays, copy-number arrays, and reverse-phase protein arrays, with matched normal tissue for the distinction of somatic from germline variation [Weinstein et al., 2013]. The programme established several principles that now govern molecular oncology: that tumours cluster by cell of origin more strongly than by tissue of residence, that a limited number of recurrently altered pathways account for a large fraction of the mutational burden across histologies, and that molecular subtypes within a single histological diagnosis can differ substantially in prognosis and therapeutic vulnerability. The subsequent pan-cancer atlas analysis of more than 10,000 tumours confirmed that cell-of-origin patterns dominate molecular classification and demonstrated that integrative clustering yields subtypes with distinct clinical behaviour [Hoadley et al., 2018].

The medical consequences of these resources are extensive. They provided the reference against which the frequency and prognostic significance of individual somatic mutations is judged, the discovery set from which such targets as isocitrate dehydrogenase in glioma and fibroblast growth factor receptor alterations in urothelial carcinoma were identified, and the empirical basis for tumour-agnostic drug development in which a molecular alteration rather than a histological diagnosis defines eligibility. The resource also established the practical importance of matched normal sequencing: without it, germline variants are systematically misclassified as somatic, and clinically significant inherited predisposition is missed in the very patients for whom it matters most.

The limitations of the programme are now well recognised. Sample sizes per tumour type were modest by contemporary standards, and many tumour types were dominated by a single histology; the cohort was drawn largely from North American and European centres, so that the representation of ancestrally diverse populations is limited; the data are largely from primary untreated tumours, so that the molecular evolution of metastasis and of acquired resistance is underrepresented; and the clinical annotation, while extensive, was not designed for the evaluation of treatment response in the way that modern registry-linked cohorts are.

6.2 The International Cancer Genome Consortium and whole-genome analysis

The International Cancer Genome Consortium was established in 2008 to extend cancer genome characterisation internationally and to a larger number of tumour types, with the stated objective of systematically studying more than 25,000 cancer genomes at genomic, epigenomic, and transcriptomic levels and releasing the data rapidly to the research community [Hudson et al., 2010]. Its successor programme, ICGC ARGO, was designed to add treatment and outcome data at scale, converting a catalogue of mutations into a resource for clinical association. The most consequential output of the consortium was the pan-cancer analysis of whole genomes, which characterised 2,658 cancers across 38 tumour types using whole-genome sequencing and documented the prevalence of non-coding driver mutations, the architecture of structural variation, the timing of mutational processes in tumour evolution, and the presence of recurrent alterations in regulatory regions that exome-based studies could not detect [ICGC/TCGA Pan-Cancer Analysis of Whole Genomes Consortium, 2020]. This analysis demonstrated that a substantial fraction of cancer drivers lie outside protein-coding sequence, that mutational

signatures can be used to infer the aetiological exposures that generated a tumour, and that whole-genome sequencing provides clinically relevant information beyond that obtainable from panels, a finding that has since informed the adoption of genome-wide testing in several national health systems.

6.3 COSMIC and cBioPortal

The Catalogue Of Somatic Mutations In Cancer, maintained at the Wellcome Sanger Institute, is the most comprehensive expert-curated resource for somatic variation in human cancer. It integrates data from the literature, from large-scale sequencing screens, and from genome-wide systematic screens, and covers coding and non-coding mutations, gene fusions, copy-number alterations, and mutational signatures, together with resistance and prognostic annotations [Tate et al., 2019]. Its clinical function is to answer whether a somatic variant has been observed recurrently in cancer, at what frequency, in which histologies, and with what therapeutic or prognostic significance, which is precisely the question a molecular tumour board must resolve. Its principal methodological caution is ascertainment: because COSMIC aggregates published and screened data, the frequency of a variant within COSMIC reflects the intensity with which the relevant gene has been studied rather than the population frequency of the alteration, and hypermutated tumours and well-studied genes are overrepresented.

The cBioPortal for Cancer Genomics addresses the complementary problem of access and integration, providing an open platform through which multidimensional cancer genomics data sets, including those generated by TCGA and by individual institutions, can be queried, visualised, and analysed without programming expertise [Cerami et al., 2012; Gao et al., 2013]. Its importance lies less in adding data than in reducing the technical barrier to using data: a clinician or biologist can examine the alteration frequency of a gene across cohorts, the co-occurrence and mutual exclusivity of alterations in a pathway, the correlation of expression with copy number, and the survival of patients stratified by alteration status, within a single interface. The design principle of the portal, that data should be both explorable and downloadable, has become a model for subsequent resources.

6.4 Registry-linked clinical cancer genomics

A distinct class of resource has emerged from the embedding of genomic profiling in routine oncology practice. AACR Project GENIE aggregates de-identified clinical-grade targeted panel sequencing data from participating institutions internationally and links each profile to limited clinical annotation, producing a resource of well over 100,000 tumours that is large enough to support the identification of rare variant–drug associations and to characterise the genomic landscape of histologies too uncommon for single-institution study [AACR Project GENIE Consortium, 2017]. National health system programmes have generated analogous resources. The 100,000 Genomes Project of Genomics England sequenced tumours with matched normal tissue alongside rare disease probands within a national health service, establishing the feasibility of clinical-grade whole-genome cancer testing at national scale and providing the data infrastructure for England's subsequent cancer testing programmes [Turnbull et al., 2018; Smedley et al., 2021]. In the United States, institutional programmes such as MSK-IMPACT have produced prospective, longitudinally annotated clinical sequencing cohorts of tens of thousands of patients, in which genomic alterations are linked to treatment and outcome, enabling the evaluation of biomarker-defined drug response outside the constraints of trial eligibility.

The medical value of registry-linked cancer genomics is concentrated in three applications: the identification of off-label therapeutic vulnerabilities in patients who have exhausted standard options, the characterisation of resistance mechanisms through paired pre- and post-treatment sequencing, and the estimation of the true population frequency of actionable alterations, which determines the cost-effectiveness of universal testing strategies. The limitations are those of all observational registry data: treatment exposure is recorded rather than randomised, outcomes

are incompletely captured, and the institutions that contribute are those with the resources to sequence, so that the populations represented are systematically advantaged.

6.5 Functional cancer genomics

A final component of the cancer data ecosystem shifts the question from what is altered to what is required. The Cancer Dependency Map project performed genome-scale loss-of-function screens using RNA interference and CRISPR–Cas9 across hundreds of cancer cell lines, identifying genetic dependencies and linking them to molecular features of the cell lines, thereby producing a resource in which the vulnerability of a tumour can be predicted from its molecular profile rather than discovered empirically [Tsherniak et al., 2017]. This resource complements the mutational catalogues: a mutation establishes association with disease, whereas a dependency establishes that the gene is required for the viability of a defined cellular context, which is the stronger evidence for therapeutic targeting. Its limitations concern model fidelity, since immortalised cell lines do not recapitulate the tumour microenvironment, immune context, or pharmacokinetics, and its clinical translation therefore depends on validation in patient-derived models and trials (Fig. 4).

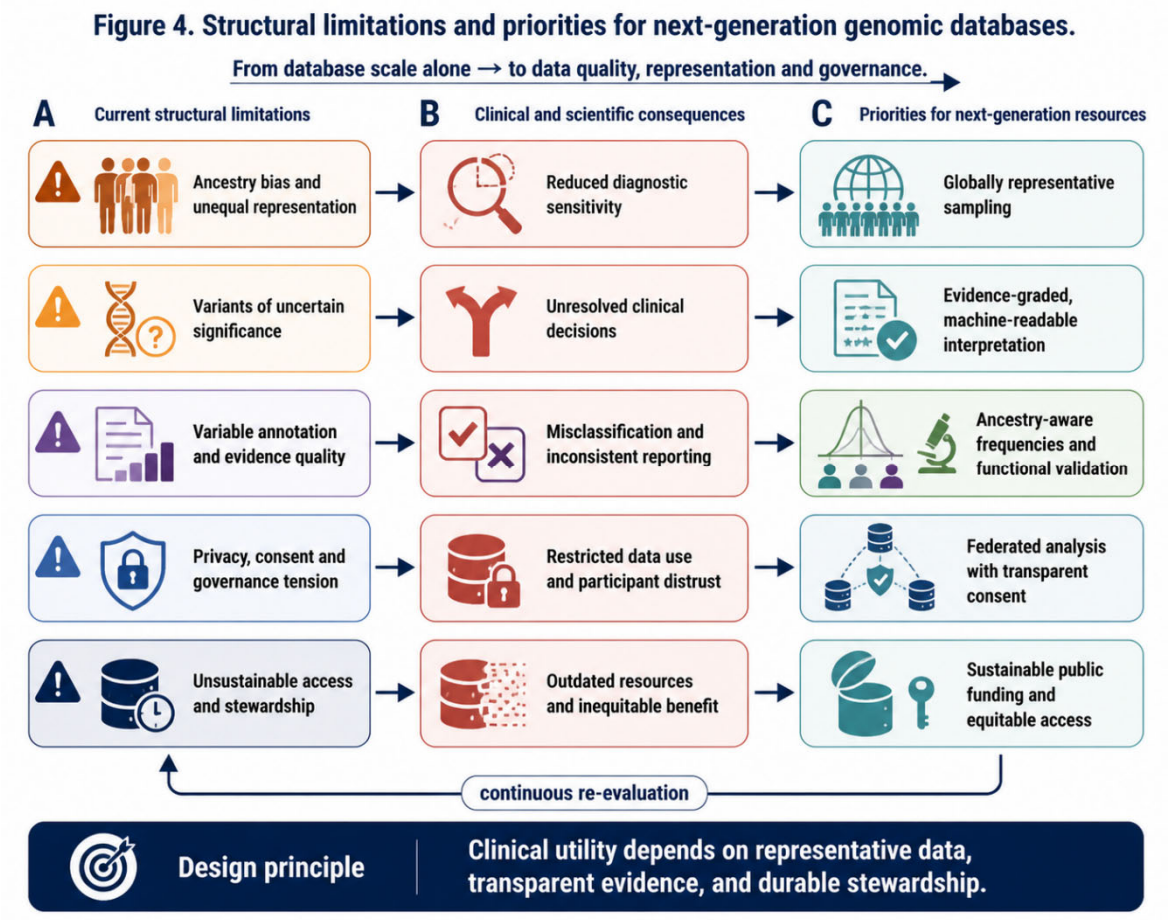


Figure 4. Structural limitations and priorities for next-generation genomic databases. Conceptual framework linking major limitations of current genomic databases with their clinical and scientific consequences and proposed priorities for future resource development. **(A)** Five structural limitations are shown: ancestry bias and unequal population representation; the accumulation of variants of uncertain significance; variable annotation and evidence quality; tensions involving privacy, consent, and governance; and unsustainable access and long-term stewardship. **(B)** These limitations may lead to reduced diagnostic sensitivity, unresolved clinical decision-making, variant misclassification and inconsistent reporting, restricted data use and participant distrust, and outdated resources with inequitable distribution of benefit. **(C)** Corresponding priorities include globally representative sampling; evidence-graded and machine-readable variant interpretation;

ancestry-aware frequency estimates combined with functional validation; federated analysis supported by transparent consent frameworks; and sustainable public funding with equitable access. Arrows indicate the relationship between structural limitations, their downstream consequences, and potential corrective strategies. The lower banner summarizes the central design principle that clinical utility depends on representative data, transparent evidence, and durable stewardship. Continuous re-evaluation is required as new populations, annotations, functional data, and governance models are incorporated into genomic resources.

7. Functional and regulatory genomic atlases

7.1 GTEx

The interpretation of non-coding variation, which constitutes the overwhelming majority of disease-associated variants identified by genome-wide association, requires knowledge of what the non-coding sequence does. The Genotype-Tissue Expression project was established to map the effect of genetic variation on gene expression and splicing across human tissues, and its atlas release reported expression quantitative trait loci and splicing quantitative trait loci derived from 15,201 samples across 49 tissues from 838 donors, together with the identification of shared and tissue-specific regulatory effects, the colocalisation of regulatory variants with disease-associated loci, and a substantially improved ability to interpret the mechanism of non-coding associations [GTEx Consortium, 2020]. For clinical genomics, GTEx supplies the mechanistic link between a statistical association and a plausible biological consequence: a variant in tight linkage disequilibrium with a disease-associated locus that also alters the expression of a nearby gene in a disease-relevant tissue provides evidence of mechanism that a bare association does not.

The limitations of the resource are structural. Sample sizes per tissue are modest, all donors are post-mortem and largely of European ancestry, tissue collection is opportunistic rather than representative of disease states, and the atlas describes regulatory effects in bulk tissue rather than at the resolution of individual cell types. The consequence is that the absence of a regulatory effect in GTEx is weak evidence of no effect, while a detected effect provides a mechanism that still requires functional confirmation.

7.2 ENCODE, the Human Cell Atlas, and single-cell resolution

The Encyclopedia of DNA Elements project provided the comprehensive annotation of functional elements in the human genome, integrating transcription factor binding, chromatin accessibility, histone modification, DNA methylation, and transcription across hundreds of cell types and experimental conditions, and reporting that the great majority of the genome shows evidence of biochemical activity in at least one context, with a substantial fraction of disease-associated variants falling within annotated regulatory elements [Moore et al., 2020]. The practical clinical value of ENCODE is in prioritisation: candidate regulatory variants can be evaluated against cell-type-specific chromatin state and transcription factor motifs, converting an undifferentiated set of non-coding candidates into a ranked list.

The Human Cell Atlas and related single-cell initiatives address the resolution problem left by bulk atlases, characterising gene expression and chromatin state at the level of individual cells across tissues and developmental stages, and thereby identifying the cell types in which a disease-associated gene is expressed and the cellular programmes that are dysregulated in disease [Regev et al., 2017]. For genomic medicine, the significance is that many disease phenotypes are consequences of the dysfunction of a small number of specialised cell types that bulk tissue analysis averages away, and that the interpretation of a gene's role accordingly requires cell-type-resolved data. The limitations are technical and interpretive: single-cell data are sparse, sensitive to dissociation artefacts, expensive, and for human tissues often derived from a small number of donors, so that the atlases function as hypothesis-generating resources rather than as reference standards.

7.3 Multi-omic and proteomic resources

The integration of proteomic, metabolomic, and imaging data with genotype has become the newest layer of population-scale resources. In UK Biobank, plasma proteomic profiling of more than 50,000 participants across approximately 3,000 proteins has enabled proteome-wide association studies that identify protein quantitative trait loci, distinguish cis from trans regulation, provide instruments for Mendelian randomisation of drug targets, and identify circulating proteins with predictive value for incident disease [Sun et al., 2023]. The medical attraction of proteomic resources is that proteins are the proximate agents of most drug action, so that a genetic variant that changes protein abundance is a more direct proxy for a therapeutic target than a variant that changes disease risk. The limitations are those of affinity-based measurement, which is subject to epitope effects, cross-reactivity, and limited absolute quantification, so that protein quantitative trait loci sometimes reflect assay behaviour rather than biology.

8. Data access, aggregation, and governance infrastructure

The databases described above are accessible through an array of intermediate infrastructures that determine, as much as the data themselves do, what research and clinical use is possible.

The Database of Genotypes and Phenotypes, established by the National Center for Biotechnology Information in 2006, was the first general-purpose federal archive for individual-level genotype and phenotype data from studies funded by the National Institutes of Health, and it established the model of controlled access through data access committees, in which summary data are public but individual-level data require an approved research use statement [Mailman et al., 2007]. The European Genome-phenome Archive performs the analogous function for European studies, archiving controlled-access sequence and phenotype data consented for biomedical research and providing a brokering service that keeps data at the hosting institution while managing authentication and authorisation centrally [Lappalainen et al., 2015]. These archives are the mechanism through which the majority of individual-level genomic data in the world is made available, and their design embodies a specific policy judgement: that summary-level openness and individual-level control can coexist, and that the friction of controlled access is an acceptable price for participant trust.

Federated analysis architectures have been developed to reduce that friction without abandoning control. The Global Alliance for Genomics and Health has produced technical standards, including the Beacon protocol for querying the presence of an allele without transferring data, the htsget protocol for streaming sequence reads, and the phenopacket schema for exchanging structured phenotypic information, together with a policy framework addressing consent, security, and data use [Global Alliance for Genomics and Health, 2022]. Matchmaker Exchange and GeneMatcher implement a complementary model in which laboratories and clinicians register a gene and a phenotype, or a candidate variant and a phenotype, and are automatically matched with others who have registered a compatible case, enabling the aggregation of evidence for ultra-rare conditions that no single centre could assemble [Sobreira et al., 2015; Philippakis et al., 2015]. This mechanism has been responsible for the resolution of a substantial number of previously undiagnosable cases and for the establishment of many gene–disease relationships.

Clinical data commons platforms, of which the All of Us Researcher Workbench is the most prominent example, combine cloud-hosted data with tiered access and bring-your-own-analysis environments, so that researchers can compute against individual-level data without downloading it, and can publish reproducible notebooks alongside their findings [All of Us Research Program Genomics Investigators, 2024]. This model addresses two persistent problems of genomic data sharing simultaneously: the impracticality of transferring petabyte-scale datasets, and the difficulty of verifying computational analyses that were performed on data the reader cannot access.

The governance dimension is not administrative detail. Consent models range from broad consent for future unspecified research, through dynamic consent in which participants can modify permissions over time, to tiered consent in which specific uses are individually authorised. Re-identification risk is a function of the data rather than of identifiers alone, since genomic data are intrinsically identifying and can be linked to public genealogy and ancestry resources; the practical consequence is that de-identification cannot be treated as anonymisation, and that governance must rely on access control, use agreements, and penalties rather than on the removal of names. Return of results raises a further set of questions about duty of care, clinical validity, the management of variants of uncertain significance in participants who are not patients, and the resource implications of following up findings in cohorts of hundreds of thousands. The programmes that have addressed these questions most systematically, including UK Biobank, All of Us, the Estonian Biobank, FinnGen, and Genomics England, have converged on a common model: a defined list of actionable genes, an accredited laboratory pathway for confirmation, a clinical route for management, and an explicit statement that participants may decline to receive findings.

9. Comparative synthesis of scale, function, and access

The resources reviewed above differ by five orders of magnitude in the number of individuals represented and by a comparable range in the depth of their phenotypic annotation. The table below summarises the principal resources according to their primary medical function, their approximate scale, the categories of data they hold, and their predominant access model. Figures are those reported in the primary descriptions cited and should be treated as indicative rather than current, since most of these resources are updated continuously.

Resource	Primary function	Approximate scale	Principal data types	Dominant access model
1000 Genomes Project	Global haplotype reference for imputation	2,504 individuals, 26 populations	Low-coverage whole genome, exome, phased haplotypes	Fully open
ExAC	Population allele frequency, gene constraint	60,706 exomes	Exome variants and frequencies	Fully open
gnomAD v2	Population allele frequency, gene constraint	141,456 individuals (125,748 exomes, 15,708 genomes)	Exome and genome variants, constraint metrics	Fully open
gnomAD v4	Population frequency, non-coding constraint	807,162 individuals (730,947 exomes, 76,215 genomes)	Variants including structural and copy-number, constraint maps	Fully open
TOPMed	Diverse deep-coverage reference, imputation	53,831 genomes in first release	Whole genomes, >400 million variants	Controlled access for individual data; summary open

ClinVar	Curated clinical variant interpretation	Several million variant records, >7 million submissions	Classifications, evidence, review status	Fully open
ClinGen	Authoritative gene and variant adjudication	Expert panels across major disease domains	Gene–disease validity, dosage sensitivity, expert classifications	Fully open
OMIM	Phenotype–gene knowledge base	>25,000 entries	Curated descriptions, inheritance, molecular basis	Open with registration; professional tier
HGMD	Published disease-causing germline lesions	>200,000 lesions in >8,000 genes	Curated published mutations	Subscription (public version lagged)
UK Biobank	Deeply phenotyped population cohort	~500,000 participants; 490,640 whole genomes	Genotypes, exomes, genomes, imaging, biomarkers, proteomics, health records	Application-based access fee
All of Us	Ancestrally diverse cohort with health records	~245,000 whole genomes released, growing to >1 million participants	Genomes, surveys, electronic health records	Cloud workbench with tiered access
FinnGen	Isolate population with national registries	~500,000 participants	Genotypes, imputed variants, registry endpoints	Application-based; summary results open
Million Veteran Program	Large clinical cohort with prescription data	>1 million enrolled	Genotypes, health records, survey data	Controlled access via federal programme
BioBank Japan	Disease-focused Japanese cohort	>260,000 participants	DNA, serum, clinical data, genotypes	Application-based
Taiwan Biobank	Han Chinese population reference	>100,000 genotyped, >500,000 in precision medicine initiative	Genotypes, whole genomes, medical records	Application-based

China Kadoorie Biobank	Prospective cohort with exposure data	512,891 adults	Genotypes, questionnaires, registry linkage, biosamples	Application-based
Estonian Biobank	National cohort with return of results	>200,000 participants	Genotypes, genomes, national health records	Application-based; participant return
deCODE	Isolate population with genealogy	Whole genomes of a large national fraction	Genomes, genealogy, national health data	Commercial and collaborative access
TCGA	Pan-cancer molecular characterisation	>11,000 tumours, 33 cancer types	Exome, genome, RNA, methylation, copy number, protein	Fully open (controlled for germline)
ICGC / PCAWG	International cancer genome analysis	>25,000 genomes planned; 2,658 in pan-cancer analysis	Whole genomes, transcriptomes, epigenomes	Open with controlled tiers
COSMIC	Somatic variant catalogue	Millions of curated somatic records	Mutations, fusions, copy number, signatures	Open with registration; commercial licence
cBioPortal	Integrated cancer genomics exploration	Hundreds of studies, >100,000 samples	Multi-omic cancer datasets	Fully open
AACR GENIE	Registry-linked clinical cancer genomics	>100,000 tumours	Clinical-grade panel sequencing with annotation	Open with registration
GTEx	Tissue-specific regulatory effects	15,201 samples, 49 tissues, 838 donors	Expression, splicing, eQTL, sQTL	Open with controlled tiers
ENCODE	Functional element annotation	Hundreds of cell types and assays	Chromatin, transcription factor binding, methylation	Fully open
Human Cell Atlas	Cell-type-resolved expression	Millions of cells across tissues	Single-cell RNA and chromatin data	Open with controlled tiers
Cancer Dependency Map	Functional target validation	>500 cell lines in initial release	Genome-scale CRISPR and RNAi screens	Fully open

Three patterns emerge from this comparison. First, scale and phenotypic depth are inversely related. The largest variant catalogues, gnomAD and TOPMed, hold almost no clinical phenotype, while the most richly phenotyped cohorts, UK Biobank, All of Us, and FinnGen, represent at most a few hundred thousand to about a million people. No resource combines million-scale sequencing with comprehensive longitudinal clinical phenotyping, and the cost of doing so explains why federated and registry-linked designs have become the dominant strategy. Second, openness is inversely related to identifiability. Resources built from aggregate counts and summary statistics, including gnomAD, ClinVar, and cBioPortal, are fully open, whereas resources holding individual-level genomes linked to health records are accessible only through controlled application. Third, the resources that have most directly changed clinical practice are not the largest but those whose outputs are formatted for clinical decision-making: ClinVar and ClinGen because they supply classifications that laboratories can cite, gnomAD because it supplies frequencies that laboratories can filter against, and GTEx because it supplies mechanisms that can be stated in a report.

10. Clinical applications

10.1 Rare disease diagnosis

Rare disease is the application in which genome databases most directly and demonstrably alter clinical outcomes. The diagnostic process is essentially a filtration of the four to five million variants in a genome against successive databases: population frequency to remove common benign variation, gene constraint and predicted consequence to prioritise plausible functional effects, phenotype–gene resources to restrict the search to genes compatible with the presentation, and curated clinical archives to identify previously interpreted variants. The contribution of each database layer can be quantified by the effect of removing it, and the literature on reanalysis demonstrates that diagnostic yield depends on the currency of all layers simultaneously.

The English 100,000 Genomes Project provided the most rigorous evidence of what this pipeline achieves in a public health system. Its pilot analysis of patients with rare disease across multiple diagnostic categories reported a genetic diagnosis in 25 per cent of probands, a figure substantially higher than that obtained from standard testing in many of the same categories, with a further substantial proportion carrying variants of uncertain significance in genes plausibly related to the phenotype; approximately one quarter of the diagnoses had immediate implications for clinical management of the patient or relatives [Smedley et al., 2021]. Crucially, a substantial fraction of diagnoses were made only through the combination of clinical testing and research analysis, indicating that the interpretive database layer and the research reanalysis layer add yield that routine reporting does not capture. Comparable yields have been reported in national programmes in Australia, Canada, and the United States, and the consistent finding across them is that diagnostic rate is a function of the completeness of the reference databases and the persistence of reanalysis rather than of sequencing technology alone.

The specific value of large population databases in this context is best illustrated by the reclassification problem. Variants once reported as pathogenic on the basis of small case series have repeatedly been shown, when their frequency is estimated in a large reference population, to be too common to cause the severe disease with which they were associated. The ExAC analysis quantified this directly, finding that the average individual carries dozens of variants annotated as disease-causing in the literature, a result that could not have been obtained from any single study and that has since altered reporting practice for hundreds of variants [Lek et al., 2016]. The corollary is that diagnostic laboratories must re-examine historical classifications against current population data, and health systems that fund systematic reanalysis recover diagnoses that were technically achievable years earlier.

10.2 Molecular oncology

In oncology the databases serve a different clinical function: not the identification of a single causal variant but the matching of a tumour's mutational profile to a therapeutic option. The routine use of tumour sequencing in advanced disease depends on curated catalogues that establish which alterations are recurrent, actionable, and associated with response or resistance, and on integrated portals that allow a molecular tumour board to compare a patient's profile with cohorts of similar tumours. The TCGA and ICGC catalogues defined the baseline landscape [Weinstein et al., 2013; ICGC/TCGA Pan-Cancer Analysis of Whole Genomes Consortium, 2020]; COSMIC provides the curated annotation of individual alterations [Tate et al., 2019]; cBioPortal provides the exploratory interface [Cerami et al., 2012; Gao et al., 2013]; and registry-linked programmes provide the clinical outcomes that allow actionability to be assessed in real practice [AACR Project GENIE Consortium, 2017].

Three clinically consequential findings have emerged from this layer. First, tumour-agnostic biomarkers, defined by molecular alteration rather than histology, have entered routine practice, and their validation required databases large enough to assemble sufficient patients across rare histologies. Second, the distinction between germline and somatic variation has become a clinical safety issue, since tumour sequencing without matched normal tissue misclassifies inherited pathogenic variants as somatic and thereby misses the opportunity to test relatives; programmes that mandate matched normal sequencing have documented clinically significant germline findings in a meaningful minority of patients. Third, the analysis of paired pre- and post-treatment samples has identified resistance mechanisms that are now targets for second-line therapy, an application that requires longitudinal rather than cross-sectional databases and that motivates the linkage of genomic data to treatment registries.

10.3 Pharmacogenomics

Pharmacogenomic implementation depends on databases of a specific structure: gene–drug pairs with defined actionability, star-allele definitions that map diplotypes to phenotypes, and population frequency data that determine the proportion of patients affected. The Clinical Pharmacogenetics Implementation Consortium produces peer-reviewed, freely accessible guidelines for gene–drug pairs, specifying how genotype should alter prescribing rather than merely asserting an association [Relling & Klein, 2011]. The Pharmacogenomics Knowledge Base provides the underlying annotation of variant function, drug labels, and pathway information. Population frequency data from gnomAD and from national biobanks determine allele frequencies that differ substantially across ancestries, with direct consequences for the number of patients needing dose adjustment; the Estonian Biobank has used its national cohort to implement pharmacogenomic prescribing decision support at health system scale, and FinnGen and several other programmes have developed comparable infrastructure [Leitsalu et al., 2015; Kurki et al., 2023].

The clinical yield of pharmacogenomics has been extended by biobank-based studies in which prescription records serve as both exposure and outcome, enabling the identification of genotype–drug interactions that influence drug discontinuation, adverse events, and efficacy. The Million Veteran Program is particularly suited to this design because its prescription records are complete, longitudinal, and linked to laboratory and outcome data [Gaziano et al., 2016]. The principal limitation is that observational prescription data reflect clinician behaviour as much as pharmacology, so that database-derived pharmacogenomic associations require prospective confirmation before they change guidelines.

10.4 Polygenic risk and common disease prediction

The use of genome-wide polygenic scores in clinical practice is the application in which the dependence on database composition is most explicit. Scores derived from large genome-wide association studies, such as those enabled by UK Biobank and FinnGen, can identify individuals

whose risk of coronary artery disease, atrial fibrillation, type 2 diabetes, inflammatory bowel disease, and breast cancer is equivalent to that conferred by monogenic mutations, and can do so for a far larger fraction of the population than monogenic testing reaches [Khera et al., 2018]. The medical logic is that earlier identification of high-risk individuals permits earlier initiation of preventive therapy, and several health systems have begun pilot programmes in which polygenic scores are returned alongside conventional risk factors.

The limitation is equally explicit and is a direct consequence of database composition. Because the overwhelming majority of genome-wide association data are drawn from individuals of European ancestry, the predictive accuracy of polygenic scores is substantially lower in other populations, and the disparity increases with the divergence of the target population from the discovery population [Martin et al., 2019]. Deploying a score derived in Europeans in a health system serving diverse populations therefore risks widening rather than narrowing health disparities, both by miscalibrating risk in underrepresented groups and by directing preventive resources toward the populations in which the score performs best. This is the clearest example in genomic medicine of a technical limitation that is simultaneously an equity problem, and it cannot be resolved by statistical adjustment; it requires the inclusion of diverse participants in the underlying databases at a scale that only the largest biobanks and national programmes can achieve [Popejoy & Fullerton, 2016; Sirugo et al., 2019].

10.5 Population screening and return of results

The final application, population-scale genomic screening, converts biobanks from research resources into public health infrastructure. The model that has emerged is targeted screening of a defined set of actionable genes in unselected adults, on the argument that the combined population frequency of actionable pathogenic variants is high enough to justify systematic ascertainment, and that the conditions concerned are sufficiently treatable for early identification to change outcome. UK Biobank contributed the essential empirical input to this argument by measuring the frequency and penetrance of pathogenic variants in unselected participants, showing that carriers are more numerous than clinic-based estimates implied and that penetrance is generally lower than in family-based studies [Sudlow et al., 2015; UK Biobank Whole-Genome Sequencing Consortium, 2025]. The Estonian Biobank and FinnGen have demonstrated operational return of results within national health systems, and All of Us has established a return pathway designed for a diverse population [All of Us Research Program Genomics Investigators, 2024].

The unresolved questions in population screening are clinical and economic rather than technical: what list of genes is appropriate, what evidence threshold justifies returning a variant of uncertain significance, how confirmatory testing and cascade testing should be funded, how the psychological and insurance consequences of a positive result should be managed, and how the substantial proportion of carriers who decline follow-up should be handled. Databases supply the frequency and penetrance estimates that inform these decisions, but they cannot resolve them, and the heterogeneity of national approaches reflects genuine differences in health system structure and social values rather than differences in evidence.

11. Limitations and challenges

11.1 Ancestry bias and the portability of knowledge

The most consequential limitation of the current database ecology is the concentration of genomic data in populations of European ancestry. Systematic surveys have documented that the great majority of participants in genome-wide association studies have been of European descent, that this proportion has remained high even as total sample sizes have grown substantially, and that the imbalance is not self-correcting because discovery in well-powered cohorts yields more discoveries that motivate further study of the same cohorts [Popejoy & Fullerton, 2016; Sirugo et al., 2019]. The consequences are both scientific and clinical. Scientifically, the restricted sampling

limits the discovery of variants and loci that are common only in unstudied populations, reduces the resolution of fine-mapping, and produces a distorted picture of the genetic architecture of disease. Clinically, it produces variant classifications of lower confidence in non-European patients, higher rates of variants of uncertain significance, greater likelihood of misclassifying a benign population-specific variant as pathogenic, and polygenic scores of reduced accuracy [Martin et al., 2019].

The remedies are known and are being implemented unevenly. Deliberate oversampling of underrepresented groups, as in All of Us, changes the composition of cohorts but requires sustained community engagement and attention to the reasons for distrust, which are historical and legitimate. Sequencing of diverse populations changes reference panels but must be accompanied by ancestry-appropriate frequency reporting in clinical interfaces, since a variant common in one population and rare in another will otherwise be interpreted inconsistently depending on which reference the laboratory happens to consult. Pangenome graph references reduce alignment bias in structurally diverse regions but do not by themselves correct frequency ascertainment [Liao et al., 2023]. The GenomeAsia 100K project and African sequencing initiatives have demonstrated both the scientific yield and the scale of the remaining gap [GenomeAsia100K Consortium, 2019; Mulder et al., 2018].

11.2 Variants of uncertain significance

The second structural problem is the accumulation of variants whose significance cannot be determined. Because rare variation is abundant and functional evidence is scarce, the majority of variants newly observed in a clinical test cannot be classified, and the proportion classified as uncertain rises with the divergence of the patient's ancestry from the reference populations. The clinical costs are borne by patients: uncertain results fail to end diagnostic odysseys, may prompt inappropriate surveillance or prophylactic intervention, and generate anxiety that persists because reclassification is not guaranteed. Programmes that systematically reanalyse variant files have reported reclassification rates sufficient to justify periodic review as a standard of care, but reanalysis is labour-intensive, poorly reimbursed, and inconsistently implemented across health systems.

Three strategies are in use to reduce the uncertain fraction. The first is functional evidence generation at scale, using multiplexed assays of variant effect and deep mutational scanning to classify thousands of variants in a single experiment, with the results deposited in databases and referenced in classifications; this approach is most advanced for well-characterised genes and is being extended through coordinated efforts to standardise assay validation. The second is computational prediction, in which machine learning models trained on population constraint patterns, evolutionary conservation, protein structure, and saturation mutagenesis data assign probabilistic pathogenicity; such predictions are now usable as supporting evidence under ACMG/AMP criteria but are explicitly not sufficient alone. The third is data sharing across laboratories, in which the aggregation of cases and segregations converts uncertain variants into classifiable ones; Matchmaker Exchange and GeneMatcher provide the mechanism for rare genes, and national programmes provide it for common genes [Sobreira et al., 2015; Philippakis et al., 2015].

11.3 Annotation quality and the provenance problem

A third limitation concerns the quality of what databases contain. Curated archives inherit the errors of the literature they curate, and the literature contains a documented burden of variants described as pathogenic in small studies that are in fact benign polymorphisms, of gene–disease associations that fail to replicate, and of phenotype attributions that reflect ascertainment rather than causation. Because these assertions are copied from paper to database to report, an error introduced once can propagate indefinitely, and the propagation is invisible to users who consult only the aggregated classification rather than the underlying evidence.

The response has been structural rather than merely technical. Evidence grading, as implemented in ClinGen's gene–disease validity framework, makes the strength of the underlying evidence an explicit attribute of every assertion [Rehm et al., 2015]. Review status in ClinVar distinguishes expert-panel consensus from single-submitter opinion [Landrum et al., 2018]. The ACMG/AMP framework requires that population and curation databases be weighted according to the quality of their evidence rather than treated as authoritative [Richards et al., 2015]. Gene constraint metrics, derived from population data rather than from publication, provide an independent check on claims of haploinsufficiency [Karczewski et al., 2020]. None of these mechanisms eliminates error, but together they make the provenance of an assertion inspectable, which is the precondition for rational disagreement between laboratories.

11.4 Privacy, consent, and governance

The fourth limitation is the tension between the scientific value of data linkage and the privacy interests of participants. Genomic data are intrinsically identifying: a sequence can be linked to a named individual through public genealogy databases even in the absence of direct identifiers, and the risk increases with the richness of the linked phenotype. Linkage to health records is precisely what makes biobanks medically valuable and precisely what makes re-identification consequential, since the harm of disclosure is not the sequence but the diagnosis, prescription, or reproductive information attached to it. The practical consequence is that the concept of anonymisation is inapplicable, and that governance must rest on controlled access, enforceable use agreements, transparency about commercial involvement, and meaningful penalties for misuse [Mailman et al., 2007; Lappalainen et al., 2015].

The consent architecture is a related and contested question. Broad consent for future unspecified research is efficient and has been widely adopted, but it delegates to governance bodies decisions that participants might wish to make themselves. Dynamic consent, in which participants can modify permissions over time, respects autonomy but imposes an ongoing administrative burden and may produce a dataset that is less useful because permissions are heterogeneous. Tiered consent attempts a middle path. The empirical evidence suggests that participants are generally more willing to permit broad use than researchers anticipate, provided that the purpose, the commercial dimension, and the return-of-results policy are clearly stated, which implies that the limiting factor is often the quality of communication rather than the breadth of consent. Federated architectures, in which analysis occurs at the data holder and only aggregate results leave, offer a technical mechanism for reconciling use with control, and the standards produced by the Global Alliance for Genomics and Health provide the interoperability layer that such architectures require [Global Alliance for Genomics and Health, 2022].

11.5 Sustainability and equity of infrastructure

The final limitation is economic and institutional. The databases described in this review are public goods whose funding is typically time-limited, project-based, and vulnerable to shifts in public and philanthropic priorities, while their costs are recurrent: storage, computation, curation, help-desk support, security, and the maintenance of application programming interfaces on which clinical pipelines depend. The withdrawal or interruption of a reference resource creates a direct clinical hazard, because laboratories have embedded its identifiers and frequency estimates in validated pipelines and reports. Locus-specific databases have disappeared with the retirement of individual investigators, taking with them variant-level knowledge that was not captured elsewhere, and the same risk applies at larger scale to any resource without a durable institutional home.

Equity of participation compounds the problem. The populations most underrepresented in genomic databases are frequently those served by health systems with the least capacity to contribute data and the least capacity to use it, so that the benefits of genomic medicine risk accruing disproportionately to well-resourced populations while the costs and risks of participation are borne more broadly. The counterargument, that global data sharing benefits all

populations by improving reference resources, is sound in principle but insufficient in practice unless accompanied by investment in local capacity, local governance, and the return of results to the communities that contributed. The programmes that have managed this best have treated data contribution and capacity building as a single commitment rather than as separate transactions [Mulder et al., 2018; All of Us Research Program Genomics Investigators, 2024].

12. Future directions

Four developments are likely to determine the next decade of large-scale genomic databases.

The first is the shift from variant catalogues to phenotype-anchored, multi-omic cohorts. The marginal value of additional exomes in already well-represented ancestries is declining, whereas the marginal value of linking genomic data to proteomics, metabolomics, imaging, and longitudinal clinical outcomes remains high, as the UK Biobank proteomic release demonstrates [Sun et al., 2023]. The implication is that future investment should prioritise phenotypic depth and linkage over raw sequence count.

The second is the systematic replacement of the single linear reference with graph-based pangenome representations, which is expected to reduce reference bias in alignment and to improve variant calling in regions of structural diversity that are currently poorly characterised. The clinical translation of pangenome pipelines will require revalidation of existing analytic workflows and careful attention to the comparability of variant representation across reference systems [Liao et al., 2023].

The third is the industrialisation of variant effect measurement. Multiplexed functional assays, deep mutational scanning of disease genes, and saturation genome editing convert uncertain variants into measured ones, and the systematic deposition of these measurements in databases, with standardised validation criteria, is the most plausible route to a substantial reduction in the uncertain fraction. Coupled with improved computational prediction trained on experimental data, this approach could shift classification from literature curation to measurement, which would also reduce the ancestry-dependence of interpretation because functional effects are largely ancestry-independent.

The fourth is the integration of genomic databases into routine clinical information systems. The endpoint of this integration is not a portal that a specialist visits but a service that a clinical decision support system queries, returning actionable findings at the point of prescribing, screening, or diagnosis. The technical requirements are standardised interfaces, machine-readable evidence with provenance, versioning that permits reproducibility of historical reports, and governance that permits the use of individual-level data within the clinical environment. The policy requirements are reimbursement for reanalysis and reinterpretation, and public funding for the reference resources on which every clinical laboratory depends.

13. Conclusion

Large databases of human genomes have become the interpretive infrastructure of genomic medicine. The evidence that a variant is pathogenic is, in almost every case, comparative: it rests on the frequency of the variant in a population reference, the constraint of the gene in which it lies, the observation of the variant in affected individuals recorded in a curated archive, and the compatibility of the associated phenotype with the patient's presentation. Each of these comparisons depends on a database, and the databases are therefore not optional tools but the medium through which sequence data acquires clinical meaning.

The resources reviewed here differ in function, scale, and access model, and the most common error in their use is to treat one as a substitute for another. Population reference databases estimate frequency and constraint but cannot diagnose; clinical archives record interpretations but cannot estimate population frequency, because they are enriched for the variants they contain; biobanks establish genotype–phenotype associations with real outcomes but are not clinical services; cancer catalogues define the somatic landscape but are subject to profound

ascertainment bias; functional atlases supply mechanism but describe tissues rather than patients. Correct clinical reasoning requires knowing which resource answers which question, and weighting each according to the quality and representativeness of its evidence.

The achievements of the past two decades are substantial. Diagnostic yield in rare disease has risen to approximately one quarter of probands in national programmes, with immediate management implications in a meaningful fraction of those diagnosed. Molecular oncology now routinely matches tumour profiles to targeted therapy through curated catalogues and integrated portals. Pharmacogenomic prescribing is implemented at health system scale in several countries. Polygenic scores identify individuals at risk comparable to monogenic mutation carriers. Population screening for actionable variants has moved from proposal to pilot. None of these applications would be possible without the databases described in this review, and none of them is yet distributed equitably.

The limitations are equally clear and are structural rather than incidental. The persistent concentration of genomic data in European-ancestry populations degrades the accuracy of every downstream application in everyone else, and cannot be corrected statistically. Variants of uncertain significance remain the dominant output of clinical sequencing in many contexts, imposing real costs on patients who receive them. Annotation quality depends on evidence grading that is applied inconsistently. Governance must reconcile linkage with privacy in a domain where anonymisation is not available. And the public resources on which clinical care depends remain funded on project cycles that are shorter than the clinical pipelines that rely on them.

The priorities that follow are consequently not primarily technological. They are the globally representative sampling of human variation, the industrialisation of functional evidence, the standardisation of machine-readable evidence with provenance, the equitable distribution of the capacity to contribute and to use genomic data, and the durable public financing of openly accessible reference resources. Sequencing capacity is no longer the constraint on genomic medicine. The constraint is the completeness, quality, representativeness, and sustainability of the databases against which every sequence is read, and it is on those that the next phase of progress depends.

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Арпаның тас қаракүйе ауруына төзімділігін бағалаудың фитопатологиялық әдістері: қоздырғыштың биологиясы, патогенезі және өсімдіктің қорғаныш реакциялары

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Аңдатпа. Мақалада арпаның Hordeum vulgare тас қаракүйе аурының қоздырғышs Ustilago hordei саңырауқұлағының биологиясы, аурудың пайда болу себептері, инфекциялық процестің кезеңдері, өсімдіктің қорғаныш реакциялары және фитопатологиялық бағалау әдістері ғылыми әдебиеттер негізінде қарастырылды. Тұқым арқылы инфекцияның таралуы, өскіннің залалдануы, патогеннің жүйелі дамуы, генеративтік мүшелердің бұзылуы және төзімділік көрсеткішінің әдістемелік шектеулері талданады.
Түйін сөздер: арпа, тас қаракүйе, фитопатология, патогенез, телейтроспора, төзімділік, инокуляция.

Кіріспе. Арпа туыстың құрамында түр бар, оның 12-сі Қазақстанда кездеседі. Гүл шоғыры күрделі масақ, масақ өсінің әр бір кертпегінде 3 бір гүлді масақша орналасады. Гүлдену барысында өздігінен тозаңданады, тек бір жағдай бар: құрғақ әрі ыстық жаз айының уақытында айқас тозаңдануы мүмкін. Қосқатар арпаның 3 масақшадан тұратын тобы бар, оның тек ортаңғысында ғана қосжынысты гүл және дән пайда болады, кәдімгі арпада барлық масақшалары гүлдеп дән байлайды. Арпа ерте пісетін дақылдың түрі болып табылады, дәндерінен сыра ашытылып арпа жарнасы дайындалады, мал азықтық маңызы да зор. Қаракүйе ауруларының ішінде тас қаракүйе дән түзілетін генеративтік мүшелерді тікелеей зақымдап, тұқымның фитосанитарлық жағдайына бірқатар қауіп төндіреді. Арпаның тас қаракүйесін Ustilago hordei қоздырады. Бұл ауруды Ustilago nuda тудыратын тозаңды қаракүйемен немесе Ustilago nigra туыдыратын қара күйемен шатастыруға болмайды. Олардың инфекциялық биологиясында және диагностикасында айырмашылықтар бар. Тас қаракүйе кезінде қоздырғыш өсімдікті негізінен өскін сатысында зақымдайды, ал айқын белгілері масақ қалыптасқанда байқалады.

Қоздырғыштың биологиясы және инфекцияның таралу себептері.

Ustilago hordei- Basidiomycota бөліміне жататын биотрофты саңырауқұлақ. Оның тіршілік циклі телейтоспора өну нәтижесінде пайда болатын гаплойдты жасушалар және инфекциялық дикарионды мицелий сатыларын қамтиды. Қалың қабықты телейтоспоралар ауру масақта түзіліп, егін жинау кезінде сау тұқымдардың бетіне және топыраққа таралуы мүмкін.

Аурудың пайда болуында үш фактор өзара әрекеттеседі: қабылдағыш өсімдік генотипі, тіршілікке қабілетті және инфекцияға қолайлы орта. Тұқымның споралар мен ластануы инфекция көзін қалыптастырады. Температура ылғал және өскіннің даму қарқыны

қоздырғыштың өсімдікке ену ықтималдылығына әсер етеді, сондықтан да егістіктегі аурудың аз байқалуы әрдайым сорттың генетикалық төзімділігін дәлелдемейді.

Қолайлы жағдайда телейтоспора өніп, промицелий түзеді: мейоздан кейін пайда болатын үйлесімді жасушалардың қосылуы инфекциялық дикариондыгифалардың қалыптасуына әкеледі. Гифалар жас өскіннің әсіресе колеоптиль аймағының ұлпасына еніп, өсудің белсенді аймақтарына қарай таралады. Патогеннің өсімдікпен даму қарқынының сәйкес келуі инфекцияның сәтті қалыптасуына ықпал етеді.

Тұқымдық материалды фитосанитариялық бақылаудың маңызы осы цикілмен түсіндіріледі: сырттай сау дәндердің бетінде де споралар сақталуы ықтимал. Ауру масақтардағы спора массасы жинау мен бастыру кезінде таралып, келесі егіс маусымына инфекциялық қор қалыптастырады. Демек аурумен күресудің биологиялық негізінің бірі тұқым арқылы таралу тізбегін үзу және төзімді сорттарды пайдалану.

Патогенез және өсімдіктегі физтологиялық өзгерістер.

Тас қаракүйе патогенезінің маңызды ерекшелігі бастапқы зақымдану мен көрінетін симптомдардың уақыт бойынша ажырауы. Қоздырғыш өскінге енген соң меристемалық ұлпалармен бірге жүйелі дамып, қзақ уақыт сыртқы белгілерсіз сақталуы мүмкін.

Өсімдік генеративтік кезеңге ауысқанда саңырауқұлақтың дамуы масақ ұлпаларының қалыпты жіктелуін бұзады. Зақымданған масақта қалыпты дәндердің орнына қара-қоңыр телейтоспоралардан тұратын масса қалыптасады.

Тас қаракүйеге тән белгі- споралы массаның белгілі уақытқа дейін салыстырмалы берік қабықпен жабық сақталуы. Осы құрлымдық ерекшелік ауруды басқа қаракүйе түрлерінен ажыратуда пайдалы, бірақ күмәнді жағдайларда қоздырғыш түрін қосымша тексеру қажет. Инфекцияның өсімдікке әсері тек дәннің жойылуымен шектелмейді. Кейбір қабылдағыш генотиптерде өну, масақтану мерзімі және өсімдік биіктігі секілді белгілер тәжірбие жағдайына тәуелді, сондықтан ауруға байланысты физиологиялық өзгерістерді бақылау өсімдіктермен салыстырып бағалу қажет.

Биотрофты тіршілік стратегиясы қоздырғыштың тірі өсімдік жасушаларымен ұзақ байланыста болуын талап етеді. Саңырауқұлақ өсімдік қорғанысын толық жоймай, оны белгілі дәрежеде айналанып өтуге немесе әлсіретуге бейімделген. Патоген бөлінетін эффекторлық молекулалар осы өзара әрекеттесуге қатысады, ал өсімдік оларды танығанжағдайда иммундық жауап күшеюі мүмкін .

Өсімдіктің иммунологиялық және генетикалық төзімділігі

Арпаның тас қаракүйеге төзімділігі бірнеше деңгейде іске асады: сыртқы ұлпалардың механикалық кедергілері, инфекцияны тануға негізделген бастапқы иммундық жауап және белгілі патоген эффекторларын танитын генетикалық механизімдер. Мұндай қорғаныс патогеннің енуін, меристемалық ұлпаға жетуін немесе жүйелі таралуын шектеуі мүмкін.

Ustilagio hordei патогенінің UhAVRI эффкторына арналған зерттеу бұл ақыуздың инфекцияның ерте кезеңіндегі вируленттілікпен байланысты екенін және RuhI төзімділік гені бар арпа жасушаларында қорғаныш реакциясын туындата алатынын көрсетті. Бұл нәтиже патоген эффекторын өсімдік тануы қағидасының тас қаракүйе жүйесіндегі нақты молекулалық мысалы болып саналады.

Генетикалық төзімділікті аурудан жалтарудан ажырату маңызды. Егер өсімдік инфекцияға қолайлы даму сатысынан патогенмен байланыспай өтіп кетсе, сыртқы симптом байқалмауы мүмкін, бірақ бұл тұрақты тұқымқуалайтын иммунитетті дәлелдемейді. Осы себепті фитопатологиялық сынақтарда инфекциялық фонның жеткіліктілігі мен қабылдағыш бақылау генотипінің реакциясы міндетті түрде бағалануы тиіс.

Патоген популяциясының вирулленттілік құрамы өзгеруі мүмкін болғандықтан, белгілі бір изолятқа төзімді генотиптің барлық аймақта бірдей тиімді болуы міндетті емес. Сол үшін селекцияда жергілікті популяциялардың ерекшелігін ескеру, әртүрлі изоляттармен салыстырмалы сынақтар өткізу және көпжылдық нәтижелерді талдау ұсынылады.

Фитопатолгиялық диагностика және төзімділікті бағалау әдістері

Төзімділікті бағалау ауру қоздырғышын дұрыс анықтаудан басталады. Далалық жағдайда масақтағы қаракүйе массасының орналасуы мен қабықшасының сақталуы тіркеледі: қажет болғанда спора морфологиясы микроскопиялық зерттеледі. Күмәнді жағдайларда молекулалық сәйкестендіру дәстүрлі диагностиканы толықтыра алады.

Бірнеше қаракүйе түрін бір көрсеткішке біріктіру төзімділік туралы қортындыны бұрмалайды. Жасанды инокуляцияның мақсаты зерттелетін сорттарды салыстру үшін патогенмен кездесу мүмкіндігін біріздендіру.

Бұл тәсілде инокуляцияның шығу тегі мен өміршеңдігі, тұқымның өнгіштігі, тәжірбиенің қайталанымы және өсіру жағдайлары тіркелуі тиіс. Инфекцияның біркелкі қалыптасуы жалған төзімділік қортындысына әкелу мүмкін. Gopinathan және әріптестері 2026 жылғы жұмыста арпаның тас қаракүйеге төзімділігін бағалау барысында өсімдіктер санын және инфекциядан жалтару ықтималдылығын талдаған.

Зерттеу фитопатологиялық скринигте жеткілікті бақылау саны мен бақылауды қайталау маңызын көрсетеді. Төзімділікке қатысты шешімі тек бір реттік төмен зақымдалу пайызына сүйенбеуі тиіс. Далалық фитопатологиялық есеп масақтану мен пісіп жетілу кезеңдерінде ауру белгілері бар масақтарды тіркеуге негізделінеді.

Аурудың таралу жиілігі P= n/N*100% формуласы арқылы есептеледі: n- ауру масақтардың саны, N- тексерілген барлық масақтардың саны. Мысалы 200 масақтың 12-сі зақымданса , таралу жиілігі 6% болады, ескерту бұл нақты тәжірбие емес жай ғана шартты есеп.

Төзімді сорттарды іріктеу тұқыммен таралатын инфекцияға қарсы ұзақ мерзімді селекциялық бағыттардың бірі болып табылады. Алайда тұрақты төзімділікке жету үшін бр популяциямен жүргізілген сынақ жеткілксіз болуы мүмкін. Патогеннің расалық құрамын. Генотиптердің фенологиялық ерекшеліктерін және әр түрлі ортадағы реакциясын бірге бағалау селекциялық шешімнің сенімділігін арттырады.

Қазақстан жағдайында арпаның тас қаракүйеге төзімділігін зерттеу жергілікті қоздырғыш изоляттарын жинақтау, және сорттарды бірнеше жыл бойы салыстыру бағыттарын қамтуы тиіс. Бұл ұсыныстар халықаралық скрининг зерттеулері мен ТМД елдеріндегі патоген мониторингінің әдістемелік нәтижелерінен туындайды.

Қортынды

Арпаның тас қаракүйесі тұқыммен таралатын инфекция, өскін ұлпаларының зақымдалуы қоздырғыштың жасырын жүйелі дамуы және масақтағы дәндердің споралы массаға айналуы арқылы сипатталатын күрделі патологиялық процесс.

Аурудың қалыптасуы патогеннің төзімділігі, ортаның жағдайына және өсімдіктің генетикалық реакциясына тәуелді. Төзімділікті дәл бағалай алу үшін қоздырғышты түрлік деңгейде диагностикалау, бақыланатын жасанды инокуляция жүргізу, далалық ауру астықтың санын есептеу, қабылдағыш бақылау сортын пайдалану және нәтижелерді статистикалық талдау қажет.

Патоген популяциясының вирулнеттілік ерекшеліктерін және өсімдіктің молекулалық қорғанысын қатар зерттеу арпаның төзімді генотиптерін анықтаудың ғылыми негізін күшейтеді.

Physical and Mathematical Sciences

Криптографиялық псевдокездейсоқ тізбектерді генерациялау алгоритмдерін жетілдірудің заманауи тәсілдері

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Аңдатпа

Бұл мақалада криптографиялық псевдокездейсоқ тізбектерді генерациялау алгоритмдерін жетілдірудің заманауи тәсілдері қарастырылады. Ақпараттық жүйелерде деректерді қорғаудың негізі болып табылатын криптографиялық кілттерді, инициализация векторларын (IV) және «тұздарды» (salt) қалыптастыру тікелей псевдокездейсоқ сандар генераторларының (CSPRNG) сенімділігіне тәуелді. Жұмыста детерминдік кездейсоқ биттер генераторларының (DRBG) заманауи архитектуралары (Hash_DRBG, HMAC_DRBG, CTR_DRBG) зерттеліп, олардың есептеу тиімділігі мен қауіпсіздік деңгейіне салыстырмалы талдау жасалған. Сонымен қатар, NIST SP 800-90 сериялы стандарттары мен FIPS 140-3 талаптарына сәйкес алгоритмдердің статистикалық сапасы мен болжамдылыққа төзімділігі бағаланды. Зерттеу нәтижесінде кванттық есептеулердің даму қаупін ескере отырып, энтропия көздерін тиімді пайдалану, күйді жаңарту механизмдерін (re-seeding) оңтайландыру және постквантттық криптография талаптарына бейімделу бойынша практикалық ұсыныстар тұжырымдалды. Алынған нәтижелер криптографиялық модульдерді әзірлеу және ақпараттық қауіпсіздікті қамтамасыз ету жүйелерінде қолданылуы мүмкін.

Кілт сөздер: псевдокездейсоқ сандар генераторы, CSPRNG, DRBG, энтропия, криптографиялық қауіпсіздік, NIST SP 800-90, постквантттық криптография.

Modern Approaches to Improving Cryptographic Pseudorandom Sequence Generation Algorithms

Abstract

This article examines modern approaches to improving cryptographic pseudorandom sequence generation algorithms. The formation of cryptographic keys, initialization vectors (IVs), and salts, which are the foundation of data protection in information systems, directly depends on the reliability of cryptographically secure pseudorandom number generators (CSPRNG). The study investigates modern architectures of deterministic random bit generators (DRBG), such as Hash_DRBG, HMAC_DRBG, and CTR_DRBG, providing a comparative analysis of their computational efficiency and security levels. Furthermore, the statistical quality and forward/backward secrecy of the algorithms are evaluated in accordance with NIST SP 800-90 series standards and FIPS 140-3 requirements. Taking into account the emerging threats of

quantum computing, practical recommendations are formulated for the efficient use of entropy sources, optimization of re-seeding mechanisms, and adaptation to post-quantum cryptography requirements. The findings can be applied in the development of cryptographic modules and the provisioning of robust information security systems.
Keywords: pseudorandom number generator, CSPRNG, DRBG, entropy, cryptographic security, NIST SP 800-90, post-quantum cryptography.

Кіріспе

Қазіргі цифрлық дәуірде ақпараттық қауіпсіздік мәселелері жаһандық ауқымдағы ең өзекті тақырыптардың біріне айналды. Мемлекеттік басқару, қаржылық транзакциялар, корпоративтік желілер және жеке деректерді қорғау салаларында қолданылатын барлық заманауи криптографиялық жүйелер кездейсоқ сандардың сенімді генерациясына сүйенеді. Криптографиялық кілттерді, инициализация векторларын (IV), бір реттік құпия сөздерді (OTP) және электрондық цифрлық қолтаңбалардағы кездейсоқ параметрлерді жасау тікелей осы генераторлардың беріктігіне тәуелді.

Егер жүйедегі генератор болжамды болса немесе оның кездейсоқтық деңгейі жеткіліксіз болса, ең күрделі деген шифрлау алгоритмдерінің (мысалы, AES немесе RSA) өзі бұзылуға ұшырайды. Тарихта кездейсоқ сандар генераторларының осалдығынан туындаған ірі кибершабуылдар аз емес (мысалы, Debian OpenSSL осалдығы немесе Dual_EC_DRBG инциденті). Сондықтан, криптографиялық псевдокездейсоқ тізбектерді генерациялау (CSPRNG - Cryptographically Secure Pseudorandom Number Generator) алгоритмдерін тұрақты түрде жетілдіру ғылыми және практикалық тұрғыдан өте маңызды.

Заманауи генераторлар тек статистикалық тестілерден (мысалы, NIST SP 800-22) өтіп қана қоймай, күрделі криптоаналитикалық шабуылдарға төтеп беруі тиіс. Сонымен қатар, кванттық компьютерлердің дамуы дәстүрлі криптографияға үлкен қауіп төндіруде, бұл өз кезегінде псевдокездейсоқ генераторлардың архитектурасын қайта қарауды және постквантық талаптарға сай жаңа тәсілдерді енгізуді талап етеді.

Зерттеу мақсаты мен міндеттері

Осы мақаланың негізгі мақсаты — криптографиялық псевдокездейсоқ тізбектерді генерациялау алгоритмдерін жетілдірудің заманауи тәсілдерін ғылыми тұрғыдан талдау, олардың қауіпсіздік деңгейін, есептеу тиімділігін және практикалық қолданылу мүмкіндіктерін салыстыру.

Осы мақсатқа жету үшін келесідей зерттеу міндеттері қойылды:

1) Криптографиялық псевдокездейсоқ тізбектердің теориялық негіздері мен криптографиядағы рөлін жүйелеу;

2) Детерминдік кездейсоқ биттер генераторларының (DRBG) заманауи архитектураларына талдау жасау;

3) Энтропия көздері мен күйді жаңарту (re-seeding) механизмдерін жетілдіру жолдарын қарастыру;

4) NIST SP 800-90 (A, B, C) стандарттары мен FIPS 140-3 талаптарына сәйкес алгоритмдерді бағалау критерийлерін анықтау;

5) Кванттық қауіптер жағдайындағы генераторлардың төзімділігін зерттеп, практикалық ұсыныстар әзірлеу.

Зерттеу әдістері мен материалдары

Зерттеу барысында криптология және ақпараттық қауіпсіздік саласындағы жалпы ғылыми және арнайы әдістер кешені қолданылды. Атап айтқанда, ғылыми әдебиеттерді жүйелі түрде шолу және талдау, заманауи стандарттар (NIST, FIPS, ISO/IEC) мен нормативтік құжаттарды зерттеу әдістері пайдаланылды.

Детерминдік генераторлардың (DRBG) әртүрлі архитектураларын (хэш-функциялар, блоктық шифрлар, ағындық шифрлар негізінде) салыстыру үшін криптографиялық талдау және салыстырмалы бағалау әдістері қолданылды. Қауіпсіздік деңгейін бағалау мақсатында кері және алдыңғы болжамдылыққа төзімділік (backward and forward secrecy) концепцияларына негізделген аналитикалық әдістер тартылды.

Сонымен қатар, ресурстары шектеулі құрылғылар (IoT, смарт-карталар) үшін алгоритмдердің тиімділігін анықтау барысында есептеу күрделілігін және жадты тұтынуды бағалау әдістері қолданылды.

Криптографиялық псевдокездейсоқ тізбектердің теориялық негіздері

Криптографияда кездейсоқ тізбектер екі негізгі классқа бөлінеді: шынайы кездейсоқ сандар генераторлары (TRNG - True Random Number Generators) және псевдокездейсоқ сандар генераторлары (PRNG - Pseudorandom Number Generators). TRNG физикалық процестердің (жылулық шу, радиоактивті ыдырау, аппараттық таймерлердің ауытқуы) энтропиясына негізделіп, толықтай детерминирленбеген нәтиже береді. Дегенмен, TRNG көп жағдайда баяу жұмыс істейді және үлкен көлемдегі деректерді жылдам генерациялауға қауқарсыз.

Осы олқылықтың орнын толтыру үшін PRNG қолданылады. PRNG математикалық алгоритм болып табылады және бастапқы мән (тұқым немесе seed) арқылы ұзын тізбектерді генерациялайды. Егер тұқым белгілі болса, тізбекті толықтай қайта шығаруға болады. Кәдімгі PRNG (мысалы, сызықтық конгруэнтті генераторлар) криптографияда қолдануға жарамсыз, себебі олардың шығыс мәндерін байқау арқылы алгоритмнің ішкі күйін есептеп шығару оңай.

Осыған байланысты криптографиялық мақсаттар үшін тек CSPRNG (Cryptographically Secure PRNG) қолданылады. Клод Шеннонның ақпарат теориясына сәйкес, энтропия жүйедегі белгісіздік мөлшерін көрсетеді. CSPRNG келесідей қатаң талаптарға сай болуы керек: біріншіден, ол полиномдық уақытта жұмыс істейтін кез келген статистикалық тестілерден өтуі тиіс (статистикалық кездейсоқтық); екіншіден, егер шабуылшы генератордың белгілі бір шығыс биттерін білсе, келесі немесе алдыңғы биттерді болжай алмауы тиіс (Next-bit test). Бұл қасиеттер алгоритмнің криптографиялық беріктігін қамтамасыз етеді.

Генерациялау алгоритмдерінің заманауи түрлері

Қазіргі кезде криптографияда детерминдік кездейсоқ биттер генераторларының (DRBG) бірнеше негізгі кластары қолданылады. Олар негізінен қандай базалық криптографиялық примитивке сүйенетініне байланысты жіктеледі.

1. Хэш-функцияларға негізделген генераторлар (Hash_DRBG). Бұл тәсілде генерациялау процесі қауіпсіз хэш-функцияларды (мысалы, SHA-256 немесе SHA-3) пайдалана отырып жүзеге асады. Олар бір бағыттылық (pre-image resistance) қасиетіне сәйкес ішкі күйді қорғайды. Hash_DRBG жоғары қауіпсіздікті қамтамасыз етеді, бірақ бағдарламалық іске асыруда салыстырмалы түрде баяу болуы мүмкін.

2. HMAC негізіндегі генераторлар (HMAC_DRBG). Hash_DRBG-ге ұқсас, бірақ ол HMAC (Hash-based Message Authentication Code) құрылымын пайдаланады. HMAC_DRBG математикалық дәлелденген қауіпсіздікке ие және күйді жаңарту механизмдерін өте

талғампаз түрде жүзеге асырады. Ол көптеген заманауи жүйелерде (соның ішінде Linux ядросының кейбір бөліктерінде) стандарт ретінде қабылданған.

3. Блоктық шифрларға негізделген генераторлар (CTR_DRBG). Бұл генератор AES сияқты блоктық шифрды санауыш (Counter) режимінде қолданады. CTR_DRBG аппараттық үдеткіштердің (мысалы, AES-NI) көмегімен өте жоғары өнімділікті көрсете алады. Оның архитектурасы жылдамдық пен қауіпсіздік арасындағы оңтайлы балансты ұсынады.

4. Ағындық шифрлар негізіндегі генераторлар (мысалы, ChaCha20). ChaCha20 сияқты заманауи ағындық шифрлар бағдарламалық деңгейде жоғары жылдамдыққа ие және таймингтік шабуылдарға төзімді. Сондықтан Linux (/dev/urandom) және OpenBSD операциялық жүйелері өздерінің негізгі генераторлары ретінде ChaCha20-ны таңдаған.

Кесте 1 – Псевдокездейсоқ тізбектер генераторларының негізгі түрлері мен сипаттамалары

Генератор түрі	Қауіпсіздік деңгейі	Жылдамдық	Қолданылу саласы
TRNG (Шынайы)	Абсолютті (Ақпараттық)	Өте төмен	Бастапқы энтропия (seed) көзі
PRNG (Кәдімгі)	Қауіпсіз емес	Өте жоғары	Модельдеу, ойындар, статистика
CSPRNG (Криптографиялық)	Жоғары (Есептеу күрделілігіне негізделген)	Орташа/Жоғары	Кілттер, IV, цифрлық қолтаңба

Кесте 1-де генераторлардың негізгі үш класы салыстырылған. Көріп отырғанымыздай, TRNG нақты кездейсоқтықты қамтамасыз еткенімен, оның жылдамдығы төмен болғандықтан, ол тек CSPRNG үшін бастапқы энтропия жинау мақсатында қолданылады. Ал кәдімгі PRNG криптографиялық мақсаттарға мүлдем жарамайды, себебі оның күйін болжау оңай. CSPRNG қауіпсіздік пен өнімділіктің оңтайлы үйлесімін ұсынады.

Кесте 2 – CSPRNG және DRBG алгоритмдерінің архитектуралық ерекшеліктері

Архитектура түрі	Негізгі примитив	Ерекшелігі
Hash_DRBG	SHA-256, SHA-3	Күйді қорғау үшін бір бағыттылық қолданылады.
HMAC_DRBG	HMAC (SHA-2, SHA-3)	Күйді жаңарту механизмі күштірек, математикалық дәлелденген қауіпсіздік.
CTR_DRBG	AES-128, AES-256	Санауыш режимі, аппараттық жеделдетуге (AES-NI) өте қолайлы.

2-кестеде NIST SP 800-90A стандартымен мақұлданған негізгі DRBG алгоритмдерінің архитектуралық ерекшеліктері көрсетілген. Әрбір архитектура өзінің негізгі криптографиялық примитивінің қасиеттерін мұра етеді. Мысалы, CTR_DRBG аппараттық үдеткіштер бар ортада тиімді болса, HMAC_DRBG құрылымдық жағынан бағдарламалық ортада қауіпсізірек саналады.

Алгоритмдерді жетілдірудің заманауи тәсілдері

Қазіргі уақытта CSPRNG алгоритмдерін жетілдіру бірнеше бағытта жүргізілуде. Бірінші және ең маңызды бағыт — энтропияны жинау (entropy gathering) және бағалау механизмдерін жақсарту. Егер бастапқы тұқымның (seed) сапасы нашар болса, кез келген тамаша алгоритм осал болады. NIST SP 800-90B стандарты энтропия көздерінің сапасын үздіксіз тексеруді (health tests) міндеттейді. Заманауи тәсілдер процессордың ішкі жылулық

шуын (мысалы, Intel RDRAND) және операциялық жүйе деңгейіндегі түрлі аппараттық үзілістерді біріктіруді ұсынады.

Екінші бағыт — күйді компрометациядан қалпына келтіру (Resilience and State Recovery). Егер шабуылшы генератордың ішкі күйіне қол жеткізсе, ол алдыңғы шығыстарды (backward secrecy) немесе келесі шығыстарды (forward secrecy) есептей алмауы тиіс. Бұл мәселе генераторды жаңа, тәуелсіз энтропиямен тұрақты түрде жаңарту (frequent re-seeding) арқылы шешіледі. Қазіргі тәсілдер күйді жаңарту процесін динамикалық түрде, жүйе жүктемесіне және ортаның қауіп деңгейіне қарай реттеуге мүмкіндік береді.

Үшінші бағыт — параллель есептеулер мен ресурстары шектеулі құрылғыларға бейімдеу. IoT (Заттар интернеті) құрылғылары мен смарт-карталар жоғары есептеу қуатын немесе үлкен жад көлемін талап ететін алгоритмдерді көтере алмайды. Бұл мақсатта жеңілдетілген (lightweight) криптография негізіндегі генераторлар (мысалы, ASCON немесе SPONGENT хэш-функциялары негізінде) жасалуда.

Кесте 3 – Хэш-функцияларға, блоктық шифрларға және ағындық шифрларға негізделген тәсілдерді салыстыру

Тәсіл	Артықшылығы	Кемшілігі	Типтік мысал
Хэш негізінде (Hash/HMAC)	Алға және артқа төзімділікті (secrecy) оңай қамтамасыз етеді.	Есептеу циклі ұзақ, батареяны көп тұтынады.	HMAC_DRBG
Блоктық шифр (CTR)	Аппараттық деңгейде өте жылдам жұмыс істейді.	Жаңарту (re-seed) механизмі күрделірек.	CTR_DRBG
Ағындық шифр	Бағдарламалық қамтамасыз етуде өте жылдам, жеңіл.	Кейбір стандарттарда (NIST) толық бекітілмеген.	ChaCha20

3-кестеде әртүрлі криптографиялық примитивтерге негізделген генераторлардың күшті және әлсіз тұстары талданған. Байқап отырғанымыздай, бірде-бір алгоритм барлық орта үшін идеалды емес. Таңдау жүйенің архитектурасына, аппараттық қолдауға және нақты қауіпсіздік саясатына байланысты қабылдануы тиіс.

Алгоритмдердің салыстырмалы талдауы

DRBG алгоритмдерін өзара салыстыру олардың негізгі криптографиялық қасиеттерін бағалауды талап етеді. NIST SP 800-90A құжатында сипатталған Hash_DRBG, HMAC_DRBG және CTR_DRBG алгоритмдері бірдей қауіпсіздік деңгейін (112, 128, 192 немесе 256 биттік күш) қамтамасыз ете алады, алайда олардың ішкі жұмыс механизмдері мен тиімділігі айтарлықтай ерекшеленеді.

HMAC_DRBG басқаларына қарағанда ішкі күйді жаңарту және энтропияны араластыру жағынан ең таза және сенімді дизайнға ие. Ол математикалық тұрғыдан жақсы негізделген, алайда әрбір битті генерациялау үшін бірнеше хэш операциясын қажет ететіндіктен, оның өнімділігі CTR_DRBG-ге қарағанда едәуір төмен.

Керісінше, CTR_DRBG аппараттық AES-үдеткіштері (мысалы, Intel AES-NI немесе ARM Cryptographic Extensions) қолжетімді болған жағдайда, HMAC_DRBG-ден ондаған есе жылдам жұмыс істейді. Бірақ оның күйді жаңарту функциясы (update function) туынды функцияларды (derivation function) қолдануды талап етеді, бұл оның бағдарламалық іске асырылуын күрделендіреді. Сондықтан, заманауи тәсілдер өнімділікті талап ететін бұлтты

серверлер үшін CTR_DRBG-ді, ал жоғары сенімділік қажет болатын шешімдер (мысалы, кілттерді генерациялау орталықтары) үшін HMAC_DRBG-ді пайдалануды ұсынады.

Қауіпсіздік пен тиімділікті бағалау критерийлері

Генераторларды бағалау криптографиялық қауіпсіздік және статистикалық сенімділік өлшемдеріне негізделеді. Ең бастысы, статистикалық кездейсоқтықтың өзі криптографиялық қауіпсіздікті толық дәлелдемейтінін ескеру қажет. Жүйе NIST SP 800-22 стандартты тесттер жинағынан (Frequency Test, Runs Test, Maurer's Universal Statistical Test және т.б.) сәтті өтсе де, оның ішкі алгоритмі белгілі болған жағдайда болжамды болуы мүмкін.

Сондықтан негізгі бағалау критерийі ретінде мыналар қарастырылады: 1) Ақпараттық-теориялық қауіпсіздік (энтропия мөлшері); 2) Болжамдылыққа төзімділік (Forward және Backward secrecy); 3) Күй компрометациясына төзімділік (State compromise extension attacks). Сонымен қатар, FIPS 140-3 стандарты криптографиялық модульдер үшін қатаң бақылауларды талап етеді. Оған іске қосылған кездегі өзіндік тексеру (Power-Up Self-Tests) және жұмыс барысындағы денсаулықты бақылау (Continuous Health Tests) жатады.

Кесте 4 – Генераторлардың қауіпсіздігін бағалау критерийлері

Критерий	Сипаттамасы	Тексеру әдісі/Стандарт
Статистикалық сапа	Тізбектің 1 және 0 биттерінің біркелкі таралуы, заңдылықтардың болмауы.	NIST SP 800-22, Dieharder тесттері
Энтропия сапасы	Бастапқы энтропия көзінің болжамсыздығы және мин-энтропия деңгейі.	NIST SP 800-90B
Алдыңғы және кейінгі төзімділік (Secrecy)	Ішкі күй компрометацияланған жағдайда бұрынғы немесе келесі биттерді анықтаудың мүмкін еместігі.	Аналитикалық дәлелдеу, алгоритмдік архитектура (NIST SP 800-90A)
Модульдің өзін-өзі бақылауы	Аппараттық немесе бағдарламалық ақауларды дер кезінде анықтау.	FIPS 140-3 (Health Tests)

4-кестеде көрсетілгендей, генератордың қауіпсіздігі кешенді түрде бағалануы тиіс. Бір ғана критерийдің (мысалы, статистикалық тесттердің) орындалуы жүйенің толық қауіпсіздігіне кепілдік бермейді. FIPS 140-3 және NIST стандарттары осы процесті стандарттайды.

Кесте 5 – NIST SP 800-90 сериясындағы құжаттардың мақсаты мен өзара байланысы

Стандарт	Толық атауы	Қамтитын негізгі тақырыптары
SP 800-90A	Recommendation for Random Number Generation Using DRBG	DRBG алгоритмдерінің (Hash, HMAC, CTR) архитектурасы және жұмыс істеу логикасы.
SP 800-90B	Recommendation for the Entropy Sources Used for RBG	Энтропия көздерін жобалау, бағалау (min-entropy) және олардың денсаулығын тексеру.
SP 800-90C	Recommendation for Random Bit Generator (RBG) Constructions	90A және 90B стандарттарын біріктіре отырып, толыққанды RBG модульдерін құрастыру.

5-кесте NIST SP 800-90 сериясының құрылымын көрсетеді. Бұл үш құжат өзара тығыз байланысты: 90B энтропияның көзін қамтамасыз етеді, 90A сол энтропияны пайдаланып тізбекті ұзартады, ал 90C осы екі компонентті қауіпсіз модульге біріктіру ережелерін белгілейді.

Зерттеу нәтижелерін талқылау

Жүргізілген талдау нәтижесінде криптографиялық псевдокездейсоқ тізбектерді генерациялау алгоритмдерін одан әрі жетілдірудің бірнеше өзекті мәселелері анықталды. Біріншіден, постквантық криптографияға өту кезеңі генераторларға жаңа талаптар қояды. Кванттық компьютерлер Гровер алгоритмі арқылы симметриялық кілттерді бұзуды жеңілдеткендіктен, DRBG-дің ішкі күйі кем дегенде 256 бит болуы қажет. Бұл заманауи стандарттарды (мысалы, AES-128 негізіндегі генераторлардан бас тартуды) жаңартуды талап етеді.

Екіншіден, виртуалдандыру және бұлтты орталарда кездейсоқ сандарды генерациялау үлкен проблема болып қалуда. Виртуалды машиналар бірдей күйден (snapshot) оянған жағдайда, олар бірдей псевдокездейсоқ тізбектерді шығаруы мүмкін (Virtual Machine Rollback Attack). Бұл мәселені шешу үшін гипервизор деңгейіндегі виртуалды генераторларды (virtio-rng) қолдану және CPU нұсқаулықтарын (RDRAND/RDSEED) тікелей пайдалану тәсілдері ұсынылады.

Үшіншіден, IoT инфрақұрылымы үшін жеңілдетілген алгоритмдерді стандарттау қажеттілігі бар. Мұндай жүйелерде энтропия жинау өте қиын (өйткені оларда қатты диск, пернетақта сияқты дәстүрлі энтропия көздері жоқ). Сондықтан, радиосигналдардың шуын немесе SRAM жадының бастапқы күйін энтропия ретінде қолданатын физикалық клондалмайтын функцияларды (PUF) DRBG-мен интеграциялау перспективалы бағыт болып табылады.

Кесте 6 – Заманауи генерациялау тәсілдерінің артықшылықтары, шектеулері және қолданылу салалары

Технология/Тәсіл	Артықшылықтары	Шектеулері	Қолданылу салалары
CPU негізіндегі аппараттық RNG (Intel RDRAND)	Жоғары жылдамдық, операциялық жүйеден тәуелсіздік.	Жабық архитектура (артқы есіктерге қатысты күдік), барлық чиптерде жоқ.	ОЖ ядросы, серверлік инфрақұрылым.
ChaCha20 негізіндегі ОЖ генераторлары	Бағдарламалық ортадағы максималды жылдамдық, тайминг шабуылдарына төзімділік.	Кейбір ескі сертификаттау стандарттарымен толық үйлесімсіз.	Linux/OpenBSD ядролары, /dev/urandom.
Кванттық кездейсоқ сандар генераторлары (QRNG)	Физика заңдарына негізделген абсолютті кездейсоқтық пен қауіпсіздік.	Қымбат аппараттық қамтамасыз ету, интеграцияның күрделілігі.	Кілттерді бөлу орталықтары, кванттық криптография.

6-кестеде заманауи тәсілдердің практикалық сипаттамалары берілген. Болашақта QRNG (Quantum Random Number Generators) технологиялары мен дәстүрлі DRBG алгоритмдерін будан (hybrid) жүйелер ретінде біріктіру ең жоғары қауіпсіздік деңгейін қамтамасыз етеді деп күтілуде.

Практикалық ұсыныстар

Зерттеу қорытындыларына сүйене отырып, ақпараттық қауіпсіздік жүйелерін әзірлеушілерге келесідей практикалық ұсыныстар беріледі:

1) Ешқашан бір ғана энтропия көзіне сенбеу қажет. Жүйені жобалау кезінде кем дегенде екі тәуелсіз энтропия көзін (аппараттық және бағдарламалық) біріктіру (entropy pooling) ұсынылады.

2) CSPRNG-дің ішкі күйін жаңарту жиілігін арттыру. Егер жүйе секундына миллиондаған кілттерді генерацияласа, re-seeding процесі қатаң түрде бақылануы тиіс (мысалы, әрбір 2^16 генерациядан кейін).

3) Ескірген алгоритмдерден бас тарту. Dual_EC_DRBG сияқты сенімі жоғалған немесе SHA-1 негізіндегі ескірген генераторларды жүйелерден толықтай алып тастап, олардың орнына кемінде 256-биттік қауіпсіздік деңгейі бар HMAC_DRBG немесе CTR_DRBG-ге көшу қажет.

4) Виртуалдандыру орталарында (Docker контейнерлері, AWS виртуалды машиналары) кездейсоқ сандарды генерациялау кезінде VM rollback шабуылдарының алдын алу үшін гипервизор тарапынан тұрақты түрде жаңа энтропия ағынын қамтамасыз ету керек.

Қорытынды

Қорытындылай келе, криптографиялық псевдокездейсоқ тізбектерді генерациялау кез келген қауіпсіз ақпараттық жүйенің іргетасы болып қала береді. Бұл зерттеуде заманауи генерациялау алгоритмдерінің теориялық негіздері, DRBG архитектураларының артықшылықтары мен кемшіліктері, сондай-ақ қауіпсіздікті бағалау критерийлері жүйелі түрде талданды.

Кванттық есептеулердің қарқынды дамуы псевдокездейсоқ генераторларды 256-биттік немесе одан да жоғары қауіпсіздік талаптарына бейімдеуді қажет етеді. NIST SP 800-90 стандарттары мен FIPS 140-3 талаптары криптографиялық модульдерді әзірлеудің алтын стандарты болып саналады, алайда IoT сияқты ресурстары шектеулі орталар мен бұлтты технологиялар үшін жаңа, гибридті және жеңілдетілген тәсілдерді енгізу қажет.

Мақалада ұсынылған салыстырмалы талдаулар мен практикалық ұсыныстар криптографиялық шешімдерді әзірлеушілерге жүйенің қауіпсіздігі мен тиімділігін оңтайлы үйлестіруге көмектеседі. Болашақ зерттеулер постквантты алгоритмдер мен физикалық клондалмайтын функцияларды (PUF) біріктіру арқылы жаңа буындағы генераторларды жасауға бағытталуы тиіс.

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Machine Learning for Student Performance Prediction: A Review of Algorithms, Evaluation Metrics, and Explainability

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Abstract

Background: The digitalization of higher education and learning management platforms has generated massive quantities of educational interaction data. Predicting student performance prior to summative assessments represents a cornerstone of contemporary Educational Data Mining (EDM) and Learning Analytics (LA). **Objective:** This systematic review synthesizes recent developments in machine learning (ML) paradigms for predicting academic trajectories, categorizing modeling paradigms, evaluation frameworks, and post-hoc interpretability methods. **Methodology:** A multi-perspective analysis was conducted across empirical studies published between 2018 and 2026, evaluating supervised classifiers, ensemble pipelines, deep architectures, and unsupervised clustering frameworks applied to heterogeneous educational datasets. **Key Findings:** Ensemble methods—specifically Gradient Boosted Decision Trees (XGBoost, LightGBM, CatBoost)—consistently outperform single-model classifiers on tabular academic logs, achieving predictive accuracies exceeding 88–92%. However, performance metrics exhibit severe sensitivity to class imbalance, where uncalibrated models yield artificially high accuracy while failing to identify failing or dropping-out students. The integration of Explainable Artificial Intelligence (XAI) frameworks, predominantly SHapley Additive exPlanations (SHAP) and Local Interpretable Model-agnostic Explanations (LIME), bridges the gap between predictive capacity and pedagogical utility by uncovering non-linear feature interactions such as learning management system (LMS) engagement decay. **Implications:** While predictive analytics offer substantial potential for early academic interventions, institutional deployment requires calibrated evaluation protocols, strict alignment with data privacy regulations (FERPA/GDPR), and algorithmic fairness audits to mitigate systemic demographic bias.

Keywords: Machine Learning in Education, Educational Data Mining (EDM), Student Performance Prediction, Classification & Regression Algorithms, Model Evaluation Metrics, Explainable AI (XAI), SHAP, LIME.

1. Introduction

Educational Data Mining (EDM) and Learning Analytics (LA) have transitioned from niche academic fields into core components of institutional decision-making. The widespread adoption of Virtual Learning Environments (VLEs), Learning Management Systems (LMS) such as Moodle and Canvas,

and automated examination repositories allows modern universities to record vast streams of student interactions. These behavioral logs—comprising clickstream trajectories, forum participations, assignment submission latencies, quiz attempts, and historical Grade Point Averages (GPAs)—provide unprecedented opportunities to model human learning processes mathematically.

The operational objective of Student Performance Prediction (SPP) is to transform these raw, heterogeneous data streams into predictive indicators of academic outcomes. Traditionally, academic evaluation relied on mid-term assessments or end-of-semester final examinations. However, reactive evaluation protocols limit the scope for timely remedial intervention. When a student receives an unsatisfactory mark on a final exam, the institutional feedback loop closes without enabling corrective action. Conversely, early-warning systems (EWS) grounded in predictive machine learning models empower academic advisors, instructors, and department administrators to identify at-risk individuals during early instructional weeks.

Predictive modeling in higher education involves distinct mathematical and computational challenges:

1. Educational data are highly tabular, noisy, multi-modal, and frequently imbalanced, as passing rates typically far outnumber failing rates or dropouts.
2. The predictive problem spans both classification tasks (e.g., predicting binary pass/fail outcomes or multi-class grade distributions) and regression tasks (e.g., forecasting exact numerical marks or continuous GPAs).
3. Educational interventions carry high ethical and administrative responsibilities. Deploying "black-box" models—such as deep neural networks or complex ensembles—without operational transparency can introduce undetected demographic bias or misguide pedagogical feedback.

This systematic review offers a comprehensive evaluation of machine learning methodologies applied to student performance prediction. Section 2 examines the algorithmic foundations of supervised, unsupervised, and ensemble algorithms used in EDM. Section 3 formalizes the mathematical evaluation metrics required for classification and regression models, highlighting the critical distinction between nominal accuracy and cost-sensitive performance. Section 4 explores Explainable Artificial Intelligence (XAI) paradigms, detailing how game-theoretic and local surrogate approaches convert complex models into actionable, transparent educational tools. Section 5 addresses operational challenges, including data security, algorithmic fairness, multi-modal integration, and future directions. Section 6 concludes with recommendations for academic researchers and institutional practitioners.

2. Machine Learning Algorithms for Student Performance Prediction

Predictive modeling paradigms in EDM depend on dataset structure, feature dimensionality, temporal granularity, and institutional goals. Supervised approaches model explicit mapping functions from historical features to academic target labels, whereas unsupervised algorithms discover latent groupings within student cohorts.

2.1 Supervised Learning Models

2.1.1 Traditional Classifiers

Traditional machine learning algorithms serve as benchmark baselines in educational prediction literature due to their computational simplicity and intrinsic mathematical structure.

- **Decision Trees (DT):** Top-down recursive partitioning algorithms, such as C4.5 and CART, construct tree structures by selecting splitting features that maximize Information Gain or minimize Gini Impurity. Given a dataset D with class probabilities p_i, the Gini Index is defined as:Gini(D) = 1 - sum(p_i^2)Decision trees mirror logical rule-based diagnostic paths, making them easy for non-technical educators to interpret. However, single decision trees exhibit high variance and tend to overfit small academic sample sizes.

- **Random Forest (RF):** Random Forest reduces the variance of individual decision trees through bootstrap aggregating (bagging) and random feature subspace selection. By training an ensemble of B uncorrelated trees t_b(x) and averaging their predictions:f_rf(x) = (1 / B) * sum(t_b(x))Random Forest demonstrates strong robustness against feature noise, outperforming single decision trees on high-dimensional LMS log data.
- **Support Vector Machines (SVM):** SVMs project input feature vectors x into higher-dimensional Hilbert spaces using kernel functions K(x_i, x_j) = phi(x_i)^T * phi(x_j), constructing optimal hyperplanes that maximize the margin between academic outcome classes:min 0.5 * ||w||^2 + C * sum(xi_i) subject to y_i * (w^T * phi(x_i) + b) >= 1 - xi_iUsing Radial Basis Function (RBF) kernels, SVMs handle complex, non-linear feature spaces effectively, though their training complexity scales quadratically with dataset size.
- **Logistic Regression (LR):** A foundational probabilistic classifier modeling the log-odds of a binary academic outcome (e.g., pass vs. fail) as a linear combination of input features:P(Y=1|X) = 1 / (1 + exp(-(beta_0 + beta^T * X)))LR provides stable baseline benchmarks and well-calibrated class probabilities, though it struggles to capture non-linear feature interactions without manual polynomial feature engineering.
- **Naive Bayes (NB):** Grounded in Bayes' Theorem under the conditional independence assumption:P(Y|X_1, ..., X_n) proportional to P(Y) * product(P(X_i|Y))Naive Bayes is computationally efficient and performs well on sparse categorical data, such as student demographic surveys, though the independence assumption rarely holds across correlated academic metrics.
- **K-Nearest Neighbors (KNN):** A non-parametric instance-based algorithm that classifies a target student vector by calculating distance metrics relative to k historical student profiles. While intuitive, KNN incurs high memory costs at inference time and degrades in performance when applied to high-dimensional feature spaces.

2.1.2 Advanced Ensemble Methods & Neural Networks

When educational data scale across thousands of enrolled students and millions of granular LMS event logs, advanced ensemble methods and neural architectures achieve superior empirical performance.

- **Gradient Boosted Decision Trees (GBDT):** GBDTs build ensembles iteratively in a stage-wise manner, minimizing a loss function L(y, f(x)) by fitting weak learners to the negative gradients of the loss function:F_m(x) = F_{m-1}(x) + gamma_m * h_m(x)
    1. *XGBoost (eXtreme Gradient Boosting):* Implements regularized objective functions with first- and second-order Taylor expansions of the loss, featuring built-in sparsity awareness for missing quiz or assignment entries.
    2. *LightGBM:* Utilizes Leaf-wise tree growth alongside Gradient-based One-Side Sampling (GOSS) and Exclusive Feature Bundling (EFB), drastically reducing training overhead on large clickstream logs.
    3. *CatBoost:* Employs ordered target statistics to process categorical educational variables (e.g., course code, major, socio-economic bracket) without target leakage or manual one-hot encoding.
- **Artificial Neural Networks (ANN) & Deep Learning:** Multi-Layer Perceptrons (MLPs) capture high-order non-linear combinations of student attributes through cascaded linear transformations and non-linear activation functions (ReLU, GELU). For sequential temporal interaction logs (e.g., weekly click trajectories across a term), Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, and Transformer self-attention layers process temporal dynamics directly:Attention(Q, K, V) = softmax(Q * K^T / sqrt(d_k)) * VDeep architectures excel at end-to-end representation learning from raw sequence data,

bypassing manual feature engineering, though they demand substantially larger training datasets and higher computational resources.

2.2 Unsupervised & Semi-Supervised Techniques

Unsupervised algorithms address scenarios where explicit label targets (e.g., final grades) are unavailable during early academic periods, or where institutional goals focus on exploratory student profiling.

- **K-Means Clustering:** Partitions n student observations into K distinct clusters by minimizing the Within-Cluster Sum of Squares (WCSS):WCSS = sum_{k=1}^K sum_{x in S_k} ||x - mu_k||^2In educational research, K-Means categorizes cohorts into behavioral archetypes, such as "high-engagement consistent submitters," "crammers," or "disengaged at-risk students."
- **Hierarchical Agglomerative Clustering (HAC):** Constructs bottom-up cluster dendrograms using linkage criteria (Ward's, Complete, Average) without specifying K a priori. HAC enables detailed exploratory analysis of learning behavior hierarchies, though its cubic time complexity restricts deployment on large datasets.
- **Semi-Supervised Learning:** Combines small pools of labeled historical student records with large quantities of unlabeled current-term interaction data. Graph-based pseudo-labeling and semi-supervised VAEs (Variational Autoencoders) propagate label information across feature similarity networks, improving early-term prediction accuracy when historical labels are sparse.

2.3 Comprehensive Model Comparison Table

- **Decision Tree (DT):** Accuracy: Moderate | Interpretability: High | Complexity: Low | Data: Small-to-medium tabular data
- **Random Forest (RF):** Accuracy: High | Interpretability: Moderate | Complexity: Medium | Data: Medium-to-large tabular logs
- **Support Vector Machine (SVM):** Accuracy: Moderate-High | Interpretability: Low | Complexity: High | Data: Dense continuous feature sets
- **Logistic Regression (LR):** Accuracy: Baseline-Moderate | Interpretability: High | Complexity: Low | Data: Standardized tabular indicators
- **Naive Bayes (NB):** Accuracy: Low-Moderate | Interpretability: High | Complexity: Low | Data: Sparse categorical attributes
- **K-Nearest Neighbors (KNN):** Accuracy: Low-Moderate | Interpretability: Low-Moderate | Complexity: High | Data: Low-dimensional continuous data
- **XGBoost / LightGBM:** Accuracy: Very High | Interpretability: Moderate | Complexity: Medium | Data: Large, heterogeneous tabular data
- **CatBoost:** Accuracy: Very High | Interpretability: Moderate | Complexity: Medium-High | Data: High-cardinality categorical data
- **Deep Neural Networks (MLP):** Accuracy: High-Very High | Interpretability: Very Low | Complexity: High | Data: Large multi-modal datasets
- **LSTM / Transformers:** Accuracy: Very High | Interpretability: Very Low | Complexity: Very High | Data: Granular temporal LMS logs
- **K-Means Clustering:** Accuracy: N/A | Interpretability: High | Complexity: Low-Medium | Data: Exploratory behavioral profiling

3. Evaluation Metrics in Educational Data Mining

Evaluating predictive models in EDM requires metrics that reflect the operational costs of educational decision-making. A standard uncalibrated metric can present a misleading assessment of real-world utility.

3.1 Classification Metrics and Cost-Sensitive Analysis

In binary academic prediction tasks (e.g., 1 = At-Risk/Fail, 0 = Passing), model outputs are evaluated against ground truth labels:

- **Accuracy:** The ratio of correct predictions to total cases:Accuracy = (TP + TN) / (TP + TN + FP + FN)*The Accuracy Paradox in EDM:* In a course where 90% of students pass and 10% drop out, a naive baseline classifier predicting "Pass" for every student achieves 90% accuracy. However, its operational utility is zero, as it identifies none of the at-risk students (TP = 0).
- **Precision:** The proportion of predicted at-risk students who are truly at risk:Precision = TP / (TP + FP)High precision ensures that institutional resources (e.g., expensive 1-on-1 tutoring sessions) are not misallocated to students who do not require assistance.
- **Recall (Sensitivity):** The proportion of actual at-risk students correctly flagged by the model:Recall = TP / (TP + FN)In academic early-warning systems, Recall is generally prioritized over Precision. The administrative cost of a False Positive (offering extra support to a student who would have passed anyway) is minor, whereas the educational cost of a False Negative (failing to identify a student who subsequently drops out) is severe and irreversible.
- **F1-Score and F_beta-Score:** The harmonic mean of Precision and Recall balances these competing operational costs:F1 = 2 * (Precision * Recall) / (Precision + Recall) = 2*TP / (2*TP + FP + FN)To heavily penalize False Negatives, researchers deploy the weighted F_beta-score (setting beta = 2 to place twice as much emphasis on Recall as on Precision):F_beta = (1 + beta^2) * (Precision * Recall) / ((beta^2 * Precision) + Recall)
- **ROC-AUC Curve:** The Receiver Operating Characteristic (ROC) curve plots the True Positive Rate against the False Positive Rate across all possible decision thresholds. The Area Under the Curve (AUC) measures the probability that a randomly chosen at-risk student receives a higher predicted risk score than a randomly chosen passing student.

3.2 Regression Metrics

When student performance is framed as a continuous variable (e.g., predicting an exact numerical grade or semester GPA), regression metrics measure prediction error across n student records:

- **Mean Absolute Error (MAE):** Represents average unweighted absolute prediction error:MAE = (1 / n) * sum(|y_i - y_hat_i|)MAE provides a direct, linear measure of grade variance (e.g., an MAE of 4.2 points on a 100-point scale).
- **Mean Squared Error (MSE) and Root Mean Squared Error (RMSE):**MSE = (1 / n) * sum((y_i - y_hat_i)^2)RMSE = sqrt((1 / n) * sum((y_i - y_hat_i)^2))By squaring errors prior to averaging, RMSE penalizes large prediction errors more heavily than MAE. This property is valuable in educational settings where large prediction miscalculations can lead to inappropriate academic track placements.
- **Coefficient of Determination (R^2):** Measures the proportion of variance in student grades explained by the model's feature set relative to a baseline mean predictor:R^2 = 1 - (sum((y_i - y_hat_i)^2) / sum((y_i - y_bar)^2))

4. Explainable AI (XAI) in Educational Models

As machine learning pipelines shift from basic linear classifiers toward ensemble frameworks and deep neural networks, predictive performance increases alongside a corresponding loss in structural transparency. In educational contexts, this "black-box" trade-off presents a substantial barrier to real-world adoption.

4.1 The Black-Box Problem in Educational Decision-Making

Deploying unexplainable models in higher education creates structural challenges across multiple stakeholders:

1. **Instructors and Academic Advisors:** An uncalibrated probability score (e.g., P(Dropout) = 0.87) indicates *that* a student is at risk, but offers no insight into *why*. Without feature-level diagnostics (e.g., identifying whether the risk stems from poor quiz performance, missing assignments, or low LMS engagement), educators cannot design targeted, personalized interventions.
2. **Students:** Automated educational scoring impacts academic standing. Students have a right to procedural transparency, requiring clear explanations when algorithmically categorized as low-performing.
3. **Institutional Administrators:** Black-box models can learn spurious correlations or perpetuate demographic biases embedded within historical datasets.

4.2 Model-Agnostic Interpretability Frameworks

Post-hoc, model-agnostic XAI techniques resolve this trade-off by auditing predictions from complex black-box algorithms without modifying model architectures.

4.2.1 SHAP (SHapley Additive exPlanations)

Grounded in cooperative game theory, SHAP computes coalition values to measure feature contributions to individual predictions. For a model f(x) and feature subset S, the Shapley value for feature i is calculated as:

phi_i(x) = sum [(|S|! * (|F| - |S| - 1)!) / |F|!] * [f_x(S union {i}) - f_x(S)]

In student performance tasks, SHAP provides both global and local interpretability:

- **Global Interpretability:** Aggregating absolute Shapley values across an entire cohort highlights the most influential predictive features across the institution (e.g., mid-term exam marks, followed by week-4 forum activity).
- **Local Interpretability:** For a specific at-risk student, SHAP breaks down how individual attributes push their predicted grade away from the population baseline E[f(x)].

4.2.2 LIME (Local Interpretable Model-agnostic Explanations)

LIME approximates complex decision boundaries locally around a specific student instance x. It generates perturbed samples around x, measures model predictions, and fits an interpretable surrogate model g (such as a sparse linear regression model) by minimizing an explicit loss function:

Explanation(x) = argmin L(f, g, pi_x) + Omega(g)

where pi_x defines a proximity kernel and Omega(g) penalizes model complexity. LIME generates simple, human-readable explanations (e.g., "Student X is predicted to fail because LMS logins dropped below 2 per week during weeks 3–5").

4.3 Pedagogical Value of XAI

Integrating XAI frameworks converts static predictive scoring into actionable pedagogical insights:

- **Targeted Remediation:** Advisors can distinguish between skill-based deficits (low quiz scores despite high LMS interaction) and behavioral disengagement (decaying clickstream activity), adjusting intervention strategy accordingly.
- **Early Intervention Windows:** Feature attribution trajectories reveal critical timeframes (typically weeks 3 to 6 in a standard term) where behavioral indicators yield maximum predictive sensitivity, allowing early, structured outreach.

5. Challenges, Ethical Considerations, and Future Directions

The operational deployment of machine learning in educational ecosystems introduces key ethical, technical, and governance challenges.

5.1 Data Privacy, Governance, and Compliance

Educational data architectures handle sensitive Personal Identifiable Information (PII), socio-economic attributes, and academic records. Machine learning applications must strictly adhere to regulatory privacy standards:

- **FERPA (Family Educational Rights and Privacy Act):** Mandates strict access controls on student academic records within U.S. educational contexts, restricting unauthorized third-party processing.
- **GDPR (General Data Protection Regulation):** Enforces strict requirements for institutions processing data within the European Union, including the "Right to Explanation" (Article 22 regarding automated individual decision-making) and principles of data minimization.
- **Systemic Privacy Architectures:** Educational machine learning systems increasingly adopt Differential Privacy guarantees and Federated Learning frameworks. Federated learning enables multi-institutional model training by transmitting local parameter updates to a central server without centralizing raw student data.

5.2 Algorithmic Bias and Fairness

Machine learning models trained on historical educational data risk learning and perpetuating institutional biases.

- **Historical and Selection Bias:** If specific demographic, socio-economic, or minority cohorts faced historical grading disparities, an uncalibrated model may map demographic attributes to risk flags, generating self-fulfilling prophecies.
- **Algorithmic Fairness Metrics:** EDM researchers evaluate model fairness using quantitative metrics across sensitive demographic subgroups:
    1. *Demographic Parity:* P(Y_hat=1 | A=0) = P(Y_hat=1 | A=1)
    2. *Equalized Odds:* P(Y_hat=1 | A=0, Y=y) = P(Y_hat=1 | A=1, Y=y) for all y in {0, 1}
- **Mitigation Protocols:** Pre-processing (re-weighting, adversarial debiasing), in-processing (fairness-constrained optimization), and post-processing (threshold adjustment) are essential to prevent predictive models from reinforcing existing disparities.

5.3 Multi-Modal Data Fusion

Modern Learning Analytics systems extend beyond basic tabular GPAs, integrating multi-modal data streams:

1. **Tabular Data:** Administrative records, course demographics, past academic performance.
2. **Interaction Logs (Clickstream):** LMS timestamp logs, resource access sequences, video playback speed adjustments, submission latencies.
3. **Unstructured Text:** Discussion forum posts, peer review comments, essay submissions evaluated via Natural Language Processing (NLP) architectures (e.g., fine-tuned BERT/LLMs).

Integrating these heterogeneous streams requires advanced Multi-Modal Data Fusion techniques, increasing predictive stability while requiring robust infrastructure to manage missing data across modal streams.

5.4 Future Directions

The evolution of student performance prediction points toward dynamic real-time prediction and automated personalized support systems:

- **Real-Time Sequential Forecasting:** Moving from static end-of-term predictions to continuous dynamic risk tracking updated after every student interaction using online sequence models.
- **Causal Machine Learning:** Shifting from observational correlation to causal effect estimation to evaluate *which* specific intervention will maximize a given student's academic outcome.

- **Generative AI & Recommender Interventions:** Linking prediction models directly with Generative AI architectures to automatically draft personalized study schedules, targeted practice problems, and supportive instructor intervention prompts.

6. Conclusion

Predicting student performance using machine learning has emerged as a cornerstone of modern educational analytics, offering a data-driven path toward early academic intervention and personalized instruction. As detailed in this review, advanced ensemble classifiers—notably XGBoost, LightGBM, and CatBoost—consistently demonstrate superior predictive performance on tabular educational datasets, while deep neural architectures excel at processing high-frequency temporal clickstream logs.

However, deployment in institutional contexts requires moving beyond simple accuracy metrics. Evaluating predictive models demands cost-sensitive metric frameworks, prioritizing Recall and F_beta formulations to minimize the operational costs of unflagged failing students. Furthermore, integrating Explainable AI frameworks (SHAP and LIME) addresses the black-box challenge, converting high-dimensional probability scores into transparent, actionable diagnostic insights for educators.

Future research in Educational Data Mining must balance predictive performance with ethical governance. Designing fair, privacy-preserving, multi-modal predictive pipelines that integrate causal inference models will ensure these technological tools support educational equity, student retention, and academic success across diverse student populations.

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ПӘНАРАЛЫҚ ЫҚПАЛДАСТЫҚ НЕГІЗІНДЕ ОҚУШЫЛАРДЫҢ ҒЫЛЫМИ ДҮНИЕТАНЫМЫН ҚАЛЫПТАСТЫРУ

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Аңдатпа: Мақалада пәнаралық мазмұндағы сабақтарды ұйымдастырудың бастапқы кезеңінде түсіндірмелі - көрнекілік әдістерді қолданған тиімді екені негізделінген. Сонымен қатар, мұғалім жаңа материалды түсіндіру барысында сызбалар, кестелер, суреттер, бейнематериалдар мен нақты мысалдарды пайдаланып, әртүрлі пәндер арасындағы байланысты көрсете алатыны түсіндірілген. Бұл оқушылардың күрделі ұғымдарды қабылдауын жеңілдетіп, білімді жүйелі меңгеруіне көмектесетіні айқындалынған

Түйін сөздер: білімді бақылау, білім беру сапасы, физиканы оқыту, оқу жетістіктерін бағалау, қалыптастырушы бағалау, кері байланыс, физикалық эксперимент, танымдық белсенділік, цифрлық технологиялар.

КІРІСПЕ

Қазіргі білім беру жүйесінің негізгі міндеттерінің бірі – оқушылардың ғылыми дүниетанымын дамыту, алған білімдерін күнделікті өмірде қолдануға үйрету және қоршаған ортаға саналы көзқарасын қалыптастыру. Осы міндеттерді жүзеге асыруда пәнаралық байланысты тиімді ұйымдастырудың маңызы зор. Өйткені табиғаттағы құбылыстар мен үдерістер жеке бір пәннің аясында ғана қарастырылмайды, олар физика, химия, биология, география және басқа да ғылымдардың өзара байланысы арқылы түсіндіріледі.

Пәнаралық ықпалдастық білім алушылардың әртүрлі пәндерден алған білімдерін біртұтас жүйеге біріктіріп, табиғат пен қоғам арасындағы өзара тәуелділікті түсінуіне мүмкіндік береді. Мұндай тәсіл оқушылардың логикалық ойлау қабілетін жетілдіріп, зерттеушілік дағдыларын дамытады және ғылыми тұжырымдар жасауға үйретеді.

Пәнаралық мазмұндағы сабақтарды ұйымдастырудың бастапқы кезеңінде түсіндірмелі-көрнекілік әдістерді қолданған тиімді. Мұғалім жаңа материалды түсіндіру барысында сызбалар, кестелер, суреттер, бейнематериалдар мен нақты мысалдарды пайдаланып, әртүрлі пәндер арасындағы байланысты көрсетеді. Бұл оқушылардың күрделі ұғымдарды қабылдауын жеңілдетіп, білімді жүйелі меңгеруіне көмектеседі.

Кейіннен оқыту үдерісінде репродуктивті, проблемалық, зерттеушілік және шығармашылық әдістерді қолдануға болады. Мысалы, оқушылар белгілі бір экологиялық мәселенің пайда болу себептерін анықтап, оны физикалық, химиялық және биологиялық тұрғыдан талдайды. Алынған мәліметтерді салыстыру арқылы мәселенің шешу жолдарын ұсынады. Осылайша, білім алушылар дайын ақпаратты қабылдаушы ғана емес, өздігінен ізденетін және дәлелді қорытынды жасайтын тұлға ретінде қалыптасады.

НЕГІЗГІ БӨЛІМ

Пәнаралық байланыс оқу материалын терең түсінуге және оқушылардың танымдық белсенділігін арттыруға ықпал етеді. Бір тақырыптың бірнеше пәнмен сабақтастығын көрсету білім алушыларға теориялық білімнің өмірдегі қолданысын түсінуге мүмкіндік береді.

Мысалы, ауа құрамын зерттеу барысында химия пәнінде газдардың қасиеттері қарастырылса, биологияда олардың тірі ағзалар үшін маңызы түсіндіріледі. Физикада газдардың қысымы, температурасы және диффузия құбылысы талданады, ал географияда атмосфераның құрамы мен климаттық үдерістер зерттеледі. Осы білімдерді біріктіру арқылы оқушылар атмосфераның табиғаттағы рөлін жан-жақты түсінеді.

Пәнаралық байланыстың тиімділігі оқушылардың мынадай қабілеттерін дамыту арқылы көрінеді:

- ғылыми ақпаратты іздеу, жинақтау және талдау;
- әртүрлі пәндер бойынша алынған білімдерді өзара байланыстыру;
- табиғи құбылыстардың себеп-салдарлық байланыстарын анықтау;
- теориялық білімді тәжірибелік тапсырмаларды орындауда қолдану;
- өз пікірін ғылыми дәлелдермен негіздеу;
- топта жұмыс істеу, пікір алмасу және ортақ шешім қабылдау;
- экологиялық мәселелерге жауапкершілікпен қарау.

Оқушылардың жас ерекшеліктері мен білім деңгейлерін ескере отырып, тапсырмаларды күрделілік дәрежесіне қарай ұйымдастыру қажет. Төменгі сыныптарда көрнекілікке, бақылауға және ойын элементтеріне басымдық берілсе, жоғары сыныптарда зерттеу жұмыстары, пікірталастар, ғылыми жобалар мен тәжірибелік тапсырмалар тиімді нәтиже береді.Жоғары сынып оқушыларына арналған сабақтарды конференция, семинар, дебат, жоба қорғау және ғылыми талқылау түрінде өткізу олардың сыни ойлау қабілетін дамытады. Мысалы, «Су ресурстарын қорғау», «Адам және биосфера», «Атмосфералық ауаның ластануы», «Өндіріс және қоршаған орта» тақырыптарында ұйымдастырылған сабақтар бірнеше пәннің мазмұнын байланыстыруға мүмкіндік береді[1].

Пәнаралық байланысты жүзеге асырудың әдістері мен формалары

Пәнаралық оқытудың нәтижелілігі мұғалім таңдаған әдістерге және оқу әрекетін ұйымдастыру тәсілдеріне байланысты. Сабақ барысында оқушылардың белсенді қатысуын қамтамасыз ететін әдістерді қолдану маңызды:

- ***проблемалық оқыту әдісі.*** Мұғалім оқушылардың алдына нақты мәселе қояды. Мысалы: «Қаладағы көлік санының артуы атмосфераның құрамына қалай әсер етеді?» Оқушылар мәселені физика, химия, биология және география пәндерінен алған білімдері арқылы талдайды;

-зерттеу әдісі. Оқушылар белгілі бір құбылысты бақылап, өлшеулер жүргізеді, алынған нәтижелерді кестеге түсіреді және қорытынды жасайды. Мысалы, мектеп аумағының әртүрлі бөліктеріндегі температураны салыстыру немесе судың физикалық қасиеттерін зерттеу тапсырмалары орындалуы мүмкін;

-жобалық оқыту әдісі. Білім алушылар белгілі бір экологиялық мәселе бойынша жоба әзірлейді. Мысалы, «Мектептегі энергияны үнемдеу жолдары», «Пластик қалдықтарын азайту», «Таза ауа – денсаулық кепілі» тақырыптарындағы жобалар оқушылардың ізденіс қабілетін дамытады;

-цифрлық технологияларды пайдалану. Интерактивті тақта, виртуалды зертханалар, компьютерлік модельдер, электрондық карталар және деректерді визуализациялау құралдары оқу материалын түсінікті етуге көмектеседі. Мысалы, атмосферадағы көмірқышқыл газы мөлшерінің өзгерісін график арқылы көрсету немесе ластаушы заттардың таралуын картадан талдау оқушылардың ақпаратты қабылдауын жеңілдетеді;

-пікірталас және дебат. Оқушылар экологиялық мәселелер бойынша өз көзқарастарын дәлелдеп, басқа пікірлерді тыңдауға үйренеді. Бұл олардың коммуникативтік дағдыларын, сыни ойлауын және ғылыми дәлелдерді қолдану қабілетін жетілдіреді. Осы әдістерді үйлестіре пайдалану оқушылардың пәндік білімін тереңдетіп қана қоймай, олардың дербестігін, жауапкершілігін және шығармашылық белсенділігін дамытуға мүмкіндік береді.

Цифрлық технологиялардың пәнаралық оқытудағы мүмкіндіктері

Қазіргі білім беру жағдайында цифрлық технологияларды пайдалану пәнаралық байланысты жүзеге асырудың маңызды құралына айналды. Сандық ресурстар табиғи үдерістерді көрнекі түрде көрсетуге, тәжірибелік мәліметтерді өңдеуге және күрделі құбылыстарды модельдеуге мүмкіндік береді[2].

Мысалы, интерактивті модельдер арқылы оқушылар газдардың қозғалысын, диффузияны және температураның бөлшектер қозғалысына әсерін бақылай алады. Электрондық кестелер көмегімен ауа сапасы жөніндегі мәліметтерді өңдеп, нәтижелерді диаграмма немесе график түрінде ұсынады.

Экологиялық тақырыптарды оқыту кезінде ауа сапасын өлшейтін датчиктерден алынған мәліметтерді пайдалануға болады. Егер қажетті құралдар болмаса, ашық ғылыми деректер мен дайын цифрлық модельдер қолданылуы мүмкін. Оқушылар мәліметтерді салыстырып, көрсеткіштердің өзгеру себептерін анықтауға тырысады.

Сонымен қатар цифрлық технологиялар оқушылардың жеке ерекшеліктеріне сәйкес тапсырмалар дайындауға мүмкіндік береді. Мысалы, кейбір оқушылар ауаның құрамын көрсететін диаграмма құрастырса, басқалары ластану көрсеткіштерін талдайды немесе қоршаған ортаны қорғауға арналған шағын зерттеу жобасын әзірлейді.

Дегенмен цифрлық құралдар мұғалімнің әдістемелік жұмысын толық алмастырмайды. Олардың тиімділігі оқу мақсаттарына сәйкестігіне, ұсынылған ақпараттың ғылыми дұрыстығына және оқушының белсенді зерттеу әрекетін қамтамасыз етуіне байланысты.

ҚОРЫТЫНДЫ

Пәнаралық ықпалдастық оқушылардың ғылыми дүниетанымын қалыптастыруға, табиғи құбылыстарды тұтас жүйе ретінде түсінуге және теориялық білімді тәжірибеде қолдануға мүмкіндік беретін тиімді педагогикалық тәсіл болып табылады. Жаратылыстану пәндерін өзара байланыстыра оқыту барысында оқушылар физикалық, химиялық, биологиялық және географиялық үдерістердің бір-бірімен тығыз байланыста жүретінін түсінеді. Бұл олардың табиғат заңдылықтарын ғылыми тұрғыдан меңгеруіне, зерттеушілік қабілеттерінің дамуына және экологиялық мәселелерге саналы көзқарасының қалыптасуына ықпал етеді.

Пәнаралық байланысты тиімді ұйымдастыру үшін мұғалім оқу материалын жүйелі жоспарлап, пәндер арасындағы ортақ тақырыптарды анықтап, зертханалық жұмыстарды, жобалық тапсырмаларды, проблемалық сұрақтарды және цифрлық білім беру ресурстарын мақсатты пайдалануы қажет[3].

Осы бағытта ұйымдастырылған оқу үдерісі білім алушылардың танымдық белсенділігін арттырып қана қоймай, олардың дербес шешім қабылдауына, ғылыми дәлелдерді бағалауына және қоршаған ортаға жауапкершілікпен қарауына жағдай жасайды. Демек, пәнаралық оқыту – білім мазмұнын кіріктірудің ғана емес, жан-жақты дамыған, ғылыми ойлайтын, экологиялық мәдениеті қалыптасқан және қоғам алдындағы жауапкершілігін түсінетін тұлғаны тәрбиелеудің маңызды құралы.

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3.http://freesoft.ru/virtualnaya_laboratoriya_po_fizike_dlya_shkolnikov, «Виртуальная лаборатория по физике для школьников»

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БІЛІМ БЕРУ ҮДЕРІСІНДЕ АҚПАРАТТЫҚ-КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАРДЫ ТИІМДІ ПАЙДАЛАНУ

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Аннотация: Мақалада қазіргі кезеңде ақпараттық-коммуникациялық технологиялар білім беру жүйесін жаңғыртудың маңызды бағыттарының біріне айналатын мүмкіндіктерін көрсетілген. Сонымен қатар, цифрлық технологиялардың қарқынды дамуы оқыту әдістерін жетілдіруге, оқу материалдарын ұсынудың жаңа тәсілдерін енгізуге және білім алушылардың танымдық белсенділігін арттыруға кең мүмкіндік беретіні негізделінген.

Кілт сөздер: бейнеконференциялар, интерактивті, цифрлық, ресурстар, зертханалық, виртуалды, құзіреттілік, мультимедиялық, технология.

Кіріспе

Сабақ барысында компьютерлік бағдарламаларды, электрондық оқулықтарды, интерактивті тақталарды, мультимедиалық ресурстарды және интернет платформаларын қолдану оқу үдерісінің сапасын жақсартуға ықпал етеді. Сонымен қатар электрондық пошта, бейнеконференциялар, қашықтан оқыту жүйелері мен онлайн сабақтар білім алушылардың ақпарат алмасуына және оқу материалдарын өз бетінше меңгеруіне жағдай жасайды.Бүгінгі білім беру саласындағы негізгі міндеттердің бірі – оқушылардың шығармашылық әлеуетін дамыту, сыни тұрғыдан ойлау қабілетін қалыптастыру және өздігінен білім алу дағдыларын жетілдіру.

Негізгі бөлім

Осы міндеттерді жүзеге асыруда инновациялық педагогикалық әдістер мен цифрлық құралдарды үйлесімді пайдалану ерекше маңызға ие. Мысалы, интерактивті тапсырмалар, виртуалды зертханалар, білім беру платформалары және мультимедиалық түсіндірмелер күрделі тақырыптарды түсінікті жеткізуге көмектеседі. Мұндай тәсілдер оқушылардың сабаққа деген қызығушылығын арттырып қана қоймай, олардың зерттеушілік қабілеттерін дамытып, оқу үдерісіне белсенді қатысуына мүмкіндік береді.Ақпараттық-коммуникациялық технологияларды білім беру жүйесіне енгізу ұлттық білім сапасын арттыруға және халықаралық білім кеңістігімен ықпалдастықты нығайтуға ықпал етеді.

Цифрлық ресурстарды тиімді пайдалану арқылы білім алушылардың ақпараттық сауаттылығын, цифрлық мәдениетін және ақпаратпен жұмыс істеу құзыреттілігін қалыптастыруға болады. Бұл құзыреттер ақпаратты іздеу, іріктеу, салыстыру, оның сенімділігін бағалау, алынған мәліметтерді талдау және практикалық міндеттерді шешуде орынды қолдану дағдыларын қамтиды. Сондықтан ақпараттық-коммуникациялық технологиялар тек білімді жеткізу құралы ғана емес, сонымен бірге оқушының жеке тұлғалық

және зияткерлік дамуын қамтамасыз ететін маңызды педагогикалық ресурс болып саналады.

Оқу материалдарын меңгеру тиімділігін арттыруда электрондық оқулықтардың, білімді тексеруге арналған цифрлық бағдарламалардың және интерактивті оқу жүйелерінің мүмкіндіктері зор. Олар оқу мазмұнын көрнекі түрде ұсынуға, тапсырмаларды оқушының дайындық деңгейіне сәйкес ұйымдастыруға және білім нәтижелерін жедел бағалауға мүмкіндік береді.

Мұғалім осы мүмкіндіктерді пайдалана отырып, оқытуды дараландыруға, әр оқушының қабілеті мен қажеттілігін ескеруге және оқу үдерісін тиімді ұйымдастыруға жағдай жасайды. Практикалық және өндірістік оқытуда цифрлық технологияларды қолдану білім алушылардың кәсіби құзыреттілігін қалыптастыруда да маңызды рөл атқарады. Электрондық оқулықтар, мамандандырылған бағдарламалар, виртуалды модельдеу жүйелері және интернет ресурстары теориялық білімді тәжірибемен байланыстыруға мүмкіндік береді.

Мәселен, виртуалды зертханалар арқылы әртүрлі тәжірибелерді модельдеуге, физикалық үдерістердің жүру ерекшеліктерін бақылауға және алынған нәтижелерді салыстыруға болады. Мұндай мүмкіндіктер зертханалық құрал-жабдықтар жеткіліксіз болған жағдайда немесе тәжірибені қауіпсіз ортада ұйымдастыру қажет болғанда ерекше тиімді.Цифрлық технологияларды мақсатты пайдалану білім алушылардың ақпараттық құзыреттілігін дамытумен қатар, олардың дербес шешім қабылдау, шығармашылықпен жұмыс істеу және алған білімдерін күнделікті өмірде қолдану қабілеттерін жетілдіреді.

Дегенмен технологиялық құралдарды қолдану сабақтың мазмұны мен оқу мақсаттарына сәйкес ұйымдастырылуы тиіс. Мұғалім цифрлық ресурстарды таңдағанда олардың ғылыми дұрыстығын, мазмұндық сапасын, қолжетімділігін және оқушының жас ерекшеліктеріне сәйкестігін ескеруі қажет.Қорытындылай келе, ақпараттық-коммуникациялық технологияларды білім беру үдерісіне жүйелі енгізу оқытудың тиімділігін арттырудың және білім сапасын жетілдірудің маңызды шарттарының бірі болып табылады.

Цифрлық құралдарды дәстүрлі оқыту әдістерімен ұштастыру білім алушылардың танымдық белсенділігін күшейтіп, олардың ақпараттық мәдениетін қалыптастыруға және заманауи талаптарға сай құзыреттерін дамытуға мүмкіндік береді.

Сабақта ақпараттық - коммуникациялық технологиялардыпайдаланудың тиімділігі: оқушының өз бетімен жұмысы;аз уақытта көп білім алып, уақытты үнемдеу; білім - білік дағдыларын тест тапсырмалары арқылы тексеру; шығармашылық есептер шығару; қашықтықтан білім алу мүмкіндігінің туындауы; қажетті ақпаратты жедел түрде алу мүмкіндігі; іс - әрекет, қимылды қажет ететін пәндер мен тапсырмаларды оқып үйрену; қарапайым көзбен көріп, қолмен ұстап сезіну немесе құлақ пен есту мүмкіндіктері болмайтын табиғаттың таңғажайып процестері мен әр түрлі тәжірибе нәтижелерін көріп, сезіну мүмкіндігі; оқушының ой- өрісін дүниетанымын кеңейтуге де ықпалы зор. Ақпараттық технологиялар орталарын пайдаланудың мақсаттары: ақпараттық технологияларды қолдану негізінде оқу- тәрбие процесінің барлық деңгейін жетілдіру:

оқыту процесінің ықпалы мен сапасын арттыру, пәнаралық байланысты тереңдету, қажетті ақпаратты іздеуді оңайлату және көлемін ұлғайту. оқушы тұлғасын дамыту, ақпараттық қоғамда өмір сүруге даярлау.коммуникативтік қабілеттерді дамыту, күрделі жағдайда оңтайлы шешім немесе шешу нұсқаларын қабылдау дағдыларын қалыптастыру. компьютерлік графика, мультимедиа технологиясын пайдалану арқылы эстетикалық тәрбие беру, ақпараттық мәдениетті қалыптастыру, ақпаратты өңдей білу.

Қазіргі ақпараттық технологиялардың қарқынды даму кезеңінде орта білім беретін оқу орындарының оқу үдерісінің тиімділігі - болашақ мұғалімнің кәсіби дайындығына тікелей қатысты. Сол себепті ақпараттық- қатынастық технологиялар құралдарын педагогикалық іс-

әрекетке кеңінен қолдана білу іскерліктерінің жоғары деңгейде қалыптасуы мектеп мұғалімдерінің кәсіби дайындығына қойылатын талаптар қатарына енеді.

Қорытынды

Қазіргі қоғамды ақпараттандыру үдерістері және олармен тығыз байланыстағы білім беру жүйесінің барлық формаларын ақпараттандыру, жаңа ақпараттық және қатынастық технологияларын (АҚТ) меңгеру және жаппай тарату үдерістерімен сипатталады. Мұндай технологиялар білім берудің жаңа жүйелерінде оқытушы мен оқушының арасында қарым-қатынас орнату және мағлұмат алмасу үшін белсенді қолданылады. Қазіргі оқытушы АҚТ төңірегіндегі білімдерді игеріп қана қоймай, сондай- ақ оларды өзінің кәсіби іс- әрекетінде пайдалана алатын маман болуы тиіс.

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Political Studies

«ХАЛЫҚ ҮНІНЕ ҚҰЛАҚ АСАТЫН МЕМЛЕКЕТ» ТҰЖЫРЫМДАМАСЫ: ЦИФРЛЫҚ КЕҢІСТІКТЕГІ ДИАЛОГТЫҢ ТИІМДІЛІГІ МЕН ҚАЙШЫЛЫҚТАРЫ

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Аңдатпа

Мақалада соңғы 5 жылда (2019–2024 жж.) Қазақстан Республикасында «Халық үніне құлақ асатын мемлекет» саяси тұжырымдамасының жүзеге асырылу барысы IMRAD форматында кешенді түрде талданады. Зерттеудің басты мақсаты – цифрлық платформалар (e-Otinish, «Ашық үкімет», iKomek 109) арқылы билік пен қоғам арасындағы диалогтың тиімділік көрсеткіштерін айқындау және бюрократиялық формализм, аймақтық теңсіздіктер мен әлеуметтік желілердегі манипуляциялық тәуекелдер сияқты институционалдық қайшылықтарды зерделеу. Эмпирикалық деректер, әлеуметтанулық сауалнамалар (ҚСЗИ, жергілікті респонденттер), мемлекеттік статистика және халықаралық индекстер (БҰҰ EGDI, WJP Rule of Law) негізінде цифрлық инфрақұрылымның кеңеюі азаматтардың өтініш беру белсенділігін 2 есеге арттырғаны дәлелденді. Дегенмен, жергілікті атқарушы органдардың (әкімдіктердің) жауап қайтару сапасы мен азаматтардың қанағаттану деңгейі арасында елеулі алшақтық сақталып отыр.

Кілт сөздер: Халық үніне құлақ асатын мемлекет, цифрлық диалог, кері байланыс, e-Otinish, жергілікті атқарушы органдар, коммуникациялық қайшылықтар.

Аннотация

В статье в формате imrad комплексно анализируется ход реализации политической концепции «слышащее государство» в республике казахстан за последние 5 лет (2019–2024 гг.). Основная цель исследования – определить показатели эффективности диалога между властью и обществом через цифровые платформы (e-otinish, «открытое правительство», ikomek 109) и изучить институциональные противоречия, такие как бюрократический формализм, региональный дисбаланс и риски манипуляций в социальных сетях. На основе эмпирических данных, социологических опросов (киси, региональные респонденты), государственной статистики и международных индексов (оон egdi, wjp rule of law) доказано, что расширение цифровой инфраструктуры увеличило активность обращений граждан более чем в 2 раза. Однако сохраняется значительный разрыв между качеством ответов местных исполнительных органов (акиматов) и уровнем удовлетворенности населения.

Ключевые слова: слышащее государство, цифровой диалог, обратная связь, e-otinish, местные исполнительные органы, коммуникационные противоречия.

Abstract

This paper provides a comprehensive analysis of the implementation of the "listening state" political concept in the republic of kazakhstan over the last 5 years (2019–2024) using the imrad format. The main objective of the study is to evaluate the efficiency metrics of dialogue between the government and society through digital platforms (e-otinish, open government, ikomek 109) and to examine institutional contradictions such as bureaucratic formalism, regional disparities, and manipulation risks in social media. Based on empirical data, sociological surveys (kaziss, regional respondents), official statistics, and international indices (un egdi, wjp rule of law), it is proven that the expansion of digital infrastructure has doubled citizen engagement in submitting appeals. However, a substantial gap remains between the quality of responses provided by local executive bodies (akimats) and public satisfaction levels.

Keywords: listening state, digital dialogue, public feedback, e-otinish, local executive bodies, communication contradictions.

Кіріспе

2019 жылғы 2 қыркүйекте мемлекет басшысы қасым-жомарт тоқаев қазақстан халқына арнаған жолдауында «халық үніне құлақ асатын мемлекет» (listening state) стратегиялық тұжырымдамасын жария етті. Бұл модель тік басқару вертикалынан бас тартып, мемлекеттік аппараттың азаматтар сұранысына жедел, ашық әрі тиімді**ѕпѕпѕпѕ** жауап беруін, яғни азаматқа бағдарланған (человекоцентричный) басқару жүйесін қалыптастыруды көздейді. Соңғы 5 жыл ішінде бұл тұжырымдама елдегі саяси трансформация мен мемлекеттік басқаруды модернизациялаудың басты идеологиялық-практикалық фрейміне айналды.

Әлеуметтік коммуникация теориясы тұрғысынан алғанда, билік пен қоғам арасындағы монологтан диалогқа көшу әлеуметтік қашықтықты қысқартып, мемлекеттік институттарға деген легитимділік пен сенімді нығайтудың негізгі механизмі болып табылады. Бұл процестің техникалық драйвері ретінде «ашық үкімет» (open government) жүйесінің құрамдас бөліктері («ашық деректер», «ашық диалог», «ашық нқа», «ашық бюджеттер»), «e-otinish» бірыңғай өтініштер платформасы, 1414 байланыс орталығы, ikomek 109 жедел сервисі және мемлекеттік қызметшілердің әлеуметтік желілердегі ресми аккаунттары іске қосылды.

Зерттеудің өзектілігі мен мәселесі тұжырымдама жарияланғаннан бергі 5 жыл ішінде цифрлық арналар арқылы түскен өтініштер мен арыз-шағымдардың саны еселеп өсті. Алайда, санның өсуі автоматты түрде сапалық өзгерістерге әкелген жоқ. Мемлекеттік органдардың (әсіресе жергілікті әкімдіктердің) қызметінде формальды жауап қайтару (отписка), шешімдердің орындалмауы, аймақтық цифрлық сауаттылық пен ресурстардың теңсіздігі, сондай-ақ әлеуметтік желілерде шынайы диалогтың орнына пиар мен бот-фермаларды қолдану сияқты терең қайшылықтар белең алды.

Зерттеудің мақсаты 2019–2024 жылдар аралығындағы эмпирикалық, статистикалық және әлеуметтанулық деректерді жүйелеп, цифрлық кеңістіктегі мемлекет пен қоғам диалогының нақты тиімділік көрсеткіштерін айқындау және оны жүзеге асырудағы негізгі институционалдық қайшылықтарды ашып көрсету.

Зерттеу әдістері

Зерттеу процесінде 2019–2024 жылдар аралығын қамтитын кешенді сандық (quantitative) және сапалық (qualitative) әдістер ұштастырылды. Зерттеудің эмпирикалық базасын құрастыруда мынадай дереккөздер мен методологиялық тәсілдер пайдаланылды:

1. Әлеуметтанулық репрезентативті сауалнамалар:

- Қазақстан стратегиялық зерттеулер институтының (қсзи) 2023–2026 жылдардағы республикалық зерттеу нәтижелері (n=1200+ респондент), онда халықтың «азаматтарды еститін мемлекет» идеясын қабылдауы және институционалдық сенім деңгейі бағаланған.
- Түркістан қаласы мен өңірлік деңгейде жүргізілген эмпирикалық зерттеу (д.о. тубекова және б., 2023 ж., n=300 респондент). Мұнда спирмен корреляциялық талдауы (spearman correlation), дурбин-уотсон коэффициенті (durbin-watson, dw=1.978) және регрессиялық модельдеу (regression analysis) арқылы жергілікті атқарушы органдар мен халық арасындағы кері байланыс сапасы есептелген.

2. Мониторингтік және статистикалық аудит:

- Ranking.kz аналитикалық орталығының 2021 жылы жергілікті исполнительдік органдарға (жао) түскен 28 000-нан астам өтініштерді өңдеу жылдамдығы мен азаматтардың қанағаттану деңгейі бойынша жасаған өңірлік рейтингтік талдауы.
- Қр бас прокуратурасының құқықтық статистика және арнайы есепке алу комитеті мен құқық қорғау органдары академиясының e-otinish және ердр жүйелері арқылы азаматтардың арыз-шағымдарын қарау сапасына жүргізген ведомстволық талдаулары (2021–2023 жж.).

3. Институционалдық және дискрус-талдау:

- Саясаттанушылар мен сарапшылардың (т. Умбеталиева, д. Көшербаев, ж. Әшімжанов және б.) Цифрлық петициялар (epetition), қоғамдық кеңестер және әлеуметтік медиадағы мемлекеттік коммуникация сапасына берген сараптамалық бағалары.
- Бұұ электрондық үкіметті дамыту индексі (un egdi) және world justice project (wjp) rule of law халықаралық индикаторларындағы қазақстан позициясын салыстырмалы талдау.

Нәтижелер

Цифрлық диалог инфрақұрылымы және азаматтар белсенділігінің өсуі. Соңғы 5 жылда мемлекеттік органдардың инфрақұрылымын цифрландыру азаматтардың өтініш беру кедергілерін айтарлықтай төмендетті. E-otinish бірыңғай платформасының енгізілуі арқасында өтініштерді тіркеу және қарау процесі орталықтандырылды.

- Өтініштер динамикасы: тек 2024 жылдың өзінде мемлекеттік органдарға 4 миллионға жуық, ал президент әкімшілігіне 50 мыңнан астам өтініш келіп түскен. Соңғы 5 жылда азаматтар тарапынан жолданған арыз-шағымдардың жалпы көлемі 2 еседен астам өсті.
- «ашық үкімет» порталының көрсеткіштері: «ашық деректер» порталында 3,6 мың деректер жиынтығы; «ашық нқа» платформасында 118,3 мың нормативтік акт жобасы; «ашық диалогта» 483,8 мың өтініш; ал «ашық бюджеттерде» 157,7 мың бюджеттік бағдарлама жобасы жарияланып, талқылауға ұсынылды.
- Халықаралық рейтингтер: бұұ-ның электрондық үкіметті дамыту индексінде (egdi) қазақстан 28-орынға көтеріліп, теңізге шыға алмайтын дамушы елдер арасында ең жоғары көрсеткішке қол жеткізді. Сонымен қатар, қылмыстық процесті цифрландыру

арқасында wjp rule of law (заң үстемдігі) индексінде 140 елдің ішінде 65-орынға тұрақтады (1-кесте).

1-кесте. «Халық үніне құлақ асатын мемлекет» цифрлық коммуникация инфрақұрылымының негізгі көрсеткіштері (2019–2024 жж.)

Индикатор / Платформа	Өлшем бірлігі / Позиция	Нақты көрсеткіш (дереккөздер бойынша)
Жылдық өтініштер көлемі (2024 ж.)	Мемлекеттік органдарға / Президент Әкімшілігіне	~4 000 000 / >50 000 өтініш
Өтініштер өсімі (2019–2024 жж.)	Салыстырмалы динамика	2 еседен астам өсті
«Ашық НҚА» порталындағы жобалар	Жарияланған НҚА саны	118 300 жоба
«Ашық диалог» платформасы	Келіп түскен өтініштер	483 800 өтініш
БҰҰ Электрондық үкімет индексі (EGDI)	Әлемдік рейтингтегі орны	28-орын (дамушы елдер көшбасшысы)
WJP Rule of Law (Заң үстемдігі) индексі	140 елдің ішіндегі орны	65-орын (2022 ж.)

Әлеуметтанулық тұрғыдан алғанда, ҚСЗИ зерттеуі респонденттердің 69,9%-ы «мемлекет азаматтарды естиді» деген пікірді қолдайтынын көрсетті (оның ішінде 28,4%-ы «естиді және мәселелерді шешеді», 41,5%-ы «көбіне құлақ асады»). Мемлекетті «құлақ асады» деп есептейтін азаматтар арасында Президентке деген сенім 93,5%-ды, ал жергілікті әкімдерге сенім 87,5%-ды құрайды; бұл топтың 70,4%-ы елдің даму бағытын толық дұрыс деп бағалайды.

Өңірлік теңсіздіктер мен әкімдіктер қызметіндегі қайшылықтар бар. Дегенмен, цифрлық арналардың көбейгеніне қарамастан, жергілікті деңгейде өтініштерді қарау сапасы төмен күйінде қалып отыр. Ranking.kz сарапшыларының ЖАО (әкімдіктер) бойынша жүргізген мониторингі (28 мыңнан астам өтініш) біршама қайшылықтарды ашты:

1. Жауапсыз қалған өтініштер: Жалпы өтініштердің 89,4%-ына ғана жауап берілген. Шығыс Қазақстан облысы 100% жауап қайтарып көш бастаса, Алматы қаласының әкімдігі ең төменгі көрсеткіш көрсетті – өтініштердің бар-жоғы 72,9%-ына ғана жауап беріп, 2000-ға жуық арызды жауапсыз қалдырған. Қостанай (74,3%) және Маңғыстау (81,6%) облыстары да аутсайдерлер қатарына кірді.
2. Отписка мен формализм дерті: Жауап беру фактісі азаматтың мәселесі шешілді дегенді білдірмейді. Жауап қайтару көрсеткіші 100% болған ШҚО-да респонденттердің 43%-ы алған жауаптарына қанағаттанбаған. Қанағаттанбау деңгейі ең жоғары аймақтар: Астана қаласы (51%), Алматы қаласы (49%) және Атырау облысы (44%), (2-кесте).

2-кесте. Қазақстан өңірлері бойынша әкімдіктердің өтініштерге жауап беру белсенділігі мен халықтың қанағаттанбау деңгейі (Ranking.kz аудиті)

Өңір / Әкімдік	Өтініштерге жауап беру үлесі (%)	Жауап сапасына қанағаттанбағандар үлесі (%)	Негізгі сипаттамасы
Шығыс Қазақстан облысы	100,0% (Көшбасшы)	43,0%	Сандық қамту жоғары, бірақ сапасы төмен (формальды жауаптар)
Алматы қаласы	72,9% (Аутсайдер)	49,0%	2000 өтініш жауапсыз қалған; жоғары қанағаттанбау
Астана қаласы	Орташа деңгей	51,0% (Ең нашар көрсеткіш)	Жауаптардың жартысынан астамы формальды сипатта
Қостанай облысы	74,3%	Орташа деңгей	Төмен респонсивтілік (реагирование)
Атырау облысы	Орташа деңгей	44,0%	Жауап сапасының төмендігі
Жамбыл, БҚО, Қызылорда	Орташадан жоғары	< 30,0% (Үздік көрсеткіш)	Жауап сапасы бойынша салыстырмалы оң динамика

Д.О. Түбекова және авторлар ұжымының Түркістан қаласында жүргізген эмпирикалық зерттеуі (N=300) бұл мәселені тереңдете түседі:

- Респонденттердің 49%-ы жергілікті атқарушы органдар халықтың талаптарын әрдайым ести бермейді деп мәлімдеген.
- 13%-ы кері байланыс атымен жоқ десе, 15%-ы сыбайлас жемқорлық жағдайында сындарлы диалог мүмкін емес деп есептейді.
- Спирмен корреляциясы көрсеткендей, жергілікті органдардың ашықтығы мен «ХҮҚАМ» қағидаларының тиімділігі арасындағы байланыс төмен ($r = 0.153$), бұл жүйенің реттелмегенін айғақтайды.
- Дурбин-Уотсон регрессиялық моделі ($DW=1.978$) азаматтардың қанағаттануы мемлекеттік қызметшілердің этикасы мен АКТ-ны дамыту деңгейіне тікелей тәуелді екенін ($p < 0.05$) растады.

Құқық қорғау саласы мен әлеуметтік рискілер. Прокуратура органдарына түскен арыздарды талдау көрсеткендей, 2021 жылы тергеудің созылбалылығына (волокита) қатысты 866 өтініш қаралып, өткен жылмен салыстырғанда 57%-ға өскен. Прокурорлық қадағалау араласқанда бұл шағымдардың қанағаттандырылуы 80–90%-ға жетеді (мысалы, Қостанайда 92%), бұл бастапқы полиция немесе жергілікті орган деңгейінде өтініштердің формальды жабылатынын дәлелдейді. Сонымен қатар, интернет-коммуникацияның кеңеюі жаңа әлеуметтік катализаторларды тудырды. М.Б. Тоқтағазин және авторлардың зерттеуі бойынша, цифрландырумен қатар кибербуллинг және онлайн-құдалау қаупі күшейді: 11–15 жас аралығындағы мектеп оқушыларының 12%-ы онлайн құдалауға ұшырайды. Бұл цифрлық

кеңістікті реттеу мен азаматтық қауіпсіздікті қамтамасыз ету арасындағы жаңа құқықтық қайшылықты тудырды.

Талқылау

Алынған нәтижелер соңғы 5 жылда қазақстанда «халық үніне құлақ асатын мемлекет» тұжырымдамасы аясында техникалық-инфрақұрылымдық серпіліс болғанын айқын көрсетеді. Алайда, институттық және мазмұндық деңгейде біршама күйелі қайшылықтар сақталып отыр:

1. Сандық трансакциялар мен мазмұндық респонсивтілік қайшылығы: мемлекет өтініштерді қабылдаудың «бір терезе» жүйесін (e-otinish) сәтті құрды, бұған түсетін өтініштердің 2 есе өсуі дәлел. Аллайда, мемлекеттік бюрократия сандық есепке алуды игергенімен, азаматтардың мәселесін мазмұндық тұрғыдан шешуге келгенде формализм мен шенеуніктік қарсылыққа (сопротивление среды) тап болуда. Астана мен алматы сияқты ірі мегаполистерде халықтың қанағаттанбау деңгейінің 49–51%-ға жетуі осы бюрократиялық сүзгінің салдары.
2. «селективті есту» (selective hearing) феномені: сарапшы т. Умбеталиеваның атап өтуінше, билік жүйесі қоғамдағы эмоционалды әлеуметтік триггерлерге (мысалы, тұрмыстық зорлық-зомбылық, балалар қауіпсіздігі) жедел реакция білдіріп, заңнамалық өзгерістер енгізеді. Алайда, жүйелі саяси сұраныстар, аймақтық билік өкілеттіктерін кеңейту немесе петициялар саяси сүзгіге ұшырап, формальды түрде бұғатталады немесе реакциясыз қалады.
3. Қоғамдық кеңестер мен әлеуметтік желілердегі имитация: г.о. спабеков көрсеткендей, қоғамдық кеңестер институты маслихаттардың функцияларын қайталап, кей жағдайда формальды консультативтік органға айналған. Ал әлеуметтік желілерде мемлекеттік қызметшілердің белсенділігі жиі ашық диалог ретінде емес, пиар-стратегиялар мен бот-фермалар (коммент-фабрикалар) арқылы сыни пікірлерді тұншықтыру тетігі ретінде қолданылады.

Ұсыныстар мен шешу жолдары:

- Жао және орталық органдарда өтініштерді қарау сапасын бағалайтын тәуелсіз kpi жүйесін енгізу (себебі тек өңдеу пайызы емес, азаматтың қанағаттануы басты критерий болуы тиіс).
- Қоғамдық кеңестердің құрамын билік тағайындаудан азаматтық қоғамның өзі сайлайтын ашық модельге көшіру.
- Ауылдық және өңірлік деңгейде «халықтық бюджетке қатысу» (participatory budgeting) жобаларын міндетті түрде кеңейту.

Қорытынды

«Халық үніне құлақ асатын мемлекет» тұжырымдамасы 2019–2024 жылдар аралығында қазақстанның саяси жүйесін модернизациялауда маңызды катализатор рөлін атқарды. Елде бірыңғай цифрлық коммуникациялық архитектура қалыптасып, азаматтардың кері байланыс арналарына қолжетімділігі артты. Бұу egdi индексіндегі 28-орын мен мемлекетке деген сенімнің өсуі – осы реформалардың басты оң нәтижесі.

Сонымен бірге, зерттеу көрсеткендей, тұжырымдаманы іске асыру «цифрлық жетістіктер» мен «бюрократиялық формализм» арасындағы қайшылықпен сипатталады. Мемлекеттік аппарат әлі де болса жауап дайындауда сан артынан қуып, сапаны ысырып тастауға бейім. Цифрлық диалогтың тиімділігін арттыру үшін мемлекет селективті жауап

беруден жүйелі транспаренттілікке көшіп, жергілікті атқарушы органдардың жауапкершілігін күшейтуі және азаматтық қоғам институттарына шынайы өкілеттіктер беруі қажет.

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Ұлттық бірегейлік: қазіргі Қазақстандағы ұлттық құндылықтар мен ұлттық кодтың саяси интерпретациясы

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Кіріспе

Ұлттық бірегейлік қоғамның тарихи тәжірибесі, мәдени құндылықтары және ортақ саяси кеңістікке тиесілігі туралы түсініктері арқылы қалыптасады.

Ол тек ұлттық ерекшеліктерді сақтаумен шектелмей, тарихи өткенді түсіндіру, ортақ құндылықтарды айқындау және қоғамның болашаққа қатысты бағдарларын қалыптастыру үдерістерімен де байланысты.

Б.Андерсон ұлтты ортақ тиесілік туралы түсініктер негізінде қалыптасатын «елестетілген қауымдастық» ретінде қарастырса, Э.Смит ұлттық бірегейліктің тарихи жады, ортақ мифтер, рәміздер мен мәдени құндылықтармен байланысын негіздейді [1; 2].

Қазақстан жағдайында ұлттық бірегейлік мәселесі тарихи мұраны пайымдау, ұлттық құндылықтардың мазмұнын анықтау және азаматтық бірегейлікті қалыптастыру үдерістерімен сабақтас.

М.Ларюэльдің Орталық Азиядағы ұлт қалыптастыру саясатына арналған зерттеуі Қазақстандағы ұлттық бірегейлікті мемлекеттік дискурс, тарихи баяндаулар және қоғамдық түсініктердің өзара ықпалы арқылы қарастыруға мүмкіндік береді [3]. Бұл ұлттық құндылықтар мен ұлттық кодтың мазмұнын тек мәдени құбылыс ретінде емес, олардың саяси дискурста берілу ерекшеліктері тұрғысынан да зерттеудің маңызын көрсетеді.

Осыған байланысты мақаланың **ғылыми мәселесі** қазіргі Қазақстанда ұлттық құндылықтар мен ұлттық кодтың қандай мағыналар арқылы түсіндірілетінін және олардың ұлттық бірегейлік туралы түсініктермен қалай байланысатынын анықтауға бағытталған.

Мақаланың **мақсаты** – ұлттық құндылықтар мен ұлттық кодтың саяси интерпретациясын талдау және олардың ұлттық бірегейліктің мазмұнын қалыптастырудағы рөлін айқындау.

Мақалада саяси дискурстық және фреймдік талдау әдістері қолданылады.

Тарихи жад ұлттық құндылықтардың мағынасын түсіндіретін және өткен мен қазіргі қоғамдық-саяси бағдарларды байланыстыратын талдау өлшемі ретінде қарастырылады.

1. Ұлттық бірегейлік, ұлттық құндылықтар және ұлттық кодтың теориялық-әдіснамалық негіздері

Ұлттық бірегейлік ұғымы саясаттануда ұлттың өзіндік ерекшелігін, ортақ тиесілік сезімін және тарихи-мәдени сабақтастығын түсіндіру үшін қолданылады. Б.Андерсон ұлтты адамдардың бір-бірімен тікелей таныс болмаса да, өздерін ортақ қауымдастықтың мүшесі ретінде елестетуі арқылы қалыптасатын саяси қауымдастық ретінде қарастырады [1]. Бұл тұжырым ұлттық бірегейліктің табиғи түрде берілетін белгілермен ғана емес, ортақ түсініктер мен мағыналардың қалыптасуымен де байланысты екенін көрсетеді.

Э.Смит ұлттық бірегейлікті тарихи жад, ортақ мифтер, рәміздер, дәстүрлер мен мәдени құндылықтар арқылы түсіндіреді [2]. Оның этносимволистік көзқарасы бойынша, тарихи мұра мен символдық бейнелер ұлттық қауымдастықтың өзін-өзі тануына ықпал етеді.

Осы тұрғыдан алғанда, тарихи тұлғалар, маңызды оқиғалар, мәдени дәстүрлер мен ұлттық рәміздер өткен туралы білімді сақтаумен шектелмейді. Олар қоғамның тарихи сабақтастық жөніндегі түсініктерін қалыптастырып, ұлттық бірегейліктің мазмұнын айқындауға қатысады.

Ұлттық құндылықтар осы үдерістің маңызды құрамдас бөлігі болып табылады. Олар қоғамда маңызды деп танылатын мәдени ұстанымдарды, мінез-құлық қағидаларын және ортақ мұраттарды қамтиды.

Алайда құндылықтардың ұлттық бірегейлікке ықпалы олардың тарихи қалыптасуымен ғана анықталмайды. Олардың қазіргі қоғамдық-саяси жағдайда қалай түсіндірілетіні, қандай идеялармен байланыстырылатыны және қоғамдық дискурста қалай ұсынылатыны да маңызды.

Сондықтан ұлттық құндылықтарды зерттеу олардың мазмұнын сипаттаумен қатар, саяси интерпретациясының ерекшеліктерін анықтауды қажет етеді.

Ұлттық код ұғымын осы мәселемен байланыстыра қарастыруға болады. Бұл ұғым ұлттық мәдениеттің ерекшеліктерін, тарихи тәжірибесін, тілін, дәстүрлері мен символдық бейнелерін жинақтап түсіндіру үшін қолданылады. Дегенмен ұлттық кодтың мазмұнын өзгермейтін және барлық қоғам мүшелеріне бірдей тән белгілердің жиынтығы ретінде қабылдау ғылыми тұрғыдан шектеулі болар еді.

Ұлттық мәдениеттің көріністері тарихи жағдайларға қарай өзгеріп, жаңа мағыналарға ие болуы мүмкін.

Осы себепті мақалада ұлттық код ұлттық бірегейліктің мазмұнын түсіндіруге қатысатын тарихи-мәдени белгілер мен құндылықтардың интерпретациялық жүйесі ретінде қарастырылады.

Қазақстан жағдайында бұл мәселелер ұлттық бірегейліктің қалыптасуын мемлекеттік саясатпен, тарихи баяндаулармен және қоғамдық түсініктермен байланыстыра зерттеуді талап етеді.

М.Ларюэльдің Орталық Азиядағы ұлт қалыптастыру үдерістеріне арналған зерттеуі ұлттық бірегейлікті мемлекеттік және қоғамдық деңгейлердегі өзара ықпалдастық тұрғысынан қарастыруға негіз береді [3]. Бұл тәсіл Қазақстандағы ұлттық құндылықтар мен ұлттық кодтың саяси дискурста берілуін талдауға мүмкіндік береді.

Осы теориялық пайымдаулар негізінде ұлттық бірегейлікті тарихи жад, құндылықтар және олардың саяси интерпретациясы өзара ықпалдасатын үдеріс ретінде қарастыруға болады. Мұнда тарихи жад ұлттық қауымдастықтың өткені туралы түсініктерді қалыптастырса, ұлттық құндылықтар сол өткенге берілетін мағыналарды қазіргі қоғамдық бағдарлармен байланыстырады. Ал ұлттық код осы тарихи-мәдени мазмұнды жинақтап түсіндіретін ұғым ретінде көрінеді.

2. Қазіргі Қазақстандағы ұлттық құндылықтар мен ұлттық кодтың саяси интерпретациясы

Қазақстандағы ұлттық құндылықтар мен ұлттық кодтың саяси интерпретациясын талдау үшін мемлекеттік дискурста ұсынылатын құндылықтық бағдарлар мен тарихи мұраның берілу тәсілдерін қарастыру қажет.

Бұл ретте ресми құжаттар ұлттық бірегейлікке қатысты мемлекеттің ұстанымдарын анықтауға мүмкіндік берсе, ғылыми еңбектер олардың мазмұнын талдауға негіз болады.

Қазақстандағы ұлттық код туралы түсініктің саяси дискурста айқын көрінуінің бірі – 2017 жылы жарияланған «Болашаққа бағдар: рухани жаңғыру» бағдарламалық мақаласы [4]. Онда ұлттық бірегейлікті сақтау мен жаңғырту өзара байланысты міндеттер ретінде қарастырылып, ұлттық кодты сақтау мәселесі қоғамның қазіргі заман талаптарына бейімделуімен ұштастырылды.

Осы тұрғыдан ұлттық код тек өткеннен қалған мәдени белгілердің жиынтығы емес, ұлттық ерекшелікті сақтай отырып, қоғамдық өзгерістерге бейімделу идеясын негіздейтін ұғым ретінде ұсынылды.

Кейінгі кезеңде ұлттық құндылықтарды түсіндіруде тарихи мұра мен қазіргі заман талаптарын ұштастыру мәселесі де алға шықты.

2018 жылғы «Ұлы даланың жеті қыры» мақаласында тарихи мұраны зерделеу, ұлттық тарихты кеңінен таныту және мәдени сабақтастықты сақтау бағыттары ұсынылды [5].

Бұл бастама тарихи өткенді тек еске алу нысаны ретінде емес, қазіргі ұлттық сана мен тарихи өзіндік түсінікті қалыптастыру ресурсы ретінде қарастыруға мүмкіндік береді.

Аталған құжаттардағы ортақ ерекшелік – ұлттық бірегейлікті тарихи сабақтастық пен жаңғырудың өзара байланысы арқылы түсіндіру.

Дегенмен мұндай ұстанымда маңызды мәселе бар: тарихи мұраны сақтау оның мазмұнын өзгеріссіз қабылдауды білдірмейді.

Қоғамдық-саяси дискурста тарихи оқиғалар мен мәдени рәміздер белгілі бір құндылықтарды негіздеу үшін іріктеліп, қазіргі қажеттіліктерге сәйкес түсіндіріледі. Сондықтан саяси интерпретацияны зерттеу кезінде қандай тарихи мазмұнға басымдық берілетінімен қатар, оның қандай ұлттық құндылықтармен байланыстырылатынын да анықтау қажет.

Бұл бағыттың қазіргі мемлекеттік саясаттағы көрінісін Қазақстан Республикасы Президентінің 2025 жылғы 5 қарашадағы № 1081 Жарлығымен бекітілген «Қазақстан Республикасы ішкі саясатының негізгі қағидаттары, құндылықтары мен бағыттары» құжатынан байқауға болады.

Құжат 2026 жылғы 1 шілдедегі № 1337 Жарлықпен жаңа редакцияда жазылған. Онда жалпыұлттық құндылықтар ретінде тәуелсіздік пен патриотизм, бірлік пен ынтымақ, әділеттілік пен жауапкершілік, заң мен тәртіп, еңбекқорлық пен кәсібилік, жасампаздық пен жаңашылдық белгіленген [6].

Бұл құндылықтардың жиынтығы ұлттық бірегейліктің тек этномәдени мазмұнын емес, азаматтық және қоғамдық-саяси өлшемдерін де қамтитынын көрсетеді.

Мәселен, тарихи мұра мен мәдени дәстүр ұлттық сабақтастықты түсіндіруге мүмкіндік берсе, заңға құрмет, жауапкершілік, кәсібилік және жасампаздық қазіргі қоғамның даму бағдарларын сипаттайды.

Осылайша ұлттық бірегейлік туралы мемлекеттік дискурста тарихи-мәдени негіздер мен қазіргі қоғамдық міндеттерді байланыстыруға ұмтылыс байқалады.

Сонымен бірге ресми құжаттарда құндылықтардың бекітілуі олардың қоғам мүшелері тарапынан бірдей қабылданатынын өздігінен дәлелдемейді.

Мемлекеттік деңгейде ұсынылған құндылықтар мен азаматтардың күнделікті түсініктері арасында сәйкестік те, айырмашылық та болуы мүмкін. Сондықтан ұлттық бірегейлікті талдағанда ресми дискурстың мазмұнын қоғамның нақты көзқарастарымен теңестіруге болмайды.

Ұлттық кодтың саяси интерпретациясына қатысты тағы бір мәселе – оның мазмұнын айқындау.

Егер ұлттық код тек дәстүрлер мен мәдени рәміздер арқылы түсіндірілсе, оның қазіргі қоғамдық-саяси өзгерістермен байланысы толық ашылмайды.

Ал оны ұлттық бірегейліктің барлық қырын түсіндіретін әмбебап ұғым ретінде қолдану мәдени және әлеуметтік айырмашылықтарды ескермеуге әкелуі мүмкін. Осы себепті ұлттық кодты тарихи жады, мәдени тәжірибе, тіл, дәстүр және рәміздер арқылы берілетін ұлттық өзіндік ерекшеліктің мағыналық жүйесі ретінде қарастыру орынды.

Қорыта айтқанда, қазіргі Қазақстандағы ұлттық құндылықтар мен ұлттық кодтың саяси интерпретациясы екі өзара байланысты бағыттан көрінеді: тарихи-мәдени сабақтастықты сақтау және ұлттық бірегейлікті қазіргі қоғамдық-саяси бағдарлармен ұштастыру.

«Рухани жаңғыру» мен «Ұлы даланың жеті қыры» бастамалары тарихи мұраны жаңаша пайымдауға басымдық берсе, ішкі саясаттың қазіргі қағидаттары жалпыұлттық құндылықтарды жүйелеуге бағытталған. Олардың арасындағы сабақтастық ұлттық бірегейліктің тарихи негіздері мен қазіргі мазмұнын қатар қарастыру қажеттігін көрсетеді. Бұл ретте тарихи жад ұлттық құндылықтардың мағынасын түсіндіретін маңызды өлшем болып табылады.

Қорытынды

Талдау нәтижелері қазіргі Қазақстандағы ұлттық бірегейлікті тарихи жад, ұлттық құндылықтар және ұлттық кодтың өзара байланысы арқылы қарастыру қажеттігін көрсетті.

Ұлттық бірегейлік тарихи-мәдени мұраның сақталуымен ғана емес, оның қазіргі қоғамдық-саяси жағдайда қалай түсіндірілетінімен де айқындалады. Осы тұрғыдан тарихи жад өткен туралы түсініктерді қалыптастырып, ұлттық құндылықтардың мағынасын ашуға және оларды қазіргі қоғамның даму бағдарларымен байланыстыруға мүмкіндік береді.

Қазақстанның мемлекеттік дискурсында ұлттық кодты сақтау мен қоғамдық жаңғыруды ұштастыру, тарихи мұраны зерделеу және жалпыұлттық құндылықтарды жүйелеу бағыттары көрініс тапқан.

Келтірілген бағдарламалық құжаттардың бастамалары тарихи-мәдени сабақтастықты өзектендірсе, ішкі саясаттың қазіргі қағидаттары ұлттық бірегейліктің азаматтық және қоғамдық-саяси өлшемдерін айқындайды. Бұл бағыттар ұлттық құндылықтардың тарихи негіздері мен қазіргі заманға қатысты мағыналары өзара сабақтас екенін көрсетеді.

Сонымен бірге мемлекеттік деңгейде ұсынылған құндылықтарды қоғамның барлық мүшесі бірдей қабылдайды деп тұжырымдауға болмайды.

Олардың қоғамдық мағынасы тарихи тәжірибеге, әлеуметтік ортаға және саяси дискурста берілу ерекшеліктеріне байланысты қалыптасады.

Сондықтан ұлттық кодты өзгермейтін мәдени белгілер жиынтығы ретінде емес, тарихи жад пен мәдени тәжірибе арқылы ұдайы түсіндіріліп отыратын мағыналық жүйе ретінде қарастыру орынды.

Осылайша, ұлттық құндылықтар мен ұлттық кодтың саяси интерпретациясын талдау қазіргі Қазақстандағы ұлттық бірегейліктің қалыптасу тетіктерін тереңірек түсінуге мүмкіндік береді.

Бұл тұжырым тарихи жадтың фреймдерін саясаттанулық тұрғыдан талдауға негіз болады: тарихи оқиғалар мен тұлғалардың қалай іріктелетіні, қандай мағыналармен байланыстырылатыны және олардың ұлттық бірегейлік туралы қоғамдық түсініктерге қалай ықпал ететіні – әрі қарай зерттеуді қажет ететін мәселелер.

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ТОЛЕРАНТНОСТЬ КАК ОСНОВА МЕЖКУЛЬТУРНОГО ДИАЛОГА В УСЛОВИЯХ ГЛОБАЛИЗАЦИИ

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В современных условиях стирания границ и миграционных кризисов необходимо перейти к «активной толерантности» восприятию культурных различий не как угрозы, а как основы для диалога и развития.

Глобализация существенно изменила характер взаимодействия между обществами и культурами. Интенсификация международной миграции, развитие цифровых коммуникаций, расширение образовательной мобильности, рост международного туризма и транснациональных экономических связей привели к тому, что представители различных культур все чаще оказываются в едином социальном и информационном пространстве [1, 49].

Современный человек одновременно может оставаться носителем национальной, этнической, религиозной и языковой идентичности и при этом активно участвовать в глобальных коммуникациях. В результате культура перестает существовать исключительно в пределах национального пространства. Она становится частью сложной системы постоянного обмена символами, ценностями, нормами и моделями поведения.

Однако глобализация имеет противоречивый характер. С одной стороны, она создает условия для расширения культурных контактов и формирования новых форм солидарности. С другой стороны, увеличение числа контактов между различными группами не гарантирует взаимопонимания. Напротив, столкновение различных ценностных систем может усиливать культурную дистанцию, социальную напряженность и конфликт идентичностей.

Особенно заметно это проявляется в условиях миграционных процессов и формирования поликультурных обществ. Различия в языке, религии, традициях, исторической памяти и социальных нормах могут становиться объектом политической мобилизации и общественных конфликтов. Дополнительным фактором выступает цифровая среда, в которой культурные стереотипы и конфликтные интерпретации способны распространяться значительно быстрее, чем в традиционных каналах коммуникации.

В этих условиях толерантность приобретает особое значение. При этом ее понимание исключительно как «терпимости к другому» представляется недостаточным. Толерантность должна рассматриваться как способность признавать право другого человека или социальной группы на отличие, сохраняя при этом возможность конструктивного взаимодействия.

Именно поэтому проблема толерантности выходит за рамки индивидуальной этики и становится важным общественным и политическим ресурсом [2, 124].

В современном обществе глобализация затронула абсолютно все сферы жизни. Стираются физические границы, а также контакты между представителями разных народов становятся повседневной нормой. Однако несмотря на прогнозы исследователей XX века, глобализация не смогла создать единый культурный стандарт. Напротив, люди стали сильнее

ощущать необходимость отстаивать свою национальную, этническую и религиозную идентичность.

Сталкиваясь с другими традициями, люди все чаще реагируют настороженно, что приводит к росту межкультурного напряжения. На фоне происходящего терпимость перестает быть просто абстрактной ценностью. Она становится базовой необходимостью, социальной стабильности и мирного сосуществования государств в многополярном мире

Одним из главных проблем является то, что старое понимание толерантности больше не работает. Традиционно толерантность воспринималась, как «пассивная терпимость», то есть готовность мириться с существованием чужих взглядов, пока они не мешают привычному укладу жизни. Однако провал концепции культурного многообразия в ряде стран Европы показал: формальное признание чужих прав без реального общения приводит к гражданской разобщенности и росту взаимного недоверия. Появляется вопрос: как превратить толерантность из формальности ненападения в реально действующий инструмент межкультурного диалога? Для этого требуется отказ от восприятия толерантности как навязанного компромисса в пользу культурного обмена [3, 76].

Для решения этой проблемы необходимо понять, как меняется понятие толерантности, какие препятствия создает современная цифровая среда и как наладить конструктивный диалог.

В Декларации принципов толерантности ЮНЕСКО (1995 г.), толерантность - это понятие, которое означает «уважение, принятие и правильное понимание богатого многообразия культур». На сегодняшний момент толерантность- это осознанная готовность понять другого человека. Настоящий межкультурный диалог невозможен с позиции силы, он требует признания того, что все участники диалога изначально равны [4, 95].

В XXI веке межкультурный диалог все чаще становится частью внешнеполитических стратегий государств.

Культурная дипломатия использует культуру, искусство, образование, спорт, язык и историческое наследие для формирования устойчивых контактов между обществами.

В концепции «мягкой силы» Дж. Ная культура рассматривается как один из ресурсов привлекательности государства [5, 101]. При этом культурная дипломатия эффективна тогда, когда она создает пространство для взаимного обмена, а не превращается исключительно в одностороннюю презентацию национального образа. В этом контексте особый интерес представляют международные культурные фестивали, выставки, спортивные соревнования, молодежные обмены и проекты культурного наследия.

Подобные мероприятия выполняют двойную функцию.

С одной стороны, они позволяют государству представить собственную культуру международной аудитории. С другой стороны, они создают возможность для непосредственного контакта между представителями различных культур.

Таким образом, культурная дипломатия может рассматриваться как институциализированная форма межкультурного диалога.

Для Казахстана проблематика толерантности имеет особое значение в силу исторического и современного культурного многообразия общества. Казахстан представляет собой поликультурное пространство, в котором взаимодействуют различные этнические, языковые и религиозные сообщества [6, 44].

Важным институтом в данной сфере была Ассамблея народа Казахстана, созданная в 1995 году. Деятельность Ассамблеи была связана с поддержкой межэтнического взаимодействия, сохранением культурного многообразия и развитием общественного диалога. В настоящее время в стране создан высший консультативный орган - Народный совет Казахстана (Қазақстан Халық Кеңесі).

Современная глобализация происходит в интернете, что создает новые, скрытые вызовы:

- «Информационное эхо»: алгоритмы и рекомендации социальных сетей показывают людям в основном ту информацию, с которой они уже согласны. Это лишает общество возможности сталкиваться с другим мнением и мирно с ним спорить.
- Групповая агрессия: глобальная сеть противоречивым образом облегчила разделение на «своих» и «чужих». В интернете легче объединиться против другой культуры, что делает обсуждения более радикальными.

Таблица 1- Трансформация толерантности в условиях глобализации

Традиционное понимание	Современное понимание
Терпимость	Активное принятие различий
Сосуществование	Взаимодействие
Сохранение дистанции	Коммуникация
Знание о другой культуре	Опыт взаимодействия
Защита собственной идентичности	Сочетание собственной и множественной идентичности
Локальный социальный принцип	Глобальная социальная компетентность
Преимущественно офлайн-коммуникация	Офлайн + цифровая коммуникация

Таблица составлена автором

Для решения проблемы требуется переход к концепции активной (созидательной) толерантности. Эта концепция строится на трех принципах:

1. Отказ от культурного превосходства: то есть признать то, что ни одна культура не владеет абсолютной действительностью и не должна навязывать свои стандарты другим.
2. Эмпатия: попытаться взглянуть на мир глазами представителя другой культуры, отказавшись от стереотипов.
3. Сотрудничество: синтез культурных практик для преодоления глобальных вызовов (экологических, экономических, технологических).

Таблица 2 - Основные инструменты формирования толерантности

Инструмент	Механизм	Результат
Культурная дипломатия	Культурный обмен	Международное доверие
Молодёжные проекты	Совместная деятельность	Формирование горизонтальных связей
СМИ	Репрезентация культур	Изменение образа «другого»
Социальные сети	Цифровой диалог	Расширение межкультурных контактов
Международные фестивали	Непосредственный контакт	Позитивный опыт взаимодействия

Таблица составлена автором

Чтобы активная толерантность стала обыденностью, ее необходимо внедрять на нескольких уровнях:

- В образовании: обучение навыкам межкультурного общения и эмоциональному интеллекту со школы.
- В медиа-пространстве: искоренение токсичности в журналистике, разрушение стереотипов и создание нейтральных платформ для обсуждения.
- В государственной политике: переход к политике гражданского участия, которая поощряет взаимодействие представителей разных культур в общественной жизни, не допуская изолированности между культурами.

Таким образом, в результате анализа мы пришли к следующим выводам:

1. Смена парадигмы: «пассивная терпимость» уже исчерпала себя. Сегодня необходима активная толерантность, базирующаяся на взаимном уважении и признании различий для развития общества.
2. Влияние интернета: цифровая среда тормозит диалог из-за информационной изоляции пользователей. Обществу необходимо развивать цифровую этику в сети и критическое мышление.
3. Сохранение индивидуальности: успешный межкультурный диалог не означает создания единой «глобальной культуры». Цель заключается в том, чтобы сохранить уникальность каждой нации, сформировав при этом общие правила мирного соседства.
4. Практическая значимость: данные принципы активной толерантности могут использоваться на практике при создании государственных программ во время социальной адаптации мигрантов, в управлении многонациональными коллективами компаний, а также при создании современных образовательных критериев.

На основании анализа можно предложить следующую Модель толерантного межкультурного взаимодействия»:

Культурное различие
Признание различия
Уважение
Межкультурная коммуникация
Взаимное понимание
Совместная деятельность
Социальное доверие
Межкультурная интеграция

Толерантность в эпоху глобализации является главным инструментом, с помощью которого разные народы могут найти общий язык друг с другом во взаимозависимом мире.

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Medical Sciences

Diabetic Retinopathy in Kazakhstan: The Role of Optical Coherence Tomography in Early Detection and Outpatient Care

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Background: Diabetic retinopathy (DR) is a major microvascular complication of diabetes mellitus and an important cause of preventable visual impairment. A study analyzing national statistical data in Kazakhstan reported a 27% increase in the registered prevalence of diabetic retinopathy among adults between 2015 and 2018. These findings highlight the importance of improving the early detection and management of diabetic retinal changes. Optical coherence tomography (OCT) is a non-invasive imaging technique that provides detailed cross-sectional images of retinal structures and plays an important role in the assessment of diabetic macular edema.

Objective: To explore the role of OCT in the early detection of diabetic retinal changes and discuss challenges associated with its accessibility and integration into outpatient healthcare in Kazakhstan.

Methods: A narrative review approach was used to examine the clinical role of OCT in the diagnosis of diabetic retinal changes, its advantages in ophthalmic practice, and organizational challenges related to its availability in outpatient healthcare settings. Particular attention was given to equipment accessibility and referral pathways for patients requiring specialized ophthalmic examination.

Discussion: Optical coherence tomography (OCT) complements standard ophthalmological examinations by providing detailed information about retinal structure and helping to detect changes such as macular edema and intraretinal fluid. Its use may support the assessment of diabetic macular edema and inform clinical decision-making.

However, the implementation of OCT in outpatient care may be limited by the high cost of equipment and disparities in access to diagnostic technologies. Not all outpatient clinics in Kazakhstan are equipped with stationary OCT devices, meaning that some patients may require referral to specialized ophthalmological centers.

This makes coordination between primary healthcare facilities and specialized services particularly important. Establishing clear referral pathways may facilitate timely access to retinal imaging and contribute to the early detection of diabetic retinal complications.

Effective communication between general practitioners, ophthalmologists, and patients is an important component of early detection and management of diabetic retinal complications. General practitioners play a key role in educating patients with diabetes about the importance of

regular eye examinations, even in the absence of visual symptoms. Clear communication, patient-centered counseling, and effective collaboration between healthcare professionals may improve patient awareness, adherence to recommended examinations, and timely referral for OCT when clinically indicated.

Conclusion: OCT has considerable potential to improve the assessment of diabetic retinal changes in outpatient ophthalmic care. Effective coordination between general practitioners (GPs) and ophthalmologists is particularly important, as they serve as the first point of contact for patients and play a key role in the early detection of diabetic retinal complications. Strengthening collaboration between these healthcare professionals, improving referral pathways, and addressing equipment accessibility may support more timely diagnosis and better patient care. Further research in Kazakhstan is needed to evaluate OCT accessibility, referral practices, and the potential impact of OCT-based diagnostic approaches on the quality of outpatient care. In addition, strengthening communication skills among general practitioners and ophthalmologists may improve interdisciplinary collaboration, patient education, and adherence to recommended eye examinations. Integrating effective communication strategies into outpatient care may contribute to earlier detection of diabetic retinal complications and improved continuity of care.

Keywords: diabetic retinopathy; optical coherence tomography; diabetes mellitus; outpatient care; primary healthcare; Kazakhstan.

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THE IMPACT OF FATIGUE ON THE QUALITY OF LIFE OF PATIENTS WITH RHEUMATOID ARTHRITIS: A REVIEW OF CURRENT RESEARCH

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Relevance. Rheumatoid arthritis (RA) is a systemic autoimmune rheumatic disease of unknown etiology, characterized by chronic, progressive, erosive arthritis and involvement of various organs and systems.[1] The condition can lead to pain, joint stiffness, limited physical activity, and a reduced quality of life.[2] One of the most significant symptoms for patients is chronic fatigue, which may persist even when the inflammatory process is better controlled. This fatigue can restrict daily activities, social interactions, and work capacity. Therefore, assessing fatigue - alongside clinical disease activity - is essential for the comprehensive management of patients with RA.[3]

Objective. To summarize the findings of recent randomized controlled trials concerning fatigue and quality of life in patients with rheumatoid arthritis, and to explore potential ways to improve these outcomes.

Materials and Methods. A review of five scientific publications was conducted. The studies examined the effects of physical exercise, aquatic interventions, anti-inflammatory dietary approaches, and cognitive-behavioral therapy, as well as the use of Korean red ginseng for rheumatic diseases. The study designs, outcome measures, and key findings were analyzed. Given that the assessment methods and metrics varied across the studies, a direct comparison of their results was not performed.

Results. A randomized study by Bilberg et al. (2025) involved 87 patients with rheumatoid arthritis. The study investigated the impact of a 12-week program consisting of high-intensity interval training and strength exercises on fatigue and quality of life. Compared to the control group, participants in the program showed improvements in their overall physical condition, as well as increased physical activity and motivation. These differences persisted for up to 12 months of follow-up. Furthermore, the authors noted an improvement in the patients' overall quality-of-life scores, which highlights the benefits of individually tailored physical activity.[4]

In a study by Aktaş et al. (2025), 54 patients were divided into three groups: the first group received warm saline baths for their hands and feet, the second group received warm water baths, and the third group served as a control. After a six-week study period, the groups that underwent water-based treatments showed a reduction in overall pain, decreased fatigue, and an improvement in quality of life. Significant differences between the groups were also observed regarding fatigue and quality-of-life scores related to it.[5]

The ADIRA randomized crossover study, conducted by Turesson Wadell et al. (2021), evaluated the impact of an anti-inflammatory diet on 50 patients with rheumatoid arthritis.

Overall, no significant differences were found between the experimental and control groups regarding lifestyle factors, fatigue, or pain. However, specific analyses using the SF-36 scale indicated improvements in physical activity levels within the experimental group. Consequently, the findings suggest a need for further investigation through larger-scale studies to obtain reliable data and ensure accurate interpretation.[6]

Cho et al. (2024) examined the effects of Korean red ginseng on 120 patients with rheumatic diseases, including 43 patients with rheumatoid arthritis. The study followed a randomized, double-blind, placebo-controlled design. After 12 weeks, approximately 38.3% of participants in the group receiving ginseng showed improvement in fatigue-related scores on the FACIT-Fatigue scale, compared to 26.7% in the placebo group. However, no statistically significant differences were found between the two groups. Thus, the superiority of ginseng over a placebo in reducing fatigue has not been conclusively established.[7]

The RAFT study, conducted by Hewlett et al. (2019), examined the impact of group-based cognitive-behavioral programs developed by rheumatology specialists. Compared to a control group, participation in such a program helped reduce fatigue in patients with rheumatoid arthritis, with these positive changes persisting for up to two years. The study results indicate that, in addition to pharmacological treatment, psychological support and training in self-regulation strategies play an important role in managing the disease.[8]

Discussion. The studies reviewed indicate that fatigue in rheumatoid arthritis is a multifactorial issue requiring a comprehensive approach. Physical exercise and cognitive-behavioral programs have been shown to significantly reduce fatigue and improve quality of life. Conversely, research has not demonstrated clear efficacy for anti-inflammatory diets or specific dietary supplements. Variations in assessment methods and patient characteristics make it difficult to compare findings across studies. Furthermore, as not all the reviewed studies assessed quality of life as a primary outcome, the data should be interpreted with consideration for the specific objectives of each study.

Conclusion. The findings suggest that fatigue in rheumatoid arthritis is a distinct clinical issue. It leads to a decline in patients' physical and emotional activity and restricts their social engagement. The results of the reviewed studies support the inclusion of fatigue assessment as part of the comprehensive care for patients with rheumatoid arthritis. Further research, utilizing standardized fatigue assessment methods and long-term follow-up, is required to determine the most effective strategies for improving quality of life.

Keywords: rheumatoid arthritis, fatigue, quality of life, physical activity, non-pharmacological treatment.

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MODERN APPROACHES TO DEVELOPING CLINICAL AND COMMUNICATION COMPETENCIES IN HEALTHCARE PROFESSIONALS: THE ROLE OF SIMULATION-BASED AND COMPETENCY-BASED EDUCATION

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Abstract

The quality and safety of healthcare are closely associated with the professional competence of physicians and other health professionals. Contemporary medical practice requires more than the acquisition of theoretical knowledge: graduates must be able to perform clinical procedures safely, reason through patient problems, communicate with patients and relatives, work in multidisciplinary teams, use evidence appropriately, and adapt to digital healthcare environments. This article examines modern educational approaches that can support the development of clinical and communication competencies in healthcare professionals. A narrative analysis and synthesis of scientific publications and international guidance in health professions education were undertaken. Particular attention was given to competency-based medical education, simulation-based training, standardized patients, deliberate practice, structured feedback, interprofessional education, and virtual learning. The literature indicates that competency-based simulation can improve procedural skill acquisition and that simulated-participant teaching can strengthen patient-centred communication. Recent studies also demonstrate the feasibility of virtual simulation-based mastery learning for communication competencies. At the same time, educational technologies are most effective when they are linked to clearly defined outcomes, repeated practice, appropriate assessment, and high-quality feedback. The article argues that communication should be treated as a clinical competency rather than as an optional interpersonal skill. Medical universities should therefore integrate clinical, communication, teamwork, and digital competencies throughout the curriculum. Such an integrated model can strengthen the transition from academic learning to professional practice and contribute to patient safety and quality of care.

Keywords

medical education; health professions education; clinical competence; communication skills; competency-based medical education; simulation-based education; standardized patients; patient safety; interprofessional education; digital health.

Introduction

Healthcare systems are experiencing continuous changes associated with advances in medical science, the expansion of digital technologies, demographic shifts, new models of care, and increasing expectations of patients. These changes affect not only clinical practice but also the requirements placed on medical education. A contemporary healthcare professional is expected to combine sound biomedical and clinical knowledge with practical skills, clinical reasoning, effective communication, teamwork, ethical judgement, and the ability to learn throughout professional life.

The central task of modern medical education is therefore not simply to increase the amount of information delivered to students. It is to ensure that learners can translate knowledge into safe professional performance. A student may successfully reproduce a clinical algorithm during a written examination and still experience difficulty when interviewing a patient, explaining a diagnosis, obtaining informed consent, recognizing deterioration, or coordinating care with colleagues. Educational programmes must consequently provide opportunities to demonstrate competence in situations that resemble real professional practice.

Competency-based medical education (CBME) provides a framework for addressing this problem. Its focus is on clearly defined outcomes and on the progressive demonstration of professional abilities. The World Health Organization's Global Competency and Outcomes Framework for Universal Health Coverage includes domains such as people-centredness, decision-making, communication, collaboration, evidence-informed practice, and professional behaviour [1]. These domains demonstrate that modern healthcare competence is broader than clinical knowledge alone.

Communication is particularly important because it is embedded in almost every clinical task. History taking, informed consent, patient education, shared decision-making, disclosure of adverse events, and communication within a healthcare team all depend on communication competence. The Ottawa 2024 consensus statement emphasizes that communication assessment should be considered within the broader system of competency-based health professions education and should address communication with patients, peers, interprofessional colleagues, and across cultural and digital contexts [2].

Against this background, medical universities need educational approaches that connect theoretical learning with clinical practice. Simulation, standardized patients, deliberate practice, structured feedback, case-based learning, and interprofessional education offer opportunities to develop and assess competencies before students assume full responsibility for patient care.

Aim of the Study

The aim of this article is to analyse contemporary pedagogical approaches to the development of clinical and communication competencies in healthcare professionals and to determine how simulation-based and competency-based education can strengthen the transition from academic training to safe professional practice.

Materials and Methods

A narrative literature review was conducted using analysis, comparison, synthesis, and systematization of scientific publications and international policy documents concerning medical education and health professions education. The search and selection of literature focused on competency-based medical education, simulation-based education, standardized patients, communication skills, interprofessional education, and digital or virtual learning.

Priority was given to peer-reviewed publications and authoritative international sources that were directly relevant to the development or assessment of clinical and communication competencies. Recent studies published in 2024–2026 were considered particularly important for reflecting current educational practice. The identified evidence was grouped into four analytical

areas: clinical competency development; communication skills education and assessment; simulation and deliberate practice; and interprofessional and digital education.

The study is theoretical in nature and does not involve human participants, collection of personal data, or intervention in an educational institution. The purpose of the review is to synthesize existing evidence and formulate practical implications for medical education.

Competency-Based Medical Education and Clinical Performance

Competency-based medical education changes the starting point of curriculum design. Instead of asking how much content can be delivered, educators first define what a graduate should be able to demonstrate in professional practice. Learning activities and assessment are then aligned with these outcomes.

Clinical competence is multidimensional. It includes medical knowledge, history taking, physical examination, clinical reasoning, procedural performance, diagnostic and therapeutic decision-making, patient management, communication, professionalism, teamwork, and the ability to use evidence appropriately. These components interact during real clinical encounters and should not be assessed exclusively as separate theoretical units.

One of the strengths of competency-based education is the alignment between learning outcomes, teaching activities, and assessment. If a programme states that graduates must be able to perform a clinical procedure safely, the curriculum should provide supervised practice, an opportunity for repetition, explicit performance criteria, and an assessment method capable of demonstrating the required standard.

The concept of entrustable professional activities (EPAs) can further connect abstract competencies with observable clinical tasks. A recent systematic review of EPA-integrated simulation included 22 studies involving 3,144 healthcare trainees and reported that EPA-based simulation can support confidence and produce moderately to highly reliable assessment scores, although resource requirements and rater calibration remain important challenges [3].

This approach is particularly relevant to clinical education because professional competence is ultimately demonstrated through tasks. The learner does not merely possess 'communication competence' in the abstract; rather, the learner must be able to conduct a consultation, explain a procedure, obtain informed consent, communicate a treatment plan, or participate effectively in a clinical handover.

Simulation-Based Education for Clinical Skills

Simulation-based education has become an established component of medical and health professions education. It creates a controlled environment in which learners can practise procedures, clinical decision-making, communication, and teamwork without exposing patients to unnecessary risk.

Simulation may take different forms. Low-technology task trainers are appropriate for repetitive practice of specific procedures. High-fidelity mannequins can reproduce physiological changes and allow learners to manage complex clinical scenarios. Standardized patients are especially useful for communication and examination of interpersonal competencies. Virtual patients and computer-based simulations can provide additional opportunities for clinical reasoning and decision-making.

The educational value of simulation is not determined simply by the sophistication of the equipment. A well-designed simulation requires defined learning objectives, an appropriate scenario, preparation of learners, observation or assessment, and structured debriefing. The instructor must connect the learner's performance with the competency being developed.

A 2026 systematic review and meta-analysis of competency-based simulation training for procedural skills found that competency-based simulation was more effective than non-competency-based simulation for skill outcomes, with a large effect reported for skill acquisition [4]. At the same time, the authors identified gaps in evidence concerning transfer of learning to

clinical behaviour and patient outcomes. This distinction is important: improvement in a simulated procedure does not automatically prove improvement in real-world clinical care.

Therefore, simulation should be integrated into a broader educational pathway. Students should progress from explanation and demonstration to supervised practice, simulation, feedback, repeated practice, and assessment. When appropriate, performance can subsequently be evaluated in the clinical workplace.

Communication as a Core Clinical Competency

Communication is an integral part of clinical care. The clinical encounter begins with communication and depends on it throughout the process. Accurate history taking requires active listening and appropriate questioning. Physical examination and procedures require explanation and consent. Treatment planning requires the ability to communicate risks, benefits, alternatives, and uncertainties. Follow-up requires clear instructions and confirmation that the patient understands them.

Poor communication may affect adherence, patient satisfaction, shared decision-making, and the quality of information available for clinical reasoning. For this reason, communication skills should be treated as a clinical competency with explicit learning outcomes and assessment criteria.

The Ottawa 2024 consensus statement provides a contemporary framework for thinking about communication assessment in health professions education [2]. It supports the integration of communication assessment into broader competency-based systems and recognizes the relevance of patient, peer, interprofessional, cross-cultural, and digital communication.

Communication education is most useful when it is longitudinal. Early students can learn basic interviewing and active listening. More advanced learners can practise patient education, shared decision-making, informed consent, disclosure of difficult information, conflict management, and communication during emergencies. The level of complexity should increase as clinical responsibility increases.

The use of standardized patients is particularly valuable. Standardized patients can reproduce realistic consultations and provide feedback from the patient's perspective. A 2025 systematic review identified 21 studies involving 2,500 participants and found a medium pooled effect favouring simulated-participant teaching over traditional formats for communication outcomes, although substantial heterogeneity existed between studies [5].

This evidence supports the inclusion of simulated patients in communication curricula while also demonstrating the need for careful instructional design. A standardized-patient encounter should have clear objectives, an appropriate scenario, a structured assessment tool, and a debriefing process that helps the learner translate feedback into specific behavioural changes.

Simulation, Deliberate Practice, and Mastery Learning

The combination of simulation and deliberate practice is particularly relevant to competency development. Deliberate practice involves focused repetition of a defined task, attention to errors, immediate feedback, and further practice aimed at correcting weaknesses. It differs from simply repeating an activity without a clear performance standard.

Mastery learning extends this principle by establishing a predefined minimum passing standard. Learners who do not initially reach the required level receive additional instruction and practice rather than simply moving forward because a fixed amount of training time has elapsed.

A multicentre study of virtual simulation-based mastery learning for serious-illness communication among emergency medicine residents illustrates the potential of this model. Participants completed an assessment with standardized patients, received instruction and role-play, underwent reassessment, and completed additional deliberate practice when necessary.

Communication performance improved significantly, and all participants ultimately reached the predefined minimum passing standard [6].

The example is important for medical education because it demonstrates a shift from time-based learning toward achievement-based progression. The central question becomes whether the learner has demonstrated the required competence rather than whether the learner has merely completed the scheduled teaching session.

Assessment of Clinical and Communication Competencies

Assessment determines whether educational activities have produced the intended competencies. Written examinations remain important for assessing knowledge, but they cannot adequately capture all dimensions of clinical performance. Practical and communication competencies require direct observation.

Objective Structured Clinical Examinations (OSCEs), standardized patients, simulation-based assessments, workplace-based assessments, checklists, global rating scales, and programmatic assessment can provide complementary information. No single instrument is sufficient for all competencies.

The quality of assessment depends on the validity and reliability of the tools used. A 2026 systematic review of communication-skill assessment tools in health professions education highlighted the increasing use of simulation-based learning for communication and the importance of appropriate assessment instruments [7].

Assessment should also be formative as well as summative. Formative assessment allows learners to identify gaps before high-stakes examinations or independent practice. Feedback should be specific and linked to observable behaviour. For example, instead of stating that a learner 'needs better communication', the educator can identify that the learner interrupted the patient during the opening of the consultation, used unexplained medical terminology, or failed to check the patient's understanding.

Such feedback transforms assessment from a mechanism of judgement into a mechanism of learning.

Interprofessional Education and Team Communication

Healthcare delivery is fundamentally collaborative. A patient's care may involve physicians, nurses, pharmacists, laboratory professionals, psychologists, public health specialists, and other members of the healthcare team. Effective teamwork requires a shared understanding of professional roles, clear information exchange, and appropriate escalation of concerns.

Interprofessional education allows students to develop these capabilities before entering independent practice. Joint simulations can reproduce situations such as emergency response, patient transfer, multidisciplinary case discussion, discharge planning, or communication during a clinical handover.

Interprofessional education is particularly valuable when communication itself is the learning objective. Students can practise closed-loop communication, structured handover, clarification of responsibilities, and respectful challenge of unsafe decisions. These behaviours have relevance to patient safety because clinical errors can occur when information is incomplete, misunderstood, or not communicated to the appropriate professional.

A 2026 study of a simulation-based programme for inter- and intraprofessional communication used authentic activities such as referral letters, professional consultations, and multidisciplinary meetings. Participants reported improved communication skills and greater understanding of interprofessional collaboration [8]. Although self-reported outcomes should be interpreted cautiously, the study supports the feasibility of embedding authentic communication tasks into medical education.

Digital and Virtual Learning in Medical Education

Digital technologies have expanded the educational environment available to medical students and practising professionals. Learning management systems, electronic resources, virtual patients, online assessment, digital clinical cases, and remote simulation can complement classroom and clinical teaching.

Virtual patient simulation is particularly relevant to the development of clinical communication and decision-making. A 2025 pilot study investigated virtual patient simulation for medical students and focused specifically on clinical communication and decision-making skills [9]. Such approaches can provide additional opportunities for practice, especially when face-to-face simulation resources are limited.

However, digital learning should not be understood as a replacement for clinical contact. Many competencies require direct interaction with patients and colleagues, physical examination, practical procedures, teamwork, and observation by an experienced educator. The strongest model is therefore usually blended learning, in which digital resources prepare or reinforce face-to-face activities.

Digital transformation also requires healthcare professionals to understand the responsible use of health information. Students should learn how to critically evaluate online information, protect patient confidentiality, use electronic health records appropriately, understand the limitations of clinical decision-support systems, and communicate professionally through digital channels.

The World Health Organization has identified digital health competency frameworks as an important area for health workforce development. Digital competence should consequently be incorporated into professional education rather than treated as a separate technical subject.

Role of the Medical Educator

The transformation of medical education changes the responsibilities of the educator. The teacher remains a source of clinical expertise, but also becomes a designer of learning experiences, facilitator of reflection, observer of performance, provider of feedback, and assessor of competence.

This expanded role requires pedagogical preparation. Medical expertise alone does not automatically provide the skills needed to design a simulation scenario, formulate measurable learning outcomes, conduct a debriefing, or evaluate communication performance. Faculty development is therefore an important condition for successful educational innovation.

Simulation educators require particular methodological competencies. A qualitative study of simulation instructor competencies identified domains related to simulation knowledge, educational design and delivery, human factors, ethics, and assessment, with advanced roles also involving organization, research, quality improvement, and crisis management [10].

For medical universities, this means that implementation of new educational technologies should be accompanied by systematic professional development of teachers. Faculty should be supported in learning how to design competency-based curricula, use assessment tools, conduct structured feedback, and integrate simulation into existing courses.

Discussion

The evidence reviewed suggests that clinical and communication competencies develop most effectively when teaching methods are deliberately connected to professional tasks. The purpose of simulation is not simply to create a realistic environment; it is to provide a structured opportunity to practise a defined competency. Similarly, communication training is not merely a set of theoretical recommendations but a skill-development process requiring observation, repetition, feedback, and reassessment.

The strongest educational model is therefore integrative. A clinical scenario can simultaneously require the student to obtain a history, identify a clinical problem, explain the

situation to the patient, obtain consent, formulate a management plan, and communicate with another healthcare professional. Such scenarios reflect the integrated nature of real clinical practice more accurately than isolated teaching of individual skills.

The use of competency-based progression can also improve transparency. Students can understand what is expected, educators can identify specific gaps, and institutions can monitor whether programme outcomes are being achieved. EPAs and simulation-based assessment offer promising mechanisms for translating broad competencies into observable professional activities [3].

At the same time, educational innovation should be implemented critically. Simulation can be expensive, and high-fidelity equipment does not necessarily produce better learning if the instructional objectives and feedback are weak. Digital tools can increase access but may also introduce problems related to technology access, information quality, privacy, and reduced human interaction. Consequently, educational technology should always be selected according to the learning problem it is intended to solve.

Another important consideration is transfer. Improvements demonstrated in a simulation or OSCE are educational outcomes, but the ultimate objective is competent performance in clinical practice. Medical schools should therefore combine simulated assessment with workplace-based observation and, where feasible, indicators related to patient safety and quality of care.

For Kazakhstan, the development of practice-oriented medical education is particularly relevant to the continuing modernization of healthcare and professional training. Medical universities can strengthen this process by integrating clinical skills, communication, teamwork, digital competence, and patient safety throughout undergraduate and postgraduate programmes.

Medical universities should define clinical, communication, teamwork, and digital competencies as explicit programme outcomes and align learning activities and assessment methods with these outcomes. Simulation-based training should be expanded to support the development of procedural skills, clinical reasoning, and communication. Standardized patients and structured role-play should be incorporated into patient-centred communication training. Deliberate practice and mastery-learning principles should be applied where appropriate, while communication competencies should be integrated into OSCEs and other clinical assessments. Interprofessional simulation scenarios based on authentic healthcare tasks should be developed to strengthen teamwork and patient safety. Digital learning should complement rather than replace face-to-face clinical education. Finally, medical universities should provide systematic faculty development in simulation, feedback, assessment, and educational design and evaluate educational interventions using objective measures of learner performance and, where possible, evidence of transfer to clinical practice.

Practical Recommendations

Conclusion

Modern medical education must prepare healthcare professionals for complex professional situations rather than for examinations alone. Clinical competence includes not only knowledge and technical performance but also communication, clinical reasoning, teamwork, professionalism, and the responsible use of digital technologies.

Competency-based medical education provides a coherent framework for defining and assessing these outcomes. Simulation-based education, standardized patients, deliberate practice, structured feedback, and interprofessional learning provide practical mechanisms for developing professional performance in a safe educational environment. Recent evidence supports competency-based simulation for procedural skills and simulated-participant approaches for communication training, while also highlighting the importance of appropriate assessment and transfer to clinical practice [4,5].

The role of the medical educator is central to this process. Educational technologies are most effective when they are guided by clear learning objectives, evidence-based instructional design, and high-quality feedback. Medical universities should therefore develop not only the competencies of students but also the pedagogical competencies of faculty members.

An integrated model that combines clinical skills training, communication education, simulation, competency-based assessment, interprofessional learning, and digital literacy can strengthen the transition from academic preparation to safe professional practice. Ultimately, the value of medical education should be reflected in the ability of graduates to provide competent, patient-centred, and safe healthcare.

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Dietary Patterns and Colorectal Cancer Prevention: Current Evidence and Public Health Implications

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Abstract:
Objective: To synthesize evidence on dietary patterns and colorectal cancer incidence and discuss its public health implications.
Methods: A narrative review of 15 previously collected full-text documents compared systematic reviews, prospective studies, randomized controlled trials, and institutional reports.
Results: Higher overall diet quality, Mediterranean diets, and healthful plant-based diets were associated with lower incidence, although findings varied by sex, pattern definition, and study population. Proinflammatory and hyperinsulinemic dietary patterns were associated with higher risk, whereas a randomized trial of a low-fat dietary pattern found no significant preventive effect.
Conclusion: Current evidence supports improving overall diet quality by increasing whole grains and other fiber-rich foods, limiting processed meat, red meat, and alcohol, and improving access to healthy foods. The causal effects of specific patterns and the effectiveness of local implementation require further evaluation.
Keywords: dietary patterns; colorectal cancer; primary prevention; diet quality; public health

1 Introduction

Diet is a modifiable lifestyle factor relevant to colorectal cancer (CRC) prevention. Studies of individual foods and nutrients help identify dietary factors associated with CRC, but do not fully capture their combined influence in everyday diets. Dietary pattern research examines how foods are consumed together, using food combinations or scores to assess overall intake. This approach more closely reflects habitual eating and can inform population prevention[1,2]. Patterns differ in composition, scoring direction, and the populations to which they apply, so the findings do not identify a single best diet for cancer prevention for everyone.

This review examines dietary patterns and CRC incidence in the general adult population, with a focus on primary prevention. It considers which patterns are associated with incidence, how far the evidence supports inference, and what the findings imply for public health practice. Overall patterns and their shared food components are the main focus. Postdiagnosis mortality, survival, and recurrence are separate outcomes and are not used directly to explain incidence risk.

2 Scope and Review Approach

This narrative review used a predefined collection of 15 full-text documents, including systematic reviews and meta-analyses, prospective cohort studies and pooled analyses, a randomized controlled trial, institutional reports, and guidelines. The review groups evidence by overall healthy patterns, plant-based diets, inflammatory and insulinemic patterns, and food processing. It compares major outcomes and effect estimates alongside their limitations, then draws on guidelines to discuss public health implications. No new pooling of effect estimates or exhaustive search was undertaken. Analyses that shared cohorts, including those incorporated into reviews, were not counted as independent replications. Relative risks (RRs), hazard ratios (HRs), and 95% confidence intervals (CIs) are reported as presented in the original studies.

3 Main Evidence on Dietary Patterns and CRC Risk

3.1 Overall Healthy Patterns and Plant-Based Diets

Evidence generally associates higher diet quality with lower CRC risk, but its strength differs according to the pattern or score evaluated. The CUP Global review by Chu et al. included 53 observational studies and three randomized trials covering 32 dietary scores. Evidence linking Mediterranean diets, the healthful plant-based diet index, the Healthy Eating Index and its alternative versions, and Dietary Approaches to Stop Hypertension (DASH) with lower CRC incidence was graded "limited–suggestive" [1]. The Nutrition Evidence Systematic Review (NESR) concluded that patterns higher in vegetables, fruits, legumes, nuts, and whole grains, and lower in red and processed meats, refined grains, and sugary foods and beverages, among other components, were associated with lower colon and rectal cancer risk, with moderate evidence [2]. The grades reflect different assessments: CUP evaluated multiple scores separately, whereas NESR synthesized shared food characteristics. They do not necessarily indicate contradictory conclusions.

Associations for specific patterns vary across populations. In the meta-analysis by Zhong et al., nine cohorts reported CRC incidence; the pooled RR comparing the highest with the lowest Mediterranean diet adherence was 0.90 (95% CI: 0.84–0.96) [3]. However, Petimar et al. compared DASH, the Alternative Mediterranean Diet, and the Alternative Healthy Eating Index in two US cohorts and reported pooled HRs for men and women of 0.89, 0.89, and 0.95, respectively. All CIs crossed 1, and associations were stronger in men [4]. The overall inverse association is therefore not consistent for every score or population.

Plant-based food quality scores and vegetarian status measure different aspects of diet. In the Multiethnic Cohort Study, Kim et al. reported an HR of 0.80 (95% CI: 0.70–0.91) for men in the highest versus lowest quintile of the healthful plant-based diet index, with no significant association in women [5]. In a pooled analysis of nine cohorts, Dunneram et al. reported CRC HRs of 0.85 (0.77–0.93) for pescatarians and 1.40 (1.12–1.75) for vegans compared with meat eaters [6]. After excluding the first four years of follow-up, the HR for vegans was 1.25 (0.95–1.64) and was no longer statistically significant [6]. The subgroup size and the change in the sensitivity analysis limit interpretation. These findings do not establish that vegan diets cause CRC. Across both approaches, excluding animal foods alone is insufficient to assess overall food quality or nutritional adequacy.

3.2 Inflammatory and Insulinemic Patterns

Inflammatory and insulinemic dietary scores assess diet in relation to these biological characteristics. Tabung et al. reported a pooled HR of 1.32 (95% CI: 1.12–1.55) for men and women in the highest versus lowest quintile of the Empirical Dietary Inflammatory Pattern score [7]. CUP Global graded the evidence linking proinflammatory and hyperinsulinemic patterns with higher risk as "strong–probable" [1].

Within the Consortium of Metabolomics Studies (COMETS), Shi et al. harmonized data from six European and US cohorts, including 909,282 participants. During a median follow-up of 14.9 years, 16,525 CRC cases were recorded. HRs comparing the highest with the lowest quintile were 0.82 (95% CI: 0.78–0.86) for the reverse Empirical Dietary Index for Hyperinsulinemia, 0.84 (0.80–0.89) for the reverse Empirical Dietary Inflammatory Pattern, and 0.80 (0.76–0.85) for the Healthy Eating Index-2015 [8]. Higher reverse scores indicate lower insulinemic or inflammatory potential. The associations were similar in magnitude across the scores, supporting attention to overall diet quality. They do not establish that a particular biological pathway independently mediates a causal effect.

3.3 Food Processing as a Complementary Perspective

The degree of food processing adds another dimension to assessments of dietary composition. The meta-analysis by Meine et al. included five prospective cohorts with 1,128,243 participants.

Comparing the highest with the lowest ultra-processed food intake, the HR for CRC was 1.11 (95% CI: 1.03–1.21); no significant association was found for rectal cancer separately [9]. Across three US cohorts, Wang et al. reported an HR of 1.29 (1.08–1.53) for men in the highest versus lowest quintile of total ultra-processed food intake. Women showed no such overall association, and results varied by food subgroup [10].

Ultra-processed food intake and overall dietary patterns describe different dimensions of exposure. Both can inform assessments of food environments. The findings do not establish that all ultra-processed foods carry the same risk or that a particular additive explains the associations. Recommendations need to account for the specific foods, their nutritional quality, and the alternatives available.

4 From Shared Food Components to Public Health Action

4.1 Evidence Informing Food Choices

The patterns share a relatively consistent emphasis on more high-quality plant foods and fewer foods associated with higher risk. In the dose–response meta-analysis by Aune et al., each additional 10 g/day of total dietary fiber was associated with a CRC RR of 0.90 (95% CI: 0.86–0.94), and three additional daily servings of whole grains with an RR of 0.83 (0.78–0.89) [11]. Papier et al. recorded 12,251 CRC cases among 542,778 UK women. Each additional 300 mg/day of calcium was associated with an RR of 0.83 (0.77–0.89), whereas each additional 20 g/day of alcohol was associated with an RR of 1.15 (1.09–1.20) [12]. These estimates describe observational associations with dietary composition. They do not predict an equivalent change in risk for an individual who changes their intake.

The World Cancer Research Fund/American Institute for Cancer Research (WCRF/AICR) report supports links between whole grains, fiber-containing foods, and dairy products and lower CRC risk, while identifying processed meat, red meat, and alcohol as risk-related factors. It recommends healthy diets for cancer prevention and advises against relying on supplements [13]. The American Cancer Society (ACS) guideline also recommends healthy eating, weight management, and physical activity, together with social environments that support healthy choices [14]. Practical advice can encourage a variety of whole grains, legumes, vegetables, and fruits while limiting processed meat, red meat, and alcohol. Nutritional adequacy remains a requirement. Observational findings on calcium do not justify universal supplementation, and the inclusion of alcohol in some Mediterranean diet scores does not justify encouraging alcohol consumption.

4.2 Implementation Conditions and Evaluation

Healthy choices need to be accessible and affordable in the settings where people eat. Based on these guidelines, institutional food procurement, menu planning, and community nutrition education can increase whole-grain, vegetable, and fruit options while addressing price, supply, and cultural acceptability [14]. Evaluation can first track healthy food availability, purchasing, and intake, then assess health outcomes over a longer period. These are proposed directions for implementation and research; the reviewed studies do not establish the effects of these policies in a local setting.

In Kaakhstan and other specific settings, recommendations should reflect local dietary surveys, food prices, and nutritional status. The reviewed literature does not quantify the absolute benefits of local interventions or establish that dietary scores developed in Europe and the US will yield equivalent effects elsewhere. Implementation should adapt the shared food principles to local dietary alternatives, without requiring people to reproduce a named pattern in full.

5 Evidence Limitations and Research Directions

The randomized evidence places limits on inferences about intervention effects. The Women's Health Initiative (WHI) trial enrolled 48,835 postmenopausal women and aimed to reduce fat intake while increasing vegetables, fruits, and grains. After a mean follow-up of 8.1 years, the HR

for CRC was 1.08 (95% CI: 0.90–1.29), with no significant risk reduction [15]. The trial does not support the inference that a low-fat diet alone prevents CRC. Its findings apply to that population and intervention, however, and cannot rule out potential benefits of other healthy dietary combinations.

Most vidence on dietary patterns remains observational. Interpretation is limited by error in self-reported intake, dietary changes over time, clustering of health behaviors, and residual confounding. Differences by sex and anatomical subsite also need to be considered. Because papers share cohorts and reviews may include the same primary studies, these publications cannot all be treated as independent evidence. This review is limited by its reliance on previously collected material and did not reassess risk of bias across all primary studies. Future studies should use stronger repeated dietary assessments and harmonized exposure definitions. They should also test whether associations persist across populations and evaluate local implementation.

6 Conclusion

Higher overall diet quality is associated with lower CRC incidence, although the strength and consistency of the association differ by pattern and population. The evidence does not establish a definitive preventive effect. Public health practice can encourage whole grains and fiber-rich foods, limit processed meat, red meat, and alcohol, and maintain nutritional adequacy. Improving affordability and availability can help people make these choices. Dietary patterns provide a basis for sustained overall dietary improvement, but their causal effects and the benefits of local implementation still require evaluation.

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Development of evidence-based healthy eating recommendations as a tool for improving food literacy among the population

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Abstract

Food literacy is regarded as an essential prerequisite for making informed food choices and consistently applying healthy eating principles in everyday life. The aim of this article is to substantiate methodological approaches to developing evidence-based nutrition recommendations aimed at improving the food literacy of the population. The study utilizes a comparative analysis of international guidelines, materials describing the situation in Kazakhstan, and publications on food literacy and educational activities. The analysis shows that informing people about recommended intake levels of individual dietary components is insufficient unless they also acquire skills in meal planning, interpreting food labels, selecting foods, and preparing food. A step-by-step framework for developing recommendations is proposed: defining the target audience, selecting an evidence-based framework, adapting the content to the cultural context, translating scientific evidence into practical actions, pilot testing educational materials, and evaluating the results. In Kazakhstan, particular attention should be paid to accessible examples from traditional diets and national food traditions. The proposed approach is conceptual, and its effectiveness requires subsequent empirical evaluation.

Keywords: healthy eating; food literacy; nutrition literacy; evidence-based recommendations; dietary habits; nutrition education; Kazakhstan.

Introduction

Dietary habits influence the risk of developing a number of non-communicable diseases, and promoting healthy eating is an important preventative public health strategy. The World Health Organization (WHO) defines adequacy, balance, moderation, and variety as the fundamental principles of a healthy diet. However, the specific composition of a diet depends on age, physiological needs, food availability, cultural context, and established dietary habits[1]. Therefore, universal nutritional targets must be accompanied by explanations applicable to people's real-life circumstances.

Disseminating information about healthy eating alone does not guarantee changes in eating behavior. People may know that excessive salt consumption is undesirable but fail to consider the salt content of processed foods; understand the benefits of vegetables but have difficulty incorporating them into their usual dishes; or know about nutritional recommendations

but lack sufficient financial resources, time, or culinary skills to follow them. Therefore, preventative health communication must go beyond simply providing information and develop people's ability to apply this information in practice.

In this article, the term "food literacy" is used in a broad, practice-oriented sense to refer to the knowledge, abilities, and behavioral skills needed to plan meals, select and prepare food, evaluate food information, and develop diets that meet individual needs. It is linked to the broader concept of health literacy, which WHO describes as the ability to access, understand, evaluate, and use reliable information to maintain health[2].

This issue is of particular importance in Kazakhstan. A report by the WHO Regional Office for Europe highlights the consequences of changing dietary habits and the widespread consumption of foods high in salt, free sugars, and less healthy fats[3]. A study published in 2026, based on a national survey conducted in 2021–2022, found that only 15.7% of respondents with available intake data met the recommended intake of fruits and vegetables. Although 80.6% of participants were aware of the risks associated with excessive salt consumption, 39.6% reported adding salt to their food at the table[4]. These results demonstrate a gap between awareness and dietary habits and highlight the need for educational interventions.

Study Objective

To substantiate key principles and propose a consistent framework for developing evidence-based healthy eating guidelines aimed at improving food literacy among adults, taking into account their adaptation to the Kazakhstani context.

Materials and Methods

This study utilized a narrative and methodological analysis. It reviewed WHO materials on healthy eating and health literacy available at the time of writing; publications on dietary habits in Kazakhstan; and research examining the definition of food literacy, its relationship to eating behavior, and the evaluation of nutrition education programs [1–8]. The methods included thematic analysis, comparison of practical recommendations, and conceptual modeling. Based on this, an original proposed sequence for developing educational materials was formulated. This study is not a systematic review involving an exhaustive literature search, does not include primary data collection, and does not claim that the proposed framework has been experimentally tested.

Findings of the literature analysis and discussion

1. Food Literacy as a Desired Learning Outcome

One widely used concept of food literacy identifies four interrelated domains: meal planning and management, food selection, food preparation, and food consumption[5]. This approach shifts the focus from memorizing nutritional targets to solving everyday problems. For example, knowing that one should limit free sugars does not necessarily translate into the ability to identify their sources in food ingredients; similarly, knowing the benefits of dietary fiber does not guarantee the inclusion of whole grains and vegetables in an affordable diet.

When developing educational materials, it is useful to distinguish three levels of desired outcomes. The cognitive level includes understanding healthy eating principles and critically evaluating information. The practical level encompasses reading food labels, comparing products, judging portion sizes, and planning grocery shopping. The behavioral level concerns the consistent application of these skills when choosing and preparing food. Recommendations should address each level: whenever possible, the statement of a principle should be accompanied by a specific action that the person can perform independently.

A systematic review by Carmona et al. (2026) included 49 studies investigating the associations between health literacy, nutrition literacy, food literacy, diet quality, and adherence to dietary guidelines. Of the 72 relationships assessed, 42 were positive, 28 were statistically insignificant, and two were negative. The authors highlight the heterogeneity of measurement

instruments and the limitations in the quality of available studies[6]. Thus, improving literacy is a legitimate goal, but it should not be automatically equated with demonstrated improvements in nutrition or disease reduction.

2. Requirements for a robust evidence base

The primary requirement for dietary guidelines is that they be based on recommendations from reputable professional organizations and verified research results, rather than on popular dietary trends. When selecting information, developers should consider the date of the last update of the guidelines, the characteristics of the population being studied, the quality of the evidence, and the applicability of the results to the target audience. General dietary recommendations for healthy adults should also be distinguished from therapeutic diets, which require individual professional counseling.

WHO recommendations can form the core information of an educational program: diversity of food groups; emphasis on whole grains, vegetables, fruits, and legumes as sources of carbohydrates and dietary fiber; limiting the intake of free sugars to less than 10% of total daily energy intake; consuming less than 5 g of salt per day in adults; and a preference for unsaturated fats over saturated and industrially produced trans fats[1]. For individuals over 10 years of age, the WHO also recommends consuming at least 400 g of fruits and vegetables and at least 25 g of dietary fiber per day. These quantitative recommendations can serve as useful reference points, but they should be explained using examples of standard portions and readily available foods.

When developing recommendations, overly categorical designations such as "healthy food" or "unhealthy food" should be avoided unless the quantity consumed, frequency of consumption, and overall dietary pattern are taken into account. The same food can play different roles depending on the method of preparation, combination with food, and individual needs. It is more accurate to explain food choices in the context of the overall diet than to rigidly divide foods into permitted and prohibited categories.

3. Accessibility and cultural adaptation of recommendations

Even scientifically accurate information can have limited impact if it is presented in complex technical language, uses unfamiliar units of measurement, or recommends products unavailable to the target audience. WHO emphasizes that health literacy depends not only on individual efforts but also on the quality and accessibility of the information environment[2]. Therefore, educational materials should take into account age, language, education level, budget, and family circumstances.

In Kazakhstan, a promising approach is to explain healthy eating principles through familiar foods and dishes, including those from the national cuisine. For example, when discussing meat dishes, one could consider the proportions of ingredients in a serving, cooking methods, the amount of added salt, and how to incorporate vegetables. When discussing fermented dairy products, one could focus on their composition, portion sizes, and the salt content of individual varieties. The goal of this analysis is not to abandon national traditions, but to strengthen the ability to adapt familiar recipes and food combinations to modern preventive dietary recommendations. Developing reliable recommendations for specific dishes requires reviewing recipes and existing food composition tables, and, where necessary, determining nutrient content through laboratory analysis. Until such research is conducted, estimates of energy value, sodium content, or other nutrients in traditional dishes should not be presented as measured data. Educational materials should clearly distinguish between information supported by documentary evidence, values calculated from recipes, and general, qualitative recommendations.

Cultural adaptation also includes creating accessible materials in Kazakh and Russian, using familiar, everyday examples, and adopting a neutral, non-judgmental communication style. It is especially important to offer realistic alternatives across price ranges: training based solely on expensive products does not provide equal opportunities to apply the acquired knowledge.

4. Proposed Framework for Guideline Development

Based on the literature review, a six-step framework is proposed for developing brochures, methodological guidelines, and educational modules on healthy eating.

Step 1. Identify the target audience and learning objectives. Determine the age group, language, typical dietary habits, the most common understanding gaps, and the skills to be developed. Learning objectives should describe observable actions, such as comparing two foods by salt content, rather than just the abstract goal of "raising awareness."

Step 2. Select the evidence base. For each educational message, provide the scientific source, the degree of certainty of the conclusion, and its relevance to the target population. Prioritize current recommendations and high-quality research, and clearly highlight information supported by limited evidence.

Step 3. Translate recommendations into practical solutions. Supplement numerical targets and technical terminology with example portion sizes, food selection guides, brief instructions on interpreting ingredient lists, and cooking demonstrations. It is important to establish whether people can reproduce the proposed actions without professional assistance.

Step 4. Adapt to the local context. Align materials with local prices, seasonality, food availability, traditional dishes, storage conditions, and kitchen equipment. Cultural adaptation should not alter the scientific significance of the original recommendation.

Step 5. Conduct pilot testing with experts and users. Engage nutrition and public health experts to review content and test clarity of wording with representatives of the target audience. Use the feedback to correct ambiguous instructions, overly complex illustrations, and advice that is difficult to implement.

Step 6. Evaluate and update. Pre-define measurable indicators of knowledge, skills, and behavior. Revise materials when guidelines change, product composition changes, or recurring misunderstandings are identified.

The proposed sequence has not been validated as an intervention methodology. Its value lies in linking the development of recommendations to measurable educational outcomes, rather than using the number of leaflets distributed as the sole indicator of quality.

5. Educational Formats and Evaluation of Potential Effectiveness

Information can be conveyed through brief lectures, bilingual brochures, infographics, video demonstrations, practical exercises on reading food labels and menu planning, and digital materials. The format should be chosen based on its accessibility for the specific group, not simply on technological novelty. Combining a brief explanation with a practical task allows us to assess not only knowledge retention but also the ability to apply that knowledge in practice.

The results of the NEST program, evaluated by Kearsey et al. in Australia, illustrate the potential practical value of combining nutrition education with culinary skills training. In a quasi-experimental study, improvements in nutrition knowledge, cooking confidence, and some self-reported dietary measures were observed after the six-week program. However, the number of participants who completed the six-month follow-up was small, and the lack of randomized control groups limits causal interpretation[7]. Thus, international data support the feasibility of piloting similar programs but do not predetermine their effectiveness in Kazakhstan. A three-level evaluation strategy is proposed for future pilot trials. Knowledge can be assessed using questions on food groups, salt, free sugars, dietary fiber, and dietary diversity. Practical skills can be assessed using tasks including comparing product labels, choosing foods within a hypothetical budget, modifying recipes, and developing a balanced menu. At the behavioral level, structured questions on the frequency of consumption of specific food groups and eating habits can be used, preferably supplemented by repeated measurements after several weeks or months.

When developing questionnaires, it is preferable to use validated instruments; alternatively, the clarity and reliability of newly developed questions should be assessed

separately. Participant characteristics and potential exogenous factors should be considered in before-and-after comparisons. If the program lacks a control group, observed changes should be described as associated with program participation, rather than as conclusive evidence of cause and effect.

6. Limitations of the Educational Approach

Dietary behavior is not solely shaped by individual knowledge. It is influenced by food prices, availability of suitable foods, food provision in schools and workplaces, marketing, family habits, and time constraints. Therefore, educational recommendations should be considered one component of a broader prevention strategy, not a substitute for policies aimed at improving the food environment. The importance of economic mechanisms and the food choice environment is also reflected in the WHO recommendations on fiscal policy to support healthy diets[8].

A limitation of this analysis is its narrative and methodological nature. The proposed framework has not yet been empirically evaluated in the target population, and its features cannot be used to predict the magnitude of any changes in dietary behavior. Future work should include selecting a target group, developing prototype materials, obtaining expert opinion, conducting pilot testing, and assessing comprehensibility, acceptability, and potential effectiveness.

Conclusion

Evidence-based healthy eating recommendations can only serve an educational function if they go beyond lists of dietary goals and restrictions and help people understand, evaluate, and apply the information they receive when making food choices. Key requirements for developing such materials include a robust evidence base, practical relevance, accessible language, cultural acceptability, consideration of socioeconomic constraints, and measurable educational outcomes.

A six-step framework is proposed, ranging from identifying the needs of the target audience and assessing the evidence base to pilot testing and evaluating the outcomes. Its application can provide a methodological basis for recommendations tailored to the traditional diet of the population of Kazakhstan, including traditional dishes. Future research should focus on developing a specific set of educational materials and empirically assessing their impact on knowledge, practical skills, and dietary habits. At this stage, the conclusions focus more on the rationale for the approach than on evidence of the effectiveness of an intervention that has not yet been implemented.

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EPIDEMIOLOGICAL, METHODOLOGICAL ASPECTS, SCREENING EFFECTIVENESS AND RESULTS OF EARLY DETECTION OF MALIGNANT TUMORS IN THE REGIONS OF KAZAKHSTAN AT THE PRIMARY HEALTH CARE LEVEL

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Annotation: This scientific and analytical study examines the epidemiological patterns of cervical, breast, and colorectal cancer in the regions of the country, with particular emphasis on incidence and mortality rates and their regional variation. The study provides a comprehensive assessment of the current state of cancer screening and prevention, including the screening approaches used for the early detection of these malignancies in clinically asymptomatic populations. Particular attention is given to the organization and implementation of population-based screening programs, the target populations, screening intervals, diagnostic methods, and

the subsequent management of individuals with abnormal screening results. The analysis also considers the role of screening in reducing the burden of malignant neoplasms through early detection and timely referral for further diagnostic evaluation and treatment. The study presents detailed, step-by-step algorithms for the organization and implementation of screening for cervical, breast, and colorectal cancer, outlining the principal stages from identification and invitation of eligible individuals to primary screening, additional diagnostic procedures, confirmation of the diagnosis, and appropriate follow-up. The diagnostic capabilities and practical significance of the screening methods currently applied are described, with particular emphasis on their potential for detecting precancerous conditions and early-stage malignancies before the onset of clinical symptoms. The findings highlight the importance of a systematic, evidence-based approach to cancer screening and demonstrate the potential of well-organized preventive programs to improve early detection, facilitate timely treatment, and ultimately contribute to reductions in cancer-related incidence and mortality.

Key words: oncology, primary care, early diagnosis, cancer screening, cervical cancer, breast cancer, colorectal cancer, epidemiology, incidence, mortality, HPV, Pap test, smear for oncocytology, ultrasound examination, mammography, hemocult test, fecal occult blood test - FOBT, total colonoscopy.

Early detection of malignant neoplasms remains one of the fundamental priorities of modern oncology and an essential component of effective cancer control. The clinical outcomes of many malignant diseases are strongly influenced by the stage at which the tumor is diagnosed, with earlier-stage detection generally associated with a greater range of therapeutic options, improved treatment outcomes, and more favorable long-term prognosis. Consequently, the development and implementation of effective strategies for identifying malignant and premalignant conditions before the appearance of clinical manifestations represent an important direction in contemporary preventive medicine. Cancer screening is an established approach to secondary prevention aimed at detecting disease in individuals who do not yet exhibit symptoms or clinical signs suggestive of malignancy. Unlike diagnostic procedures performed in patients with suspected disease, screening is conducted among predefined target populations according to established age, sex, and risk-based criteria. Its primary objective is to identify cancer at a preclinical or early stage, when the pathological process may be more amenable to curative treatment. In addition, screening may facilitate the detection of premalignant lesions and other pathological changes that have the potential to progress to invasive cancer, thereby creating an opportunity for timely intervention and prevention of malignant transformation [1].

The effectiveness of a screening program depends not only on the diagnostic performance of individual screening methods but also on the quality of its overall organization and implementation. A well-functioning screening system requires clearly defined target populations, standardized procedures for participant recruitment and examination, appropriately trained healthcare professionals, and consistent criteria for interpreting and managing screening results. Equally important is the availability of an established pathway for the subsequent evaluation of individuals with abnormal findings, including confirmatory diagnostic procedures, specialist referral, treatment, and follow-up. Without adequate coordination between these stages, the potential benefits of screening may be substantially reduced [1,2].

Screening technologies and diagnostic approaches should meet several fundamental requirements to ensure their applicability at the population level. Ideally, screening procedures should be sufficiently simple, safe, accessible, reproducible, and acceptable to the target population, while demonstrating adequate sensitivity and specificity. High sensitivity is essential for minimizing the number of clinically significant cases that remain undetected, whereas adequate specificity helps to reduce false-positive results and unnecessary diagnostic

interventions. Therefore, the development of standardized, evidence-based screening algorithms and their systematic implementation are critical for improving the early detection of cancer and precancerous conditions and, ultimately, for reducing cancer-related incidence and mortality [3].

Screening plays an important role in improving early diagnosis and treatment outcomes. According to the Guide to Cancer Early Diagnosis by Ilbawi A. et al. [4], screening aims to detect unrecognized cancer or its prior lesions in a typically healthy, asymptomatic population through tests or other procedures that can be applied quickly and are widely available to the target population. In screening, the target population is assessed for unrecognized cancer or precancer, and most people tested will not be diagnosed with the disease. Screening should be seen as a process and not as the performance of a specific test, examination, or procedure. The screening process includes a system of informing and inviting the target population to participate; administering the screening test; following-up with test results and referral for further testing among those with abnormal test results; ensuring timely pathologic diagnosis, staging and access to effective treatment with routine evaluation to improve the process. A screening program encompasses the process from invitation to treatment and requires planning, coordination and monitoring and evaluation.

To date, the republican cancer screening program includes three nosological forms of malignant neoplasms - cervical cancer (CC), breast cancer (BC), colorectal cancer (CRC). Let's consider the current epidemiological indicators, methodology and results of cancer screening in our country.

CC in the structure of all malignant tumors of both sexes of the population in 2022 took 6th place with a share of 5.51% (2021 - 4th place, 5.54%), in women - stable 2nd place - 9.7% (9.7%) [5].

The incidence rate per 100 thousand population increased from 9.4 to 9.92. In 10 regions of the republic, the incidence rate is higher than the national average: Pavlodar - 17.2 per 100 thousand people (2021 – 16.7) – the highest level, East Kazakhstan – 14.3 (10.8), North Kazakhstan – 14.3 (10.2), Atyrau – 13.2 (13.8), Zhetysu - 11.7, Karaganda - 11.7 (12.0), Abay - 11.1, Akmola - 11.1 (11.9), Mangistau - 11.1 (9.7), Kostanay - 10.8 (10.6) regions.

Low incidence rates in Zhambyl region - 5.8 per 100 thousand population (5.7), Turkestan region - 6.1 (5.2), Aktobe region - 8.3 (11.6), Kyzylorda region - 8.5 (8.2) areas.

CC in the structure of causes of death from malignant tumors of the population of both sexes in 2022 rose from 9th to 8th position, with a share of 4.6% (2021 - 4.3%), mortality from CC is stable at 3.1 per 100 thousand population (3.1).

The mortality rate from CC in 10 regions is higher than the national average: Akmola - 4.2 per 100 thousand population (2021 - 3.1) - maximum level, West Kazakhstan - 4.1 (4.8), Pavlodar - 3.8 (5.6), Almaty – 3.7 (2.5), Zhetysu – 3.7, Atyrau – 3.4 (4.0), East Kazakhstan – 3.3 (3.8), Karaganda - 3.2 (4.7), Kostanay - 3.2 (2.4) regions and Almaty city - 3.4 (2.9).

Below the national average, mortality was recorded in Abay region, cities Astana, Shymkent - 2.9 per 100 thousand population, Mangistau - 2.8 (3.0), Turkestan - 2.3 (2.2), Aktobe - 2.2 (3.0), North - Kazakhstan - 2.0 (2.6), Kyzylorda regions - 1.7 (3.5) - the best result [5].

In 12 regions, a 100% level of morphological verification of the diagnosis was ensured, the lowest or worst indicator for the third year was in the Kyzylorda region - 94.3%, below the national average indicators in Akmola - 98.8%, Atyrau - 98.9%, Kostanay - 98, 9%, Mangistau - 97.6%, Pavlodar - 96.6%, regions and Almaty city - 98.5%;

In a number of regions, the frequency of diagnosis of stage I-II CC was below the national average (88.1%) - in Akmola - 76.2% (2021 - 73.6%) - the worst result in the country, in Karaganda - 77, 2%, Zhetysu - 82.9%, Abay - 83.8%, Kostanay - 84.3%, Aktobe - 85.5%, West Kazakhstan - 85.7%, Pavlodar - 81.3%, while that in the Atyrau region - 100.0% result.

The proportion of stage IV CC is higher than the national average (2.7%) in the following

regions: the worst result is in Zhetysu (6.1%), above the national average in Karaganda - 5.1% (2021 - 5.6%), Akmola - 4.8% (2.3%), Kostanay - 4.5% (4.4%), North Kazakhstan - 3.9% (7.4%), Almaty - 3.7 % (5.1%), Zhambyl - 2.9% (0.0) regions, cities Almaty – 3.6% (1.8%) and Shymkent – 3.8% (5.9%). The lowest neglect is in the East Kazakhstan region - 1.0% (0.7%).

Late diagnosis rates (III-IV stages) for CC are above the national average - 11.9% (15.4% in 2021) were noted in Akmola - 23.8% (2021 - 26.4%) - worst result, Karaganda - 22.8% (35.2%), Pavlodar - 18.8% (20.8%), Zhetysu - 17.1% (24.2%), Abay - 16.2% (12.8%), Kostanay - 14.6% (15.6%), Aktobe - 14.5% (9.6%), West Kazakhstan - 14.3% (32.4%) regions. The lowest neglect is in the Mangistau region - 6.0% (20.8%).

Across the country, the five-year survival rate of patients with CC registered in 2018 was 59.9% in 2022, with a decrease from the level of 2021 (67.5% for those registered in 2017), and with a significant range in by region, from the maximum – 72.9% (2021 – 70.7%) in the North Kazakhstan region, to the minimum – 34.9% (64.4%) in the Atyrau region [5].

CC screening is a periodic, comprehensive examination of women of a certain age group as part of a special medical program to prevent and reduce incidence and mortality from CC [6].

CC screening is a population-based preventive intervention aimed at detecting cervical precancerous lesions and CC at an early stage, when timely diagnostic assessment and treatment can prevent progression to invasive disease. In Kazakhstan, CC screening is organized within the national population screening program and is conducted among predefined target groups according to age and clinical eligibility criteria [7,8,9].

According to the current national screening framework, women who reach the ages of 30, 34, 38, 42, 46, 50, 54, 58, 62, 66, 70 and 74 years and who are not under dynamic follow-up for cervical malignancy constitute the target population for CC screening. Screening is performed once every four years, with the screening episode expected to be completed within 60 days.

The age-specific schedule represents a population-based strategy in which eligible women are identified through the primary healthcare system. Recent data from Kazakhstan confirm the use of a four-year screening interval and cytological examination for CC screening within the national program.

The preparatory stage is performed within the primary healthcare organization. It includes:

- identification and annual formation of the target population;
- verification and monthly updating of the list of eligible women;
- informing women about the purpose and benefits of CC screening;
- invitation to participate in screening;
- registration of screening attendance and organization of timely completion of the screening pathway.

The national regulations require primary healthcare organizations to form target groups from the population attached to the healthcare organization and to establish a sequential pathway for the provision of screening services. The target population is initially compiled annually, with subsequent monthly correction.

The primary screening examination is performed in the primary healthcare setting by an appropriately trained healthcare professional. The screening procedure includes collection of a cervical specimen for cytological examination.

Under the current Kazakhstan program, cervical screening is based on cytological examination of a cervical smear using the Papanicolaou (Pap) test, with liquid-based cytology used within the national screening program. The collected specimen is submitted to a cytology laboratory for standardized evaluation.

Before specimen collection, the woman should receive appropriate instructions concerning factors that may interfere with specimen quality. The collected material must be

properly identified, documented and transported according to laboratory requirements.

Cytological examination should be reported using standardized terminology, preferably the Bethesda System, which provides a reproducible framework for classifying cervical cytological findings [10].

The cytological result may be classified as:

- NILM (Negative for Intraepithelial Lesion or Malignancy) – no evidence of intraepithelial lesion or malignancy;
- ASC-US (Atypical Squamous Cells of Undetermined Significance);
- ASC-H (Atypical Squamous Cells, cannot exclude HSIL);
- LSIL (Low-Grade Squamous Intraepithelial Lesion);
- HSIL (High-Grade Squamous Intraepithelial Lesion);
- AGC (Atypical Glandular Cells) and other glandular abnormalities;
- cytological findings suspicious for or diagnostic of invasive carcinoma.

The Bethesda terminology is widely used in contemporary cervical screening and abnormal-result management. Current evidence-based guidelines emphasize that management should depend not only on the cytological category but also, where available, on Human papillomavirus (HPV) status, previous screening history and the estimated risk of clinically significant cervical intraepithelial neoplasia.

A woman with an abnormal cytological result should not simply return to routine screening. She should enter a diagnostic pathway according to the severity of the abnormality and the applicable national clinical recommendations.

The diagnostic pathway may include: abnormal cytology → clinical assessment → HPV testing where indicated → colposcopy → directed cervical biopsy when indicated → histological examination → definitive diagnosis → treatment or surveillance.

Risk-based management is preferable to management based exclusively on a single cytological result. The 2019 American Society for Colposcopy and Cervical Pathology consensus guidelines, published in 2020 and subsequently updated, incorporate current screening results together with previous results and clinical history when determining the need for surveillance, colposcopy or treatment.

For example, high-grade cytological abnormalities generally require prompt diagnostic evaluation, while selected low-grade abnormalities may be managed with HPV-based triage and/or surveillance depending on the patient's estimated risk. Unsatisfactory cytology requires repeat testing or further evaluation according to the applicable guideline.

The second stage of the national screening pathway is intended to determine the cause of an abnormal screening result and establish a definitive diagnosis. Under the Kazakhstan regulations, women with abnormal screening findings are referred by the primary healthcare physician for further examination. Depending on the screening result, this may include consultation with an obstetrician-gynecologist, colposcopy or videocolposcopy, cervical biopsy when indicated, histological examination and consultation with an oncologist or gynecologic oncologist.

Thus, the screening process should be regarded as a continuum extending from population identification and primary testing to diagnostic confirmation and subsequent treatment or surveillance, rather than as an isolated cytological examination.

At the final stage, the screening results and the established clinical diagnosis are documented in the healthcare information system. The woman is informed of the results and receives recommendations regarding further diagnostic evaluation, treatment, surveillance or return to routine screening.

The national regulations specifically require screening organizations to record screening results, final diagnoses and recommendations for further examination and follow-up. The

screening episode is considered complete when the appropriate endpoint of the clinical pathway has been documented.

The contemporary population-based cervical cancer screening algorithm can therefore be summarized as follows:

Identification of the target population → invitation and information → cervical specimen collection → primary cytological screening → cytological classification → assessment of abnormal results → HPV testing/triage where indicated → colposcopy and biopsy when indicated → histological confirmation → treatment or surveillance → documentation and return to routine screening.

This approach combines the organizational framework of the national screening program in Kazakhstan with contemporary principles of risk-based management of abnormal cervical cancer screening results.

Now, regarding the results of CC screening. In 2022, 771,282 women of the target group aged 30 to 70 years were examined during cytological screening (in 2021 - 757,454).

During cytological screening in 2022, 392 cases of cervical cancer were identified (319 in 2021). The detection rate increased from 0.42 to 0.51 per 1000 women examined

High detection of CC during screening is ensured in Aktobe, Almaty, Atyrau, East Kazakhstan, Kyzylorda, Pavlodar, North Kazakhstan, Turkestan regions and Shymkent city. The detection rate in these regions ranges from 0.55 to 1.59 per 1000 women examined. The best indicator is in Atyrau region - 1.59. Compared to 2021, there is an increase in detection in 10 regions, with the exception of Akmola, Aktobe, Zhambyl, Kostanay, Mangistau, North Kazakhstan regions and Shymkent city. The worst result in Astana is 0.15 per 1000 women examined [5].

Cytologically, cervical precancer was detected in 1.16% of those examined (2021 – 0.99%). The detection rate of precancer below 0.6% (the planned indicator for 2022, according to the Comprehensive Plan) was noted in Aktobe, Karaganda and Kostanay regions.

A high proportion of stage I CC (70% or more) was detected in 6 regions of the country (in 8 in 2021): Kostanay, Mangistau (94.7% - best result), North Kazakhstan, Turkestan regions, cities Almaty and Astana. Low levels of early detection of CC (below 50%) were not observed in any region.

Localized processes (stages I-II) were identified in 99.2% of all cases of detected cancer (96.5%). In the Akmola and Karaganda regions, cases of CC were identified not only in localized, but also in widespread stages of the process. A total of 3 cases of CC in stage III and no cases in stage IV were identified (11 and 0, respectively) [5].

BC ranks first in the structure of the frequency of malignant tumors of both sexes in the population with a share of 14.7% (2021 - 15.4%). This situation has been stable since 2004; in addition, BC ranks first and remains consistently in this position in the structure of female oncopathology. The incidence of BC in 2022 in the country as a whole increased to 26.5 per 100 thousand (2021 – 26.3). In the structure of cases, BC occupies the 1st ranking place in the vast majority of regions and cities of the country, except for three: Akmola, Kyzylorda and North Kazakhstan regions, where lung cancer takes the 1st ranking place [4].

Above the national average - 26.5 per 100 thousand of us. – incidence of BC in 10 regions of the country: Abay – 33.3, Akmola – 32.7 (2021 – 29.8), East Kazakhstan – 44.7 (39.9) – the highest level, West Kazakhstan – 31.2 (28.4), Karaganda – 40.2 (40.1), Kostanay – 37.5 (35.8), Pavlodar – 43.2 (47.4), North Kazakhstan – 34.7 (38.2) regions and Almaty city – 35.4 (34.5), Astana city – 31.5 (28.4). Below average indicators per 100 thousand of us. in Aktobe - 21.6 (24.3), Almaty - 21.9 (17.7), Atyrau - 22.8 (15.7), Zhambyl - 14.2 (15.1), Zhetysu - 22.8, Kyzylorda - 14.6 (14.4), Mangistau - 14.7 (17.3), Turkestan - 11.3 (11.7) regions and Shymkent city - 14.9 (21.9) [5].

BC ranks third in the structure of causes of death from malignant tumors in the population of both sexes for the thirteenth year in a row, amounting to 8.1% in 2022 (2021 – 8.7%). In the

republic as a whole, mortality from BC decreased by 13.0%, from 6.2 to 5.4 per 100 thousand people.

The regions where mortality from BC is higher than the national average include: Abay - 10.1 per 100 thousand people (maximum level), East Kazakhstan - 8.0 (2021 - 8.5), Pavlodar - 7.1 (10.0), North Kazakhstan - 7.0 (11.4), Kostanay - 6.9 (7.5), Akmola - 6.5 (8.2), West Kazakhstan - 5.7 (6.9), Zhambyl - 5.5 (4.8) and Astana city – 6.3 (6.6), Almaty city – 6.6 (9.5). The indicators are significantly lower in Aktobe - 4.5 (3.5), Almaty - 4.5 (5.8), Zhetysu - 4.0, Atyrau - 3.7 (3.0), Kyzylorda - 4.4 (4.1), Turkestan - 3.6 (3.6), Mangystau regions - 2.7 (3.6) - the lowest level [5].

Mass screening to identify BC patients should mainly involve healthy women without any signs of the disease or symptoms. Screening not only helps to detect hidden forms of cancer that can be treated, but also has psychological value for women. As a result of screening, women are convinced that they do not have BC, and this is the most important potential success of such programs. While the ultimate goal of screening is to reduce BC mortality, its immediate goal is to detect cancer before clinical manifestation. However, BC is a heterogeneous disease, which can significantly affect the effectiveness of screening. Screening models for BC are usually based on the fact that the majority of detected tumors are invasive cancers in the early stage of progression. In addition, it must be taken into account that the detection of cancer (or its precursors) before clinical manifestation increases the risk of false positive diagnosis [11,12].

Mammography has a sensitivity of 95% and a specificity of 97%. These indicators decrease when examining women with denser mammary glands (young age, use of hormone therapy), with low quality mammography, and also with insufficient qualifications of the radiologist. Detection of high-grade invasive cancer by screening, when the tumor is not yet detected by clinical examination (palpation), means the possibility of reducing mortality from BC [13].

Preventive screening for early detection of BC in the Republic of Kazakhstan includes [7]:

1) mammography of both mammary glands in two projections - direct and oblique in the mammography room of the city, district polyclinic (mobile medical complex). All digital mammograms in the presence of a system for archiving and transferring medical images are copied to CDs and other electronic media and transferred to the server of the mammography room of the Cancer Center using specialized licensed software integrated between medical organizations; in case of impossibility of digital transmission - they are printed on X-ray film at a scale of 1:1 - 100% (1 patient - 1 set - 2 or 4 mammograms) with subsequent transfer to the mammography room of the Cancer Center;

2) interpretation of mammograms according to the BI-RADS classification (M0t, M0d, M1, M2, M3, M4, M5) by two or more independent radiologists of the same medical organization - double reading or different medical organizations: a radiologist of the mammography room city, district polyclinic (mobile medical complex) - the first reading, and the radiologist of the mammography room of the Cancer Center - the second reading;

3) in-depth diagnostics - targeted mammography, ultrasound examination (hereinafter - ultrasound) of the mammary glands, trepanobiopsy, including under ultrasound or stereotaxic control for histological examination, which is carried out in case of detection of pathological changes on mammograms (M0d) in the mammography room of the Cancer Center.

√ An average medical worker or a responsible person of the organization of outpatient care sends the patient for mammography to the district, city polyclinic.

√ The X-ray laboratory assistant of the mammography room of the city, district polyclinic (mobile medical complex) performs mammography, fills out a referral for double reading of mammograms and transmits the referral through information interaction.

Radiologist of the mammography office of the city, district polyclinic (mobile medical complex): fulfills the requirements for the safety and quality of mammographic examinations; evaluates the quality of the images provided and the correctness of the installation; performs

repeated mammography in the M0t category (technical errors of mammography); determines the radiological density of the mammary glands on the ACR scale (A, B, C, D) indicating this parameter in the study protocol; conducts the first reading of mammograms with interpretation of the BI-RADS classification results. In the M0d category (undetermined or suspicious radiological changes requiring additional examination), the study protocol indicates the predominant pathology: education, asymmetry, violation of architectonics, microcalcifications; sends mammograms, electronic copies of mammograms through the archiving system and transfer of medical images to the workplace of the mammography office of the Cancer Center together with directions for double reading of mammograms; directs low–dose computed tomographic images through the system of archiving and transferring medical images to the workplace of the computer tomography office of the Cancer Center together with copies of images recorded on CD-ROMs or other electronic media and directions for double reading.

- The radiologist of the mammography room of the Cancer Center: evaluates the quality of the provided images and the correctness of the styling. Viewing digital x-ray images transferred to the server or on digital media (CD, DVD) is carried out on a monitor for interpreting digital x-ray images with a resolution of at least 5 megapixels, which has a certified grayscale transmission in accordance with the DICOM standard; conducts a double (second) reading of mammograms with the interpretation of the results according to the BI-RADS classification, using, if necessary, archival images. Organizes the third reading according to indications. With double reading, an independent interpretation of the images is carried out (blinding method - the second radiologist does not know the results of the first reading); in the M0m category (technical errors in mammography), recommends repeat mammography; in the M0d category (uncertain or suspicious radiographic changes requiring additional examination), the study protocol indicates the predominant pathology: education; asymmetry, violation of architectonics, microcalcifications; recommends that the outpatient care organization, according to indications, invite the patient for in-depth diagnostics (targeted mammography, ultrasound of the mammary glands, trephine biopsy, including under ultrasound or stereotaxic control, followed by histological examination of the material); collects and archives all mammograms (films and electronic media) made as part of the examination. The shelf life of mammograms is at least 3 years after leaving the age subject to a screening study; the results of the double (second) reading are transferred to the outpatient care organizations through information exchange.

- Indications for in-depth diagnostics are the conclusions of double reading mammograms M0d (uncertain or suspicious X-ray changes requiring additional examination).

- In-depth diagnostics is carried out in two stages. At the first stage, ultrasound is performed, according to indications, targeted mammography, possibly with an increase (with asymmetry, violation of architectonics and the presence of microcalcifications). When visualizing a suspicious pathology (M4 and M5), the second stage is performed - trepanbiopsy, including under ultrasound control and stereotaxic control for histological examination.

- Histological examination is carried out in the laboratory of pathomorphology or pathological bureau. Morphological interpretation of the biopsy is carried out in accordance with the recommendations of the World Health Organization.

- Physician or responsible person of the outpatient care organization:

1) upon receipt of a mammography result according to the BI-RADS classification:

- in case of M0t (technical errors in mammography) - sends the patient for a second X-ray examination to the mammography room of the city, district polyclinic (mobile medical complex);

- with M0d (undefined or suspicious X-ray changes requiring additional examination) - sends the patient for in-depth diagnostics to the mammography room of the Cancer Center;

- with M1 (no changes detected) - recommends that the patient undergo a follow-up mammography examination after 2 years. With radiological density of the mammary glands, C and

D are sent for ultrasound of the mammary glands to exclude a false-negative result of mammography;

- with M2 (benign changes), refer the patient for a consultation with an oncologist (mammologist) of the clinical diagnostic department, followed by a screening mammography examination after 2 years;

- with M3 (probable benign changes) - sends the patient for short-term dynamic radiation observation to the local doctor with the recommendation of control mammography or ultrasound in 6 months;

- with M4 (signs that cause suspicion of malignancy), M5 (practically reliable signs of malignancy) and if it is technically impossible to perform a trepanbiopsy or a biopsy is refused, a referral to an oncologist (mammologist) of the clinical diagnostic department for dynamic observation and decision on the verification of the identified pathology;

2) upon receipt of the result of a histological examination:

- benign education - refers the patient to an oncologist (mammologist) of the clinical diagnostic department for dynamic monitoring, followed by a screening mammography examination after 2 years;

- formation with an indeterminate malignant potential or carcinoma in situ - refers the patient to the Cancer Center for consultation and treatment, followed by dynamic observation by an oncologist (mammologist) of the clinical diagnostic department at the place of her attachment;

- malignant neoplasm - refers the patient to the Cancer Center for treatment and follow-up;

3) communicates the results of the screening examination to the patient in any available way (by telephone, in writing, through electronic means of communication);

4) enters the results of double reading, in-depth diagnostics, histological examination, recommendations of the radiologist of the Cancer Center mammography room into the information system.

Establishing the size of the primary tumor is especially important in screening. Tumor size is an important criterion for evaluating the quality of screening and determining the ability of X-ray mammography to detect non-palpable tumors. Therefore, it is extremely important that pathologists measure tumor diameter as accurately as possible. The smaller the size of the primary tumor, the greater the likelihood of error in determining its size.

Let's analyze the results of BC screening. Mammography screening identified 1,570 cases of BC in 2022 (1,402 in 2021). The cancer detection rate increased from 1.78 to 1.94 per 1000 examined. The best result is in the Karaganda region – 2.63 per 1000 women examined. Low detection rate per 1000 examined, compared to the republican average, in Atyrau (1.72), Zhambyl (0.58), Kyzylorda (1.68), Mangistau (0.42 - worst result), Turkestan (1.22) regions and cities Astana (1.5) and Shymkent (1.58). Compared to 2021, there was an increase in the detection of BC in 9 regions, with the exception of Aktobe (decrease from 2.87 to 2.19 per 1000 women examined), Karaganda (from 2.73 to 2.63), Mangistau (from 1.10 to 0.42), North Kazakhstan (from 3.27 to 2.31), Turkestan (from 1.36 to 1.22) regions and cities Astana (from 1.54 to 1.50), Almaty (from 2.24 to 2.18) and Shymkent (from 2.35 to 1.58) [5].

In 2022, the proportion of patients identified during screening studies with early stages of BC (stage 0-I) was 50.2% during screening (in 2021 - 47.9%). A high proportion of stages 0-I BC (over 50%) was recorded in 8 regions (in 8 in 2021): Akmola, West Kazakhstan, Karaganda (70.8% - best result), Pavlodar, North Kazakhstan, Turkestan regions, cities Astana and Shymkent. Low levels of early detection of BC (below 40%) were noted in Aktobe (19.3% - worst result), Zhambyl (34.8%), Kostanay (39.5%), Mangistau (27.3%) regions and Almaty city (37.3%). Localized cancer (0-I and II stages) amounted to 96.2% (2021 - 95.5%), while not a single case was detected in stages III-IV in Atyrau, West Kazakhstan, Zhambyl, Kyzylorda, Mangistau, Pavlodar regions, cities Astana

and Shymkent. A total of 46 cases of breast cancer in stage III and 14 in stage IV were identified (52 and 11, respectively) [5].

Epidemiological indicators of CRC in the form of colon cancer and colorectal cancer are considered separately for objective reasons.

Colon cancer with a specific gravity of 5.53% (2021 - 5.2%) in the structure of oncopathology of both sexes of the population has risen to 5th place, in men it remains in 6th place - 5.8% (5.5 %), for women - in the 5th - 5.3% (4.91%) The incidence rate of cancer of this localization in the country in the reporting year increased from 8.8 to 9.95 per 100 thousand population.

The incidence of colon cancer in 10 regions is higher than the national average - 9.95 per 100 thousand population: Kostanay - 20.7 (2021 - 15.9), Pavlodar - 18.8 (15.3), North Kazakhstan - 18, 0 (12.7), East Kazakhstan - 16.9 (13.4), Karaganda - 15.4 (15.0), Akmola - 14.6 (10.2), West Kazakhstan - 11.0 (10.1), Abay - 10.0 (9.0) regions and cities Almaty – 12.8 (12.1) and Astana – 10.5 (9.0). As in 2021, colon cancer was detected much less frequently in Turkestan - 3.1 per 100 thousand population (2.7), Kyzylorda - 4.1 (4.6), Zhambyl - 5.5 (5.8), Almaty - 6.3 (4.7), Zhetysu - 6.4, Mangistau - 6.8 (4.9) regions and Shymkent city - 5.0 (4.0) [5].

Rectal cancer in the structure of malignant neoplasms of both sexes retains 7th place in rank with a specific gravity of 4.9% (2021 - 4.92%), but in men it dropped from 4th to 5th place - 6.1%, for women – from 9th to 10th – 4.0%. The incidence rate per 100 thousand population increased from 8.4 to 8.8.

A high incidence rate was recorded in Kostanay - 17.8 per 100 thousand population (2021 - 16.2), East Kazakhstan - 17.7 (13.9), North Kazakhstan - 15.6 (15.1), Pavlodar – 14.9 (18.1), Karaganda – 13.3 (11.7), Abay – 12.9, West Kazakhstan – 12.9 (9.8), Akmola – 10.3 (13.1) regions and Astana city – 10.3 (9.0). Traditionally, a low incidence of rectal cancer is observed in Mangistau - 3.1 (2.8), Turkestan - 3.3 per 100 thousand population (2.7), Zhambyl - 3.7 (5.1), Kyzylorda - 4, 1 (5.3), Almaty – 5.3 (5.6) regions and in Shymkent city – 5.5 (5.0) [5].

Rectal cancer in the structure of causes of death from malignant neoplasms of the population of both sexes in 2022 remained in 5th place with a share of 5.41% (2021 – 5.41%). In the republic as a whole, the mortality rate from this form of cancer was 3.6 per 100 thousand population (3.87).

The mortality rate per 100 thousand population was higher than the national average in East Kazakhstan - 7.8 (2021 - 8.6) - the maximum level, Pavlodar - 7.5 (7.6), Abay - 5.9, North Kazakhstan - 5.8 (4.3), Kostanay - 4.9 (4.9), West Kazakhstan - 4.8 (4.2), Karaganda - 3.8 (5.2) regions. Below the national average - 3.8 per 100 thousand population, mortality in Aktobe - 3.2 (4.1), Almaty - 2.6 (2.6), Atyrau - 2.5 (3.4), Zhetysu - 2, 6, Zhambyl - 3.3 (2.7), Turkestan - 2.1 (1.6), Mangistau - 1.9 (1.2), Kyzylorda regions - 1.8 (2.1) - the lowest figure , and cities Almaty – 3.7 (4.3), Shymkent – 2.6 (2.1).

Colon cancer in the structure of causes of death from malignant neoplasms of the population of both sexes in 2022, as in 2021, ranks 6th, with a share of 5.2% (2021 – 5.0%). At the same time, the mortality rate in the country decreased by 5.6%, from 3.6 to 3.4 per 100 thousand population.

Mortality rates in 10 regions are higher than the national average: East Kazakhstan - 7.1 per 100 thousand population (2021 - 5.1) - maximum level, Pavlodar - 5.6 (6.0), Kostanay - 5.3 (5.6), Akmola – 5.2 (3.8), Abay – 5.1, Karaganda – 5.1 (5.6), West Kazakhstan – 4.8 (4.4), North Kazakhstan – 4.8 (5.0) regions and cities Astana – 3.6 (2.7), Almaty – 4.5 (5.3). Low mortality rates from colon cancer were noted in Kyzylorda - 1.2 per 100 thousand population (2.7) - the best result, Turkestan - 1.3 (1.7), Mangistau - 1.6 (2.6), Aktobe – 2.0 (2.5), Zhetysu – 2.4, Zhambyl – 2.5 (3.7), Atyrau – 2.5 (1.8), Almaty – 2.6 (1.8) regions and cities Astana – (2.7), Shymkent – (2.4).

For colon cancer (94.0%) - 100% verification level was achieved in 3 regions (Abay, Almaty

and Turkestan regions), high rates in the Astana city (98.5%), Shymkent city (98.0%), Zhambyl (98.4%), Atyrau (98.2%) regions, low – in Akmola region (86.7%), Almaty city (84.3%), in the Kyzylorda region (61.8%) – the worst result since 2017.

For rectal cancer (97.4%) - in 6 regions there is a 100% verification level, the worst level is still in the Kyzylorda region - 85.3%, lower than the republican average in the Akmola region - 92.6%, Aktobe region - 96 .8%, Mangystau region - 87.0%, Pavlodar region - 95.3%, Almaty city - 93.2% [5].

The frequency of diagnosis of stage I-II rectal cancer, as a visually accessible localization (68.9% - national average) in the regions, was: in Akmola - 34.6% - the worst result, as in 2021, in the country (2021 - 44.1%), Mangistau - 47.8%, Abay - 53.9%, West Kazakhstan - 59.1%, Almaty - 66.2%, Zhetysu - 68.6%, Karaganda - 65, 7% regions and Shymkent city - 62.9%.

For colon cancer (52.4%), early diagnosis rates are higher in Pavlodar (65.9% - best result), Abay, Aktobe, Atyrau, East Kazakhstan, Zhambyl, Zhetysu, Karaganda, Kostanay, Pavlodar, North Kazakhstan, Turkestan regions and Shymkent. The lowest figure (23.5%) is in the Kyzylorda region.

For colon cancer (17.3%), the rates of neglect at stage IV are higher - in Akmola - 31.0% - the worst result (2021 - 20.3%), Zhetysu - 27.3%, Abay - 23.1% , Turkestan - 22.2% (29.1%), Karaganda - 28.1% (28.6%), West Kazakhstan - 18.8% (8.2%), Mangistau - 17.6% (19 .4%) regions and cities Astana - 18.0% (22.9%), Shymkent - 20.0% (22.7%). The lowest level of neglect is 2.9% in the Kyzylorda region (7.9%).

The proportion of stage IV in rectal cancer (13.1%) is higher in Akmola - 29.6% - the worst result (2021 - 19.4%), Abay - 19.7%, Kyzylorda - 17.6% (9.1%), Karaganda - 16.9% (28.4%), Almaty - 15.6% (17.0%), Kostanay - 14.8% (11.1%), Zhambyl - 13.3 % (13.6%) regions and Shymkent city - 14.5% (12.5%). The lowest level of neglect - 6.0% - is in the Atyrau region (12.5%).

Late diagnosis of rectal cancer as a visually accessible localization (stages III-IV) in 2022 amounted to 31.1% (in 2021 - 33.5%).

For rectal cancer, the level of neglect is higher than the national average - 31.1%, the indicators in Akmola - 65.4% (2021 - 55.9%) - the worst result in the country, Mangistau - 52.2% (38.1%), Abay – 46.1% (30.6%), West Kazakhstan – 40.9% (25.4%), Karaganda – 34.3% (46.5%), Almaty – 33.8% (35.7 %), Zhetysu - 31.4% (34.1%) regions and Shymkent city - 37.1% (42.9%). The lowest neglect is in the Atyrau region - 12.0% (17.5%).

In the country as a whole in 2022, the five-year survival rate of patients with CRC registered in 2018 decreased to 40.4% (2021 - 52.9% for those registered in 2017); there is a significant dispersion of indicators by region, from maximum – 56.1% (47.5%) in the Kyzylorda region, to minimum – 24.3% (51.5%) in the Aktobe region [5].

Screening of CRC screening is the systematic use of screening studies in an asymptomatic population. The purpose of screening is to identify people with abnormalities suggestive of CRC. These persons in the future need additional examination to clarify the diagnosis. Opportunistic screening is the non-systematic use of screening tests in routine medical practice. A screening program is much more challenging than an early detection program. At the same time, the success of the screening program is largely determined by the awareness of the population and medical workers about the possibilities of early diagnosis of CRC. The feasibility of a screening program is determined by several factors that relate to the disease being screened, the screening test, the characteristics of the population, and the characteristics of the healthcare system.

The first factor is that the disease must be well understood, common enough in the target population to justify screening, have a recognizable early stage; treatment of the disease at an early stage should be more effective than at a later stage.

The second is that the test should be characterized by sufficient sensitivity, i.e. the ability to detect cancer among people with the disease; sufficient specificity - the probability that among people who do not have a disease, the test result will be negative; have a high positive predictive

value (positive predictive value) or, in other words, the likelihood that people with a positive test result have the disease; have a high predictive value of a negative result (negative predictive value), i.e. the likelihood that people with a negative test result do not have the disease; security; low cost; and acceptability - the likelihood that people for whom this test is intended will agree to the examination (which to some extent depends on the awareness of the population about the possibilities and importance of early diagnosis).

The third factor is that the healthcare system should be ready for maximum screening test coverage of the target group, have the resources to confirm the diagnosis, appropriate treatment and follow-up of people with positive test results, and regularly conduct screening tests at regular intervals. At the same time, the benefits of screening must outweigh the potential physical and psychological harm and justify the financial costs of its implementation [14].

The factors most significant for the development of CRC are:

- the presence of chronic inflammatory bowel diseases, adenomatous polyps, cancer of other localization, etc.;

- family history (presence of one or two first-degree relatives with CRC or familial diffuse intestinal polyposis);

- the age of men and women over 50 years old, taking into account the fact that more than 90% of patients with colorectal cancer are people of this age (medium risk).

Age, regardless of gender, is an important risk factor for CRC. After the age of 50, the incidence of CRC increases from 8 to 160 per 100,000 population. Thus, people who have reached the age of 50, even in the absence of symptoms, constitute a moderate risk group for CRC.

The second category of increased risk of CRC (20%) is made up of persons with a genetic and family predisposition, suffering from chronic inflammatory bowel diseases, diffuse familial polyposis.

The high-risk CRC group is determined by the so-called Amsterdam criteria (the presence of malignant tumors in two generations, the presence of cancer in a first-line relative under the age of 50 years), in this case, CRC screening should be carried out after the age of 30 years [15].

The degree of individual risk of developing CRC is determined before screening to select the scope of studies and the frequency of their conduct.

The interval for oncological colorectal screening is 1 time in 2 years, target group: men and women aged 50-70 years, with the exception of persons registered at the dispensary for CRC and colon polyposis. At the same time, when forming the target group, one should take into account the absence of severe concomitant diseases, such as the presence of a common malignant neoplasm, cerebrovascular diseases in the stage of decompensation, chronic obstructive pulmonary disease with respiratory failure, cirrhosis of the liver, myocardial infarction with congestive heart failure, diabetes mellitus with vascular complications. and others, which are highly likely to lead to death in the next 10 years.

The first step in screening for CRC is the fecal occult blood test (FOBT). Traditionally, such methods include a benzidine test for occult blood in the feces. This is a biochemical method based on the assessment of pseudoperoxidase activity of hemoglobin. There is ample evidence that invitation to guaiac FOBT screening (gFOBT) reduces CRC mortality by approximately 15% in age-matched average-risk populations.

To ensure the effectiveness of screening with gFOBT, the interval for screening under the national screening program should not exceed two years. To date, there is an immunochemical FOBT method - iFOBT, which is superior in efficiency to gFOBT in terms of the probability of detecting adenoma and cancer. iFOBT has improved analysis performance compared to gFOBT.

Immunochemical (immunochromatographic) examination of feces for occult blood - iFOBT or hemocult test is carried out for all men and women of the target group using an express method, which allows you to get a result within 3-5 minutes, without the participation of a medical

worker. However, the evaluation of the test is carried out only by a medical worker in the PHC preventive department.

With a positive analysis of feces for occult blood, the second stage of colorectal screening is performed, which consists in endoscopic examination of the colon - total colonoscopy [7]. At the same time, in this case, this medical manipulation is of a therapeutic and diagnostic nature, since it allows one-stage removal of adenomatous polyps, which, according to various authors, occur in every third subject after 50 years of age. At the same time, women have 20% fewer polyps than men, but they have more right-sided lesions, which are more difficult to detect using fecal blood tests, because they are less traumatic [16].

What results were obtained from screening for CRC? In 2022, 937,859 men and women of the target group aged 50 to 70 years were examined during colorectal screening (in 2021 - 920,640) [5].

Colorectal screening revealed 325 cases of colorectal cancer in the reporting year, which is 114 cases more than in the previous year (211 cases). The detection rate increased from 0.23 to 0.35 per 1000 patients examined. Low detection of colorectal cancer was noted in Zhambyl, Karaganda, Kostanay, Kyzylorda, Mangistau, Turkestan - the worst result, East Kazakhstan regions, Astana city - from 0.07 to 0.30 per 1000 examined. The best result is in the North Kazakhstan region – 0.81 per 1000 examined. Compared to 2021, there was a decrease in the detection of colorectal cancer per 1000 people examined during screening in Karaganda (from 0.22 to 0.21), Kostanay (from 0.29 to 0.28), Mangistau (from 0.20 to 0.12) regions and Astana city (from 0.20 to 0.19).

Colon precancer (adenoma detection rate) was detected in 27.5% of patients who underwent colonoscopy (2021 – 22.8%). The detection rate of precancer in Akmola, Aktobe, Almaty (8.5% is the worst result), West Kazakhstan, Zhambyl, Kostanay, Kyzylorda, Mangistau, Pavlodar, North Kazakhstan, Turkestan regions and cities is lower than the national average Astana and Shymkent. The best result is 36.2% in Almaty city. It should be noted that the planned indicator for the detection of precancer of the colon and rectum in the country for 2022, according to the Comprehensive Plan, was 23.0% and was achieved.

In 2022, the proportion of patients identified during screening studies with early stages of malignant neoplasms (stages 0-I) was 26.2% during colorectal screening (in 2021 - 27.5%).

High early detection of colorectal cancer (above 30%) was noted in Akmola, West Kazakhstan, Karaganda, Kostanay, Kyzylorda, Turkestan regions and Astana city (57.1% - the best result). Not a single case of early cancer has been identified in the Mangistau region. Cases of cancer in stages III-IV detected during screening were registered in Akmola, Aktobe, Almaty, West Kazakhstan, Zhambyl, Karaganda, Kostanay, Mangistau regions and Almaty city. A total of 21 cases of colorectal cancer in stage III and 3 in stage IV were identified (in 2021 - 18 and 5, respectively) [5].

The complex analysis carried out allows us to conclude that satisfactory results of cancer screening can be achieved only with its proper organization, high quality of implementation, active participation in population screening, the use of highly sensitive tests and instrumental methods of preventive examination, as well as subsequent accurate diagnosis of identified tumors and timely treatment. High-quality screening leads to early diagnosis of pedological diseases and malignant pathology in the early stages, which, in turn, increases the effectiveness of treatment and improves the prognosis of the disease. Target groups that, for one reason or another, do not participate in screening should be informed that there are no other methods other than screening that would reduce mortality from malignant neoplasms. Incidence and mortality rates from CC, BC and CRC clearly reflect the epidemiological situation with this pathology in the regions of our country.

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Astronomy

ALMA Band 8 деректері бойынша IRAS 07299-1651 массивті қосжұлдызды жүйесіндегі сутектің H25α рекомбинациялық сызығы

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Аңдатпа. Жұмыста түзілу сатысындағы IRAS 07299-1651 массивті қосжұлдызды жүйесінің ALMA обсерваториясының Band 8 диапазонындағы архивтік деректері талданды. Спектрлік кубтағы кең сызық сутектің H25α рекомбинациялық сызығы ретінде сәйкестендірілді; біздің білуімізше, бұл нысан үшін осы сызық бойынша нәтижелер бұрын жарияланбаған. Жүйенің негізгі құраушысы – A көзінің бағытында сызық профилі қос шыңды және бір Гаусс функциясымен сипатталмайды; екі құраушылы модель профильді едәуір жақсы сипаттайды, ал құраушылардың орта нүктесі басқа рекомбинациялық сызықтар бойынша анықталған A көзінің жылдамдығымен сәйкес келеді. Интегралдық интенсивтілік картасында ықшам көз байқалады; бақылаулардың ажыратымдылығы жүйенің A және B құраушыларын бөлуге жеткіліксіз. Сонымен қатар кубта екі сәйкестендірілмеген тар сызық табылды.

Түйін сөздер: массивті жұлдыздардың түзілуі, қосжұлдызды жүйелер, сутегі рекомбинациялық сызықтары, ALMA, IRAS 07299-1651.

Abstract. We analyse archival ALMA Band 8 data of the forming massive binary system IRAS 07299-1651. The broad line in the spectral cube is identified as the hydrogen recombination line H25α; to our knowledge, results in this line have not been reported for this object before. Towards the primary component, source A, the line profile is double-peaked and cannot be described by a single Gaussian; a two-component model fits it considerably better, and the mid-point of the components agrees with the velocity of source A derived from other recombination lines. The integrated-intensity map shows a compact source; the angular resolution is insufficient to separate components A and B. In addition, two unidentified narrow lines are detected in the cube.

Keywords: massive star formation, binary stars, hydrogen recombination lines, ALMA, IRAS 07299-1651.

1. Кіріспе

Массивті жұлдыздардың (M > 8 M⊙) басым бөлігі қосжұлдызды немесе еселі жүйелердің құрамына кіреді[1]. Қазіргі көзқарастар бойынша мұндай жүйелер массивті аккрециялық дискінің гравитациялық фрагментациясы нәтижесінде немесе бастапқыда өзара байланыспаған тығыз ядролардың жақындасып, гравитациялық тұрғыдан қармалуы арқылы пайда болуы мүмкін[2–4]. Бұл сценарийлерді түзілу сатысындағы жүйелерді тікелей бақылау арқылы ғана тексеруге болады.

IRAS 07299-1651 — қашықтығы 1,68 кпк болатын массивті протожұлдыздық нысан; ол SOFIA обсерваториясының SOMA шолуына енгізілген[5]. ALMA-ның 1,3 мм толқын ұзындығындағы жоғары ажыратымдылықты (0,035″) бақылаулары орталық көзді проекциялық арақашықтығы шамамен 180 а.б. болатын екі ықшам құраушыға — A және B көздеріне бөлді. H30α сызығы бойынша олардың сәулелік жылдамдықтары 15,5 ± 1,1 және 25,0 ± 1,6 км/с деп анықталды[6]. Кейінірек көпэпохалық бақылаулар жүйенің орбитасы параболалыққа жақын екенін көрсетті[4].

Сутектің миллиметрлік және субмиллиметрлік рекомбинациялық сызықтары жас массивті жұлдыздар маңындағы иондалған газдың кинематикасын зерттеудің тиімді құралы болып табылады[7]. Бас кванттық сан n кішірейген сайын сызықтың қысымдық (Штарк) кеңеюі шамамен $n^{7,4}$-ке пропорционал түрде азаяды[7], сондықтан жоғары жиілікті сызықтардың ені негізінен газ динамикасымен анықталады[6].

Жұмыстың мақсаты — ALMA Band 8 архивтік деректері бойынша IRAS 07299-1651 жүйесіндегі H25α сызығын сәйкестендіру, оның профилін сипаттау, нәтижелерді H30α сызығы бойынша алынған мәндермен салыстыру және сәулеленудің кеңістіктік таралуын зерттеу.

2. Бақылау деректері

Талдауға ALMA архивінен алынған 2018.1.01561.S жобасының Band 8 деректері пайдаланылды (бақылау күні 29.04.2019). ALMA-ның стандартты өңдеу конвейерімен құрылған, бастапқы диаграммаға түзетілген, континуумы алынып тасталған спектрлік куб қолданылды[8, 9]. Кубтың негізгі параметрлері 1-кестеде келтірілген. Синтезделген диаграмма H30α бақылауларындағыдан шамамен он есе үлкен, сондықтан арақашықтығы шамамен 0,11″ болатын A және B көздері бұл деректерде ажыратылмайды.

1 – кесте. ALMA Band 8 спектрлік кубының параметрлері

Параметр	Мәні
Жиілік аралығы (LSRK)	396,415–397,341 ГГц
Арналар саны / арна ені	238 / 3,907 МГц (≈ 2,95 км/с)
Синтезделген диаграмма	0,347″ × 0,268″, PA = 80,7°
Пиксел өлшемі / кескін өлшемі	0,05″ / 490 × 490 пиксел
Көз орнындағы шу	≈ 0,010 Jy/beam (бір арнаға)

3. Әдістер

Сутектің n+1 → n ауысу жиілігі келтірілген массаға түзетілген Ридберг формуласы бойынша есептелді[10]:

$$\nu_{n,n+1} = R_H\, c \left(\frac{1}{n^2} - \frac{1}{(n+1)^2}\right), \qquad R_H = \frac{R_\infty}{1 + m_e/m_p}$$

n = 25 үшін 396,9009 ГГц мәні алынды; ол файл тақырыбындағы тыныштық жиілігімен 0,02 км/с дәлдікпен сәйкес келеді. Сәулелік жылдамдық радиоастрономиялық анықтама бойынша есептелді: $V = c(1 - \nu/\nu_0)$.

Куб бастапқы диаграммаға түзетілгендіктен, шу өріс центрінен алыстаған сайын артады. Сондықтан әр арнадағы шу көзден 3–7,5″ қашықтықтағы сақина бойынша анықталып, сызықсыз арналар бойынша өлшенген орталық және сақиналық шулардың қатынасы арқылы көз орнына келтірілді. Момент 0 картасы −29…+57 км/с терезесіндегі арналардың қосындысы ретінде анықталды:

$$M_0 = \sum_{i=1}^{N} I_i\, \Delta v, \qquad \sigma_{M_0} = \sigma_{ch}\sqrt{N}\,\Delta v$$

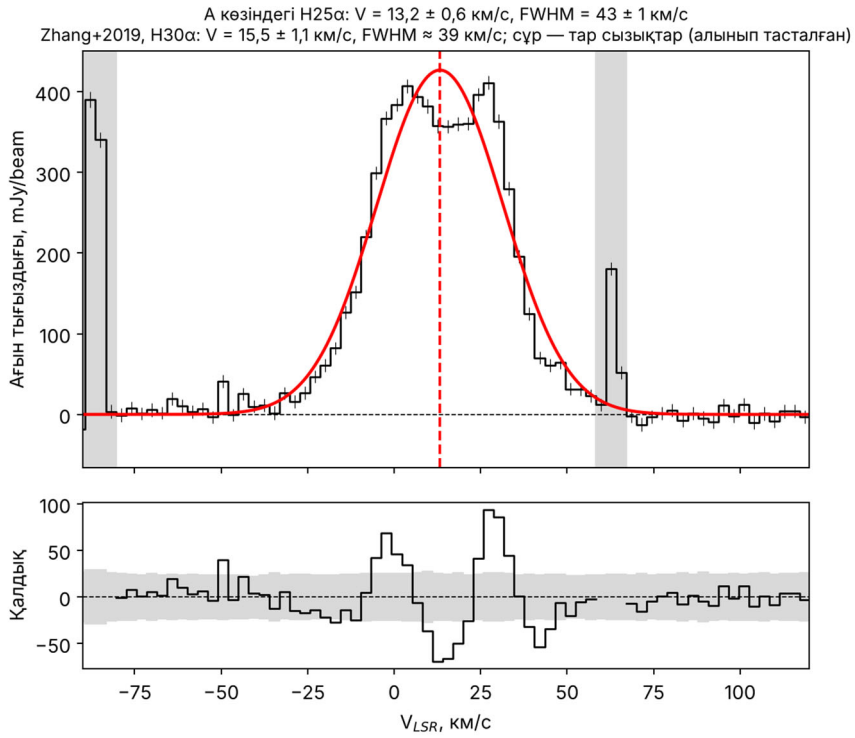
мұндағы I_i — арнадағы интенсивтілік, Δv — арна ені, N — арналар саны, σ_{ch} — бір арнадағы шу.

А көзі орнындағы спектр бір Гаусс функциясымен және екі Гаусс функциясының қосындысымен салмақталған ең кіші квадраттар әдісі арқылы аппроксимацияланды (SciPy кітапханасының curve_fit процедурасы)[11]. Аппроксимациядан тар сызықтардың арналары алынып тасталды. Параметрлердің қателіктері Монте-Карло әдісімен (500 іске асыру) бағаланып[6], $\sqrt{\chi^2_r}$ көбейткішіне көбейтілді. Деректерді өңдеу Python тілінде Astropy және SciPy кітапханаларының көмегімен жүргізілді[11, 12].

4. Нәтижелер және талқылау

4.1. А көзі орнындағы H25α профилі

А көзі орнындағы H25α сызығының шыңы шамамен 0,43 Jy/beam-ге тең, ал профилі кең әрі қос шыңды (1-сурет). Бір Гаусс функциясы V = 13,2 ± 0,6 км/с және FWHM = 43,1 ± 1,2 км/с мәндерін береді, алайда профильді қанағаттанарлық сипаттамайды: қалдықтарда шыңдарда оң, профиль центрінде теріс жүйелі құрылым байқалады ($\chi^2_r \approx 13$).

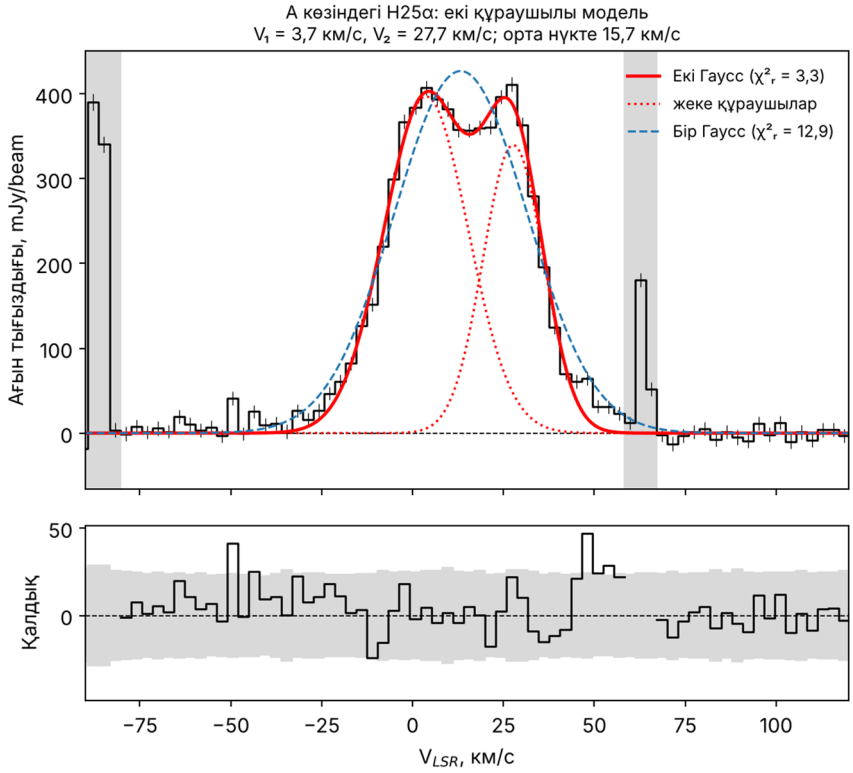


1 – сурет. А көзі орнындағы H25α спектрі және оның бір Гаусс функциясымен аппроксимациясы (қызыл қисық). Сұр жолақтар — аппроксимациядан алынып тасталған тар сызықтардың арналары. Төменгі панельде — қалдықтар, сұр аймақ ±3σ деңгейін көрсетеді.

Екі Гаусс функциясының қосындысы профильді едәуір жақсы сипаттайды ($\chi^2_r \approx 3{,}3$; 2-сурет, 2-кесте). Құраушылардың орта нүктесі (15,7 ± 0,7 км/с) H30α сызығы бойынша анықталған А көзінің жылдамдығымен (15,5 ± 1,1 км/с[6]) сәйкес келеді. Бір Гаусс моделінің центрі көк жаққа ығысқан, өйткені көк құраушы қызыл құраушыдан кеңірек. Wang және әріптестері осы көздің H26α профилінің де қос шыңды екенін көрсетіп, оны иондалған дискінің айналуымен немесе мазерлік күшеюмен байланыстырды[4]; H25α профилі бұл нәтижемен үйлеседі. Екі құраушылы модельдің қалдықтары сызық қанаттарында әлі де жүйелі құрылымды көрсетеді, сондықтан профильді толық модельдеу келесі жұмыстың міндеті болып табылады.

2 – кесте. А көзі орнындағы H25α профилін аппроксимациялау нәтижелері

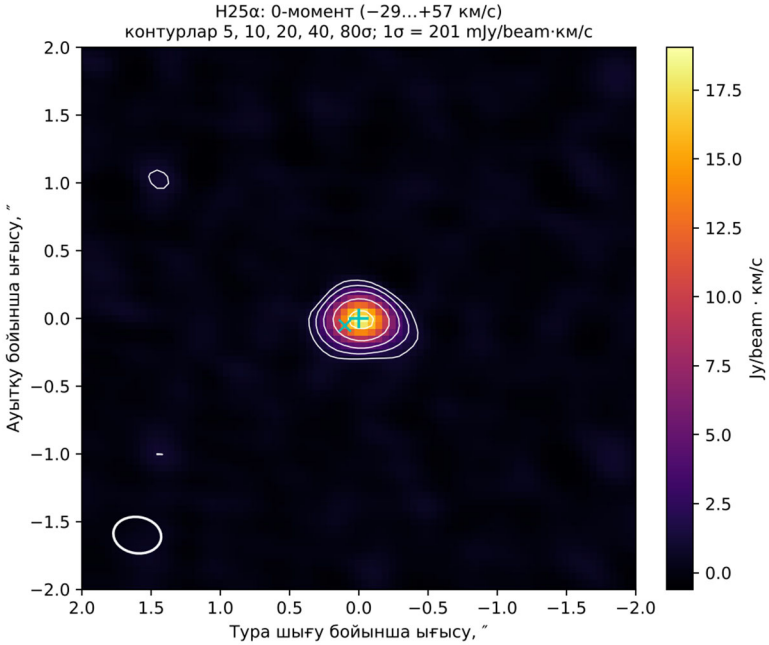
Модель	Шыңы, Jy/beam	V, км/с	FWHM, км/с	χ^2_r
Бір Гаусс	0,427	13,24 ± 0,56	43,1 ± 1,2	12,9
Екі Гаусс, 1-құраушы	0,397	3,70 ± 0,74	27,3 ± 1,3	3,32
Екі Гаусс, 2-құраушы	0,340	27,70 ± 0,60	19,6 ± 1,0	3,32



2 – сурет. Сол H25α спектрінің екі Гаусс функциясының қосындысымен аппроксимациясы. Нүктелі қисықтар — жеке құраушылар, көк үзік қисық — бір Гаусс моделі.

4.2. Момент 0 картасы

H25α сызығының момент 0 картасында (3-сурет) интегралдық интенсивтілігінің максимумы шамамен 19 Jy/beam·км/с болатын бір ықшам көз байқалады; сигнал/шу қатынасы шамамен 100. Максимум бір пиксел дәлдігімен А көзінің орнымен сәйкес келеді, ал В көзі синтезделген диаграмма шегінде жатыр. Сәулелену аймағы диаграммадан сәл ғана үлкен, яғни иондалған газ бұл деректерде әлсіз ажыратылған немесе ажыратылмаған.



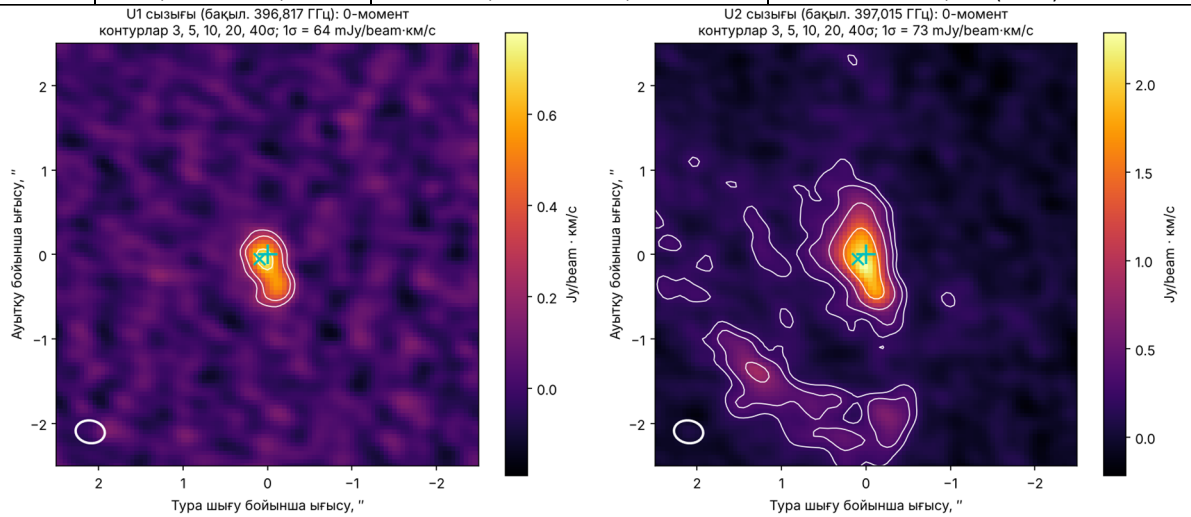
3 – сурет. H25α сызығының момент 0 картасы (−29…+57 км/с). Контурлар: 5, 10, 20, 40, 80σ. «+» — A көзі, «×» — B көзі[6]; эллипс — синтезделген диаграмма.

4.3. Тар сызықтар

Кубта H25α-ға жатпайтын, жылдамдық бойынша ажыратылмаған екі тар сызық бар (3-кесте, 4-сурет). U1 сызығының сәулеленуі ықшам және A көзінің маңында жатыр. U2 сызығы жарқынырақ және кеңістікте созылыңқы: ол солтүстік – оңтүстік бағытында созылған өзектен және көзден оңтүстік-шығысқа қарай 1,5–2″ қашықтықтағы әлсіз құрылымнан тұрады. Сызықтарды сәйкестендіру үшін олардың тыныштық жиіліктерін молекулалық каталогтармен салыстыру қажет.

3 – кесте. U1 және U2 тар сызықтарының параметрлері

Сызық	$\nu_{бақ}$ (LSRK), ГГц	ν_0 (V_{sys} = 16,5–18 км/с), ГГц	Момент 0 шыңы, Jy/beam·км/с
U1	396,8170 ± 0,0005	396,8389–396,8408	0,78 (13,8σ)
U2	397,0151 ± 0,0001	397,0369–397,0389	2,29 (33σ)



4 – сурет. U1 (сол жақта) және U2 (оң жақта) тар сызықтарының момент 0 карталары. Контурлар: 3, 5, 10, 20, 40σ. Белгілеулер 3-суреттегідей.

5. Қорытынды

ALMA Band 8 деректерінде IRAS 07299-1651 жүйесі бағытындағы кең сызық сутектің H25α рекомбинациялық сызығы ретінде сәйкестендірілді. A көзі бағытындағы профиль қос шыңды; ол бір Гаусс функциясына қарағанда екі құраушылы модельмен едәуір жақсы сипатталады, ал құраушылардың орта нүктесі H30α бойынша анықталған A көзінің жылдамдығымен сәйкес келеді. Момент 0 картасы A көзімен сәйкес келетін ықшам көзді көрсетеді; бұл ажыратымдылықта A және B құраушылары бөлінбейді. Кубта екі сәйкестендірілмеген тар сызық анықталды. Алынған нәтижелер жоғары жиілікті рекомбинациялық сызықтардың массивті протожұлдыздар маңындағы иондалған газды зерттеуге жарамды екенін көрсетеді.

Жұмыста ALMA-ның ADS/JAO.ALMA#2018.1.01561.S жобасының архивтік деректері пайдаланылды. ALMA — ESO, NSF (АҚШ), NINS (Жапония), NRC (Канада), NSTC және ASIAA (Тайвань), KASI (Корея Республикасы) серіктестігі, Чили Республикасының қатысуымен.

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Historical Sciences

THE MAIN DIRECTIONS OF SOCIO-ECONOMIC DEVELOPMENT OF LANKARAN CITY IN 2003-2006

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Abstract. The socio-economic development characteristics of Lankaran city in 2003–2006 are examined. Measures implemented in the framework of regional development policy, infrastructure renewal, state support for the agricultural sector, and improvement of the population's social conditions are investigated. The impact of state programmes on the socio-economic development of regions on the economic life of Lankaran city during the period under study is analysed. Particular attention is paid to measures aimed at developing the road transport system, public utilities, and social infrastructure facilities in the city. At the same time, the development of traditional agricultural sectors is examined. Special attention is given to the current state of citrus growing, tea cultivation, and vegetable production. The results of state policy aimed at increasing employment, creating new jobs, and expanding entrepreneurial activity are investigated. Changes in the activities of educational, healthcare, and cultural institutions are assessed as important indicators of the city's social development. The article also provides a historical assessment of the opportunities created by the economic and social measures implemented in 2003–2006 for the subsequent development of Lankaran.

Keywords: Lankaran, socio-economic development, regional policy, state programme, infrastructure, agricultural sector.

Introduction

Since the restoration of the country's state independence at the end of the 20th century, fundamental changes have taken place in the socio-political and socio-economic life of the Republic of Azerbaijan. Starting from 1993, the purposeful policy pursued by the President of the Republic of Azerbaijan, Mr. Heydar Aliyev, eliminated the political and economic crisis that had prevailed in the country during the first years of independence and paved the way for Azerbaijan's progress towards democratic state-building and a market economy [5]. Beginning in 2003, a number of socio-economic reforms were implemented in the Republic of Azerbaijan. The main directions of these reforms included accelerating regional development, making efficient use of local economic potential, and improving the social welfare of the population.

Lankaran stood out due to its favourable geographical location, agricultural potential, natural resources, and historical and cultural heritage. The years 2003–2006 can be considered a new stage in the socio-economic development of the city. During this period, regional policy was shaped and specific measures were implemented. Important steps taken during this period included making more efficient use of the region's economic opportunities, developing agriculture, and expanding production and service sectors. At the same time, the renewal of the city's infrastructure, improvement of the population's social welfare, and development of the cultural environment were among the main priorities of the state's regional policy. Thus, the

implemented measures laid a certain foundation for Lankaran's socio-economic development in subsequent years [2].

One of the important documents influencing Lankaran's socio-economic development during the period under study was the "State Programme on Poverty Reduction and Economic Development in the Republic of Azerbaijan for 2003–2005", approved by Decree No. 854 of the President of the Republic of Azerbaijan dated 20 February 2003. The programme focused primarily on expanding employment opportunities for the population. Poverty reduction and increasing economic activity were also among its important objectives. At the same time, strengthening social protection measures was envisaged. Particular attention was paid to the development of entrepreneurship in the regions. The expansion of small and medium-sized businesses was supported. The implementation of relevant measures to increase agricultural production and develop the processing sector was also planned. The measures implemented created favourable conditions for making broader use of Lankaran's economic potential. They had a positive impact on the creation of new jobs and the expansion of employment opportunities. In addition, they contributed to improving the income levels of the population. Thus, the State Programme played an important role in determining the priority directions of regional policy in the city's socio-economic development and increasing local economic activity [4].

The next important stage of regional development policy was associated with the "State Programme on the Socio-Economic Development of the Regions of the Republic of Azerbaijan (2004–2008)", approved by the Presidential Decree dated 11 February 2004. The main objective of the programme was to revitalise production in the regions, create new jobs, renew infrastructure, and support entrepreneurship. The main issues addressed in the document included the efficient use of the existing economic potential of the regions, stimulation of local production, and improvement of the living conditions of the population. In this regard, the implementation of the programme created additional opportunities for the development of agriculture, the processing industry, trade, and service sectors in Lankaran, laying the groundwork for increasing the city's economic activity [2]. The development of Lankaran's agricultural potential, production and processing of agricultural products, and support for local entrepreneurship were identified as important directions in the State Programme. In particular, tea cultivation, citrus fruit growing, and vegetable production maintained their traditional importance in the city's economic life.

The encyclopaedic publication jointly prepared by M.M. Talishli and E.A. Ahadov is one of the important sources of information for studying the socio-economic and cultural development of Lankaran city. The work contains information about the city's history, economic life, social infrastructure, cultural and educational institutions, as well as prominent personalities [1, p. 125].

On 14 September 2005, by Order No. 1001 of the President of the Republic of Azerbaijan, an additional action plan aimed at accelerating the socio-economic development of Lankaran city and other administrative territories of the southern region was approved. The document envisaged measures to eliminate existing infrastructure problems and improve electricity and water supply systems. At the same time, strengthening the material and technical facilities of healthcare and educational institutions, stimulating entrepreneurial activity, and supporting its development were among the main objectives. These measures were of great importance in terms of improving the daily living conditions of the population in the region, enhancing the quality of social services, and increasing economic activity. In particular, the renewal of utility infrastructure and expansion of the operational capacities of social facilities in Lankaran created favourable conditions for the city's subsequent development [3].

Infrastructure issues played an important role in the socio-economic development of Lankaran during 2003–2006. Improving the city's public utility services, renovating highways, and

upgrading electricity and water supply systems were among the main directions of regional development policy.

State programmes also included measures aimed at expanding the material and technical capabilities of the Lankaran Regional Agricultural Research Centre, developing the activities of the Lankaran Seaport, and improving tourism infrastructure. In this regard, the restoration of the Circular Fortress building, as well as the establishment of a tourism information and handicrafts centre there, was of particular importance among the planned projects. This initiative served not only to preserve Lankaran's historical and cultural heritage but also to expand its tourism opportunities [2].

Improving the social welfare of the population, enhancing housing and living conditions, and improving the activities of healthcare and educational institutions were among the main priorities of state policy. At the same time, increasing support for socially vulnerable groups of the population and ensuring access to social services remained in focus. Thus, the measures implemented were aimed not only at developing Lankaran's economic potential but also at improving the quality of social life in the city.

Conclusion

The years 2003–2006 are characterised as a stage in the formation and implementation of a new regional development strategy in terms of the socio-economic development of Lankaran city. The state programmes and normative documents adopted during these years created an important institutional basis for expanding the city's economic opportunities, renewing infrastructure, and supporting agriculture. At the same time, these documents created favourable conditions for the development of social sectors. The measures implemented during this period had a positive impact on promoting local production, revitalising entrepreneurial activity, and increasing employment opportunities for the population. At the same time, the attention given to education, healthcare, public utilities, and tourism contributed to certain changes in the city's social life. The preservation of Lankaran's historical and cultural heritage and the development of its tourism potential also became one of the important directions of regional policy. Furthermore, the implementation of the planned measures was aimed at gradually addressing the existing economic and social problems of the city. Thus, the development directions established during 2003–2006 laid the initial foundation for the changes that took place in Lankaran's socio-economic and cultural life in subsequent years.

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Philological Sciences

Terminological Accuracy and Quality Challenges in AI-Assisted Technical Translation: A Critical Review

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Abstract
The growing use of neural machine translation and large language models has expanded the possibilities of translating technical and other specialised documents. Yet the grammatical fluency of an automatically generated text does not necessarily establish the accuracy of its domain-specific terminology. This article critically reviews recent research on terminology management and translation quality in AI-assisted technical translation. Drawing on a focused selection of studies published between 2024 and 2026, it distinguishes terminological correctness from broader semantic accuracy, examines the roles of domain context and validated linguistic resources, and considers the limits of model-generated assurances. Rather than proposing or testing a new translation system, the article develops an analytical basis for a compact, terminology-centred quality-assessment framework. The evidence indicates that models can assist with identifying and translating specialist terms, but the reliability of their outputs depends on the domain, translation task and independent verification. The review proposes a five-part assessment framework addressing concept–term equivalence, contextual suitability, documentary consistency, semantic relations and the integrity of technical data and instructions. This framework is a synthesis-based proposal, not an experimentally validated measurement instrument.
Keywords: artificial intelligence; technical translation; large language models; terminology management; translation quality; specialised translation

1. Introduction

Artificial intelligence (AI) is increasingly incorporated into the production of multilingual technical information. Neural machine translation (NMT) systems and large language models (LLMs) can generate complete draft translations, propose equivalents for unfamiliar terms and revise passages in response to instructions. These capabilities are useful in contexts in which organisations must communicate technical information across languages, including software documentation, equipment instructions and engineering materials. However, practical convenience should not be confused with the ability to reproduce specialised meaning without error.

Unlike general conversational texts, technical documents are written within particular systems of knowledge. Their terms frequently name defined processes, components, measurements or relations. An apparently minor lexical substitution may alter the description of a procedure or the identity of a component. Moreover, technical writing often depends on consistency: the same designation may recur in a sequence of instructions, a diagram and a troubleshooting section. A translation that varies these designations without justification can become difficult to follow even when individual sentences appear fluent.

Recent empirical research makes this distinction particularly relevant. Minder, Wisniewski and Kübler (2026) evaluated LLM-generated English-to-French equivalents in two specialised fields and concluded that such models can assist terminological research but cannot simply replace specialised corpora. In a separate multilingual study, Oncevay et al. (2025) documented challenges in translating domain-specific tax and financial terminology and investigated the contribution of terminology-aided translation. Although the latter study is not an experiment on engineering manuals, it provides comparative evidence that term-level accuracy deserves separate attention alongside broader translation quality. These studies move the discussion beyond the general question of whether AI can produce readable translations.

The present article examines three closely related issues: the reliability of specialist term equivalents, the influence of context and terminology resources, and the suitability of quality-assessment criteria for AI-assisted technical translation. Its principal research question is: **According to recent research, which factors most strongly limit terminological accuracy and translation quality in AI-assisted technical translation?** Two subsidiary questions guide the analysis: **(1)** Which recurring problems arise in the identification and use of technical terms? **(2)** Which verification practices and terminology-aware approaches are supported by the available evidence?

This focused critical review does not experimentally evaluate any AI system. Its contribution is a practical assessment proposal based on a transparent comparison of recent studies.

2. Conceptual Framework

2.1. Technical translation and specialised terminology

Technical translation can be understood as a subset of specialised translation concerned with texts that communicate knowledge or instructions within technological and scientific practices. It differs from some other forms of specialised translation in its emphasis on operational descriptions, named components and relationships between procedures. The relevant distinction is not that technical language lacks ambiguity, but that acceptable equivalents must be evaluated in relation to a specific conceptual system and communicative purpose.

A term is therefore more than an isolated word that can be replaced by a dictionary entry. Its meaning depends on the field in which it is used. Minder et al. (2026), for example, note that the English word *cloud* can denote different concepts in Earth sciences and computer science. The illustration is simple, yet it captures a central risk in AI-supported terminology work: a generally plausible equivalent may refer to the wrong technical concept. Correct terminology requires identifying the intended concept before selecting its target-language designation.

Terminological accuracy must also be distinguished from terminological consistency. Accuracy concerns whether a target term correctly represents the concept expressed by the source. Consistency concerns whether the document uses compatible designations for that concept, especially when the terminology has already been specified by the client or a reference document. A consistently repeated error remains inaccurate; conversely, more than one correct designation may sometimes be acceptable if variation is justified by the context. These distinctions prevent an overly mechanical understanding of translation quality.

2.2. AI translation, fluency and semantic adequacy

NMT and LLM-based translation should not be treated as identical technologies. NMT systems are generally developed for translation tasks, whereas general-purpose LLMs can also be prompted to explain terminology, compare alternatives and revise a previously generated translation. Their different training procedures and interfaces create different possibilities for incorporating contextual information. The existence of these functions, however, does not guarantee a correct specialised output.

At least three levels of evaluation should be kept separate. The first is **linguistic well-formedness**: is the target text grammatical and readable? The second is **semantic accuracy**: does it preserve the relevant information and relationships in the source? The third is **terminological appropriateness**: does it use accepted terms for the intended concepts and domain? A translation may perform well on one level and poorly on another. For instance, a fluent target sentence may describe a technically different operation because one specialised term was misinterpreted. In that case, stylistic improvement alone will not correct the principal problem.

This separation is consistent with the Multidimensional Quality Metrics (MQM) approach to translation assessment. The MQM Council's current error typology distinguishes Terminology, Accuracy and Linguistic Conventions, as well as other dimensions relevant to translation specifications (MQM Council, n.d.). For the purposes of the present review, these dimensions provide an established vocabulary rather than a new scoring system. The aim is not to apply every MQM category, but to identify the small subset most useful for technical translation. A targeted assessment is preferable to an elaborate list of criteria that cannot be applied consistently.

2.3. Terminological resources and independent verification

Specialised translators have traditionally relied on domain-specific corpora, termbases, technical dictionaries and parallel documentation. Such resources allow them to check whether an equivalent is attested within the relevant field, whether it carries the intended meaning and whether its use is compatible with the document's conventions. AI systems add another route to terminology research, but they do not eliminate the difference between a suggested answer and a verified one.

This distinction is reinforced by Minder et al. (2026). The authors compared four LLMs across 160 English terms drawn from two specialist domains, using both terminology-oriented and translation-oriented prompts. Performance varied by model and task configuration. Importantly, model-reported confidence did not function as a dependable substitute for checking the proposed terms. In an additional experiment, asking a model to supply scientific sources did not ensure trustworthy documentary support: the authors reported invented references and example sentences. Their results caution against treating fluent explanations or confident assurances as independent evidence.

A practical implication follows. When a technical equivalent matters to the accuracy of a document, the verification process should identify the underlying concept and compare the suggested designation with an authoritative resource. Such a resource may be a project-approved termbase, an appropriate technical standard or a reliable field-specific corpus. A model's own explanation may help a translator formulate a search query, but it should not be counted as external validation merely because it resembles a citation.

3. Method and Scope of the Review

This article uses a **focused critical narrative review**. It is not a systematic review or a meta-analysis, and it does not claim to exhaust all research on AI translation. The starting set consists of selected academic studies published in 2024–2026 whose research questions bear directly on specialised terminology, terminology-aware translation or the evaluation and revision of translated texts. Conference papers from the Association for Computational Linguistics and the European Association for Machine Translation, together with a journal study on engineering terminology, form the principal research base. MQM documentation serves as a separate evaluation reference.

The selection is purposive rather than statistically representative. Priority is given to studies that report a concrete procedure, identifiable languages or subject areas, and results relevant to terminological accuracy. Engineering, computer science and other technical fields are considered directly relevant. Research on tax and financial terminology is included as adjacent evidence about domain specificity; its findings are not assumed to apply automatically to engineering translation.

Similarly, a study on AI-generated terminology assessment questions is treated as evidence about the reliability of an assessment tool, not as a direct measurement of machine-translated engineering documents.

The analysis follows four questions for each study: What translation-related task was evaluated? Which languages and domains were involved? What did the study show about terminology or quality? What limits the transfer of its findings to technical translation practice? Results are compared qualitatively. Since the research designs, language pairs and evaluation measures differ, the review will not combine their reported scores into a single effectiveness estimate. The proposed assessment framework is therefore grounded in recurring problems and carefully qualified implications.

4. Evidence from Recent Research

4.1. Domain-specific terminology as a distinct quality problem

Minder et al. (2026) provide direct evidence about terminology search with LLMs. Their comparison covered English-to-French equivalents for 80 terms in Earth, Environmental and Planetary Sciences and 80 terms in natural language processing. Four models were tested under two task formulations. The authors found meaningful variation between models and prompting approaches; no single prompting strategy was optimal across all systems. Their conclusion was neither that LLMs were unusable nor that they were adequate replacements for corpora. Rather, they could offer useful terminological support while requiring independent documentation and contextual judgment.

A complementary perspective emerges from Oncevay et al. (2025). Their study assembled a multilingual reference resource for tax and financial education, annotating over 3,000 terms and comparing machine translation systems and LLMs. The researchers showed that specialised terms could behave differently from more general vocabulary and that terminology-aided prompts offered benefits under some conditions. These results are particularly informative because the research used curated governmental publications to construct the terminology resource. The verified resource made it possible to assess term-level choices instead of inferring correctness from the naturalness of the surrounding sentence.

The studies differ considerably: Minder et al. concentrate on bilingual term-equivalent retrieval in two scientific and technological fields, whereas Oncevay et al. examine multilingual translation and term accuracy in tax and financial education. Their findings should therefore not be treated as interchangeable measurements. Their shared implication is narrower and stronger: specialised terminology is a distinct object of evaluation, and model performance must be interpreted in relation to the domain, language pair and translation task. This conclusion provides the initial basis for the quality-assessment framework proposed in Section 6.

4.2. Engineering terminology and the limits of plausible answers

The English-to-Turkish engineering study by Sánchez-Torrón, Ipek and Raído (2025) investigates a related but different problem: whether GPT-4 can generate assessment questions that reliably test a translator's recognition of terminological correspondences. Five sets of twenty multiple-choice questions were reviewed by a domain-experienced translator. The authors found that 38% of the final generated items contained cognates, which could make the right answer guessable without a demonstration of technical knowledge. Some items also offered more than one defensible correct answer. The study concluded that the automatically constructed tests required further refinement before professional use.

These findings should not be presented as a direct error rate for GPT-4 translations. The task was test construction, not the translation of whole engineering documents. Nevertheless, the study reveals an important evaluation problem: an apparently valid terminological decision may be supported by a weak or ambiguous test. If a machine-generated questionnaire mistakes several acceptable terms for a single exclusive answer, it may penalise competent translators or give an

overly favourable impression of a model's ability. The reviewer must therefore check not only translation outputs but also the reference answers and evaluation instruments used to judge them.

4.3. The trade-off between terminology constraints and contextual adequacy

Terminology management appears simple when represented as a rule that every source term must be replaced by a predetermined target expression. In real documents, however, the rule interacts with inflection, grammatical constructions, word sense and the organisation of information. A translation may preserve the exact approved word form yet become unnatural or semantically misleading in a particular context. Conversely, variation from a preferred form may sometimes be linguistically justified without changing the underlying concept. The evaluation must distinguish a legitimate contextual adaptation from a failure to apply mandatory project terminology.

Jaswal (2025) provides evidence of this tension through DuTerm, a two-stage system combining terminology-aware neural machine translation with LLM-based post-editing. Evaluated in the WMT 2025 Terminology Shared Task for English-to-German, English-to-Spanish and English-to-Russian translation, the approach examined how a later refinement stage could incorporate terminological guidance. The reported comparison favoured more flexible, context-sensitive treatment over rigid enforcement in the tested settings. The point is not that terminological standards should be abandoned; rather, the usefulness of a term constraint depends on how it is interpreted alongside the communicative meaning of the passage.

The results from Oncevay et al. (2025) complement this argument. Their use of curated terminology made it possible to study how domain-specific terms behaved within contextual translation. Such resources supply evidence that an LLM alone may not reliably retrieve, but the model still has to integrate the proposed term into an appropriate target sentence. These studies therefore suggest a two-part task: concept verification establishes which target designations are admissible, while contextual review determines whether a selected designation functions correctly in the actual passage. Neither component replaces the other.

An important boundary follows. A glossary is not necessarily a list of optional recommendations. Contracts, interfaces or standardised industrial documents may prescribe exact strings. In such cases terminological compliance is itself part of the translation specification, and a fluent paraphrase may be unacceptable. In other settings, a single enforced equivalent may distort the meaning of a polysemous expression. The correct assessment decision should therefore be based on the status of the resource: normative, project-approved or merely descriptive. Without this distinction, 'terminology accuracy' risks becoming an arbitrary preference for one wording.

4.4. Quality control through human feedback and targeted revision

Research on post-editing is relevant to terminology even when its principal objective is to improve complete translation segments. Berger, Riezler, Exel and Huck (2024) examined an approach in which a human translator first marks errors and an LLM is then prompted with relevant examples retrieved from a post-edited translation memory. The study concerns technical-domain translation and reports improvements over the automatic post-editing baselines tested. Its notable feature is the division of labour: the human provides focused error information, while the model undertakes a bounded corrective task. The findings do not establish that every human–AI workflow will be better than direct translation, but they illustrate why identifying the defect can matter as much as producing a new sentence.

Koneru et al. (2024) similarly explored LLMs as automatic post-editors at sentence and document level. Their study shows the importance of context spanning multiple segments and examines how earlier human corrections can inform later revisions. This matters particularly in manuals and specifications, where terminology and references are distributed across a whole

document. A translation that is adequate as an isolated sentence may be inconsistent with headings, captions, previous definitions or later instructions. Document-level checking should accordingly include repeated concepts, references between sections and the preservation of relations beyond a single segment.

A newer system described by Wang and Wu (2026) makes error diagnosis and repair separate tasks. The system first produces structured MQM-style assessments and then performs constrained edits targeted at diagnosed spans. Across the conditions tested, the authors reported gains over one-stage refinement baselines. The study supports an important procedural principle: editing should respond to an identified problem rather than replace the source-faithful draft with an unrestricted paraphrase. This principle is especially relevant when technical terms, measurements or conditional instructions could be changed accidentally during stylistic revision.

The professional setting considered by Nunziatini and Speroni (2026) provides complementary evidence about retrieval-supported AI post-editing. Their evaluation included 71,262 production segments across five domains and translation from English into ten target languages; 6,618 segments were also assessed by professional translators. Using quality-controlled bilingual examples and style guidance, the tested AI post-editing configurations performed better than the generic baselines reported in the study. These results illustrate the possible value of structured reference materials, although the experiment does not identify a universal workflow for every technical field or language pair. The evidence is more appropriately read as showing the benefits of a particular integrated system under defined professional conditions.

4.5. Translation quality is broader than error correction

A final qualification is needed: correct terminology and sufficient semantic accuracy are essential, but they are not equivalent to the entire quality of a technical text. Local conventions, interface restrictions, consistent formatting, readability for the intended reader and the stability of repeated instructions may also matter. The MQM Council's typology explicitly distinguishes such dimensions rather than collapsing them into a general statement that a translation is 'good' or 'bad' (MQM Council, n.d.). This distinction allows an evaluator to report that a translation is grammatically acceptable but terminologically incorrect, or terminologically correct but unsuitable for a particular use.

Volkart and Bouillon (2024) add another caution. Comparing human translation with post-edited machine translation in professional settings, they observed lower lexical diversity in the post-edited material and a greater tendency to reflect source-language syntactic structure. Their evidence concerns English-to-French and German-to-French datasets rather than an engineering-specific experiment. It nevertheless reminds reviewers that removing visible errors does not automatically make a machine-generated text indistinguishable from a human translation. In technical communication, controlled repetition may be desirable, so reduced lexical diversity is not itself proof of poor quality. The relevance of the finding is methodological: quality measures must be interpreted in the light of genre and purpose.

5. Critical Synthesis of the Literature

5.1. What the studies support—and what they do not

The studies reviewed here converge on a limited but significant proposition: specialised terminology is difficult to assess through sentence fluency alone, and reference information can materially influence the reliability of translation and revision. Their methods, however, differ. Minder et al. (2026) evaluated proposed equivalents for isolated terms; Oncevay et al. (2025) examined domain-specific terminology within multilingual translation; Sánchez-Torrón et al. (2025) evaluated model-generated competence tests; and Jaswal (2025) tested a translation architecture with terminological guidance. The post-editing studies, by contrast, focus on changing

existing translations. Combining the numerical results from these experiments would imply a comparability that the designs do not establish.

The studies also vary in what counts as success. Some emphasise term accuracy, others evaluate sentence or document metrics, and still others use expert judgements or task-specific assessments. Automatic metrics are useful for monitoring systems at scale, but they cannot independently establish whether the name of an industrial component is correct under a particular standard. Likewise, a human rating is meaningful only if the evaluator has sufficient source-language understanding and the necessary domain expertise. This review therefore treats the studies as complementary observations rather than as entries in a single ranking of models.

A second point concerns the role of the technical domain itself. The meaning of terms is institutional as well as linguistic: the accepted form may be defined by a regulatory document, a manufacturer's specifications or an internal termbase. A study conducted on financial terminology cannot establish the accuracy of electrical-engineering translations; a test built for English–Turkish cannot establish results for Persian–Azerbaijani. Evidence may justify an assessment principle across contexts, but its observed effectiveness must be tested again where the languages, topics or working conditions change.

5.2. Three complementary sources of evidence

The reviewed research points to three kinds of evidence that should be kept apart. **Source-text evidence** concerns what the technical passage actually says, including negation, modality, quantities and relations between components. **Terminological evidence** concerns whether the target expression represents an accepted concept in the relevant field. **Documentary evidence** concerns how a choice is supported by an external standard, a reliable corpus, manufacturer documentation or an approved glossary. A well-formed translation must satisfy source-text evidence; a terminologically trustworthy translation must also withstand the other two checks when they are material to the assignment.

6. A Compact Terminology-Centred Assessment Framework

6.1. Purpose and status of the proposal

On the basis of the synthesis, this article proposes a five-part assessment matrix for small and medium technical-translation assignments. The proposal is an **analytical adaptation**, not a newly validated metric. It draws on MQM distinctions and the practical problems described in the reviewed studies, but it has not been tested through an original corpus experiment. Its value lies in turning broad quality categories into a sequence of decisions that a translator or reviewer can document without advanced computational infrastructure.

The framework applies to an AI-generated draft, whether produced by a specialised MT system or an LLM. Before evaluation, the reviewer should establish the text's subject area, intended user, language pair and any binding terminology instructions. Where a technical specialist is needed to decide between competing equivalents, the reviewer should seek appropriate domain expertise rather than rely on a model's self-reported confidence. A project may also require additional checks outside the present framework, including confidentiality, formatting or formal regulatory compliance.

Assessment dimension	Diagnostic question	Minimum verification procedure
1. Concept–term equivalence	Does the target term identify the same specialist concept?	Compare with an approved termbase, standard or field-specific reference.
2. Contextual suitability	Is this term appropriate for the process, component and sentence in which it appears?	Read the source and target in context; inspect related definitions and usage.
3. Documentary consistency	Are repeated terms handled coherently throughout the document?	Compare recurring expressions with the glossary and earlier approved segments.
4. Semantic relations	Are actions, conditions, negations and technical relations preserved?	Perform source–target checks on meaning, not only on matching terms.
5. Data and instruction integrity	Are quantities, units, identifiers and procedural constraints retained accurately?	Check numbers, symbols, commands and potentially consequential instructions.

The matrix deliberately differentiates a term problem from a broader content problem. The first three dimensions focus on terminology; the fourth and fifth focus on technical meaning and instructions. These distinctions are compatible with MQM's separate categories of Terminology and Accuracy, but the five-part grouping is proposed for the purposes of this article. A project may need a different set of dimensions depending on its risks.

6.2. A simple decision procedure

A compact review can follow four actions. First, extract terms and identify material instructions or figures that must remain invariant. Second, compare the AI draft against the source and the available validated references. Third, record a brief explanation for each substantive problem, specifying the relevant dimension of the matrix. Fourth, correct the problems and recheck the affected sentences and repeated occurrences. This sequence discourages silent acceptance of suggestions that lack documentary support and makes later review more reproducible.

Severity should be determined by consequences rather than by the number of characters changed. Confusing two similarly named parts, changing a unit, deleting a negation or weakening an obligatory instruction may be more serious than multiple surface-level grammatical defects. For a low-risk glossary exercise, a terminology discrepancy may require a note; for equipment operation or safety-related documentation, it may require escalation to a responsible specialist. The present framework does not assign numerical risk weights because the reviewed studies do not provide a shared empirical basis for such weights. This is an intentional limitation, not an omission.

The proposal also separates **correction** from **verification**. If an LLM is asked to replace a term after receiving a human error marking, the revised sentence is still a candidate translation. It should be checked against the source and the authoritative terminology resource. The fact that a model obeyed the prompt is not proof that the corrected result is accurate. That distinction is

consistent with the caution expressed by Minder et al. (2026) concerning model confidence and by Berger et al. (2024) concerning targeted human-guided corrections.

7. Discussion: Implications and Limitations

The synthesis suggests that practical AI-assisted technical translation should be organised around evidence quality rather than unrestricted generation. Language models may reduce the effort needed to produce an initial draft, explore alternative equivalents or revise identifiable defects. Their usefulness is conditional on the translator's ability to recognise the technical concept, select relevant supporting documents and assess whether revision actually improves the result. This view does not reduce the professional translator to a grammatical proofreader; it locates expertise in interpretation, verification and accountable decision-making.

For organisations, the proposed matrix can guide terminology preparation, specialist review and documentation of consequential corrections. These are practical implications inferred from the literature, not results of an evaluated deployment.

The review has several limitations. Its literature selection is focused and purposive, not exhaustive; the evidence is drawn largely from studies published between 2024 and 2026. The included research involves different domains, models, language pairs and metrics, so the article cannot produce a general comparative success rate. The assessment matrix is conceptual and has not been subjected to inter-annotator agreement testing, an error-coding trial or a controlled comparison with existing professional workflows. Furthermore, the article does not measure productivity, cost or the environmental burden of AI-based translation. These issues could change the practical value of any recommendation in particular settings.

Future work could test this framework with independent reviewers and technical reference texts, including language pairs with limited terminology resources.

8. Conclusion

Recent research does not support judging AI-assisted technical translation primarily by its fluency. Studies of specialised terminology, terminology-aware translation and post-editing show that the appropriateness of term choices depends on domain knowledge, textual context and credible reference material. Some AI systems and revision workflows perform well under specified conditions; those achievements do not remove the need to verify conceptual equivalence or preserve the technical relationships expressed by the source.

This article has identified five connected dimensions for a compact assessment: concept–term equivalence, contextual suitability, documentary consistency, semantic relations and data/instruction integrity. The proposed matrix is derived from a critical synthesis of existing literature and adapted to technical-translation practice; it is not presented as an experimentally validated scoring model. Its principal contribution is a clear distinction between a plausible AI suggestion, an accepted technical equivalent and a documented verification decision. For translation professionals and educators, that distinction offers a manageable basis for using AI tools while retaining responsibility for specialist accuracy.

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Technical Sciences

AIR-ENTRAINING AND ANTIFREEZE ADMIXTURES IN NORMAL-WEIGHT CONCRETE FOR SHARPLY CONTINENTAL CLIMATES: A REVIEW

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Abstract. This paper reviews research on the effect of air-entraining and antifreeze admixtures on the frost resistance and physical-mechanical properties of normal-weight concrete. Fundamental studies, recent peer-reviewed experimental and review papers, and the standards in force in Kazakhstan were analysed. The review covers the mechanisms of frost damage (hydraulic pressure, osmotic pressure and the critical degree of saturation), the parameters of the entrained air-void system, the classification and limitations of antifreeze admixtures, and the available data on their combined use. Air entrainment is effective when the spacing factor does not exceed 0.20 mm, at the cost of roughly 5 % compressive strength loss per 1 % of entrained air; a recent meta-analysis found no correlation between the chemistry of the air-entraining agent and air-void parameters, which shifts the emphasis to construction practice. Antifreeze admixtures allow strength gain at temperatures down to −15…−25 °C, and chloride-free compositions are now preferred. In laboratory studies calcium nitrate (6 % by mass of cement) reduced the strength loss of fresh concrete after 28 freeze–thaw cycles from 72 % to 27.8 %. The available evidence on combined use is limited: chloride-free antifreeze admixtures were found compatible with air entrainment, but sodium salts alter the air-void structure in opposite directions depending on the salt. Four research gaps are identified, and an experimental programme is proposed for the sharply continental climate of Kazakhstan.

Keywords: normal-weight concrete, frost resistance, air-entraining admixture, antifreeze admixture, spacing factor, cold weather concreting, calcium nitrate.

1 INTRODUCTION

Most of the territory of Kazakhstan has a sharply continental climate with long, cold winters and frequent temperature transitions through 0 °C in spring and autumn [1]. These conditions place two conflicting demands on concrete. During construction it must set and gain strength at low or sub-zero temperatures; in service it must withstand repeated freezing and thawing without losing load-bearing capacity. Recent work on repaired concrete infrastructure in severe continental climates confirms that freeze–thaw exposure governs the long-term performance of concrete in the region [2].

Frost damage of concrete is attributed mainly to the pressure generated when water freezes in the capillary pores of the cement paste [3, 4]. The most widely used remedy is air entrainment: an air-entraining admixture creates a system of small, closed air voids that act as a reserve volume for the displaced water [5, 6]. However, each percent of entrained air reduces compressive strength by about 4–6 % [6, 7], so the dosage must be optimised.

Antifreeze admixtures address a different problem: they lower the freezing point of the liquid phase and accelerate cement hydration, which allows concrete to gain strength in winter [8, 9]. The action of each type of admixture is well documented [8, 10, 11]. Much less is known about their combined use with local raw materials: whether the accelerating effect of an antifreeze admixture compensates the strength loss caused by air entrainment, and how the combination affects the air-void system.

The aim of this review is to summarise the evidence on the effect of air-entraining and antifreeze admixtures on the properties of normal-weight concrete, including their combined use, and to identify the open questions relevant to the conditions of Kazakhstan.

2 MATERIALS AND METHODS

The literature search was carried out in ScienceDirect, Google Scholar, the American Concrete Institute (ACI) abstracts portal, eLIBRARY.RU and CyberLeninka. The search terms were “air-entraining admixture”, “antifreeze admixture”, “freeze-thaw resistance”, “cold weather concreting” and their Russian equivalents (“воздухововлекающая добавка”, “противоморозная добавка”, “морозостойкость бетона”).

Three groups of sources were included: (i) fundamental works on the theory of frost resistance and winter concreting (1945–1995); (ii) experimental and review papers in peer-reviewed journals (2013–2026); and (iii) standards and codes in force in the Republic of Kazakhstan, together with ACI guides for comparison. Priority was given to studies reporting quantitative data on admixture dosage, strength and frost resistance. Sources were grouped by topic and compared with respect to mechanisms, reported effects and limitations.

3 RESULTS AND DISCUSSION

3.1 Mechanisms of frost damage

When water turns into ice its volume increases by about 9 %, and unfrozen water is expelled from the freezing zone.

Powers proposed the **hydraulic pressure** hypothesis [3]. Expelled water flows through the capillaries towards the nearest free void, and the flow resistance generates pressure that increases with the flow path length and the cooling rate. When it exceeds the tensile strength of the cement paste, microcracks form and accumulate from cycle to cycle.

The second mechanism is **osmotic pressure** [4, 7]. The pore solution contains dissolved salts; as ice forms in larger pores, the salt concentration of the remaining liquid rises, water diffuses from smaller pores towards the ice and the crystals grow. This mechanism is important for the present review because electrolyte-based antifreeze admixtures increase the salt concentration of the pore solution and may therefore intensify it.

Fagerlund showed that damage begins once a **critical degree of saturation** is reached [12]: below this threshold concrete withstands a practically unlimited number of cycles, above it concrete fails within a few cycles. A similar approach was developed by Sheikin and Dobshits, who related frost resistance to the ratio between the volume of reserve (conditionally closed) pores and the volume of freezable water [5].

These models suggest two ways of increasing frost resistance: reducing capillary porosity (lower water–cement ratio, complete hydration) and providing a system of reserve pores that shortens the flow path of water [6, 10]. The first is achieved by mix design and curing; the second by air-entraining admixtures.

3.2 Air-entraining admixtures

Air-entraining admixtures are surfactants that stabilise small air bubbles introduced during mixing. Neutralised wood resin (abietate) salts, fatty acid salts, saponins and synthetic surfactants are used in practice [8, 11]. A stable air-void system requires four conditions: air introduction, reduced surface tension, an elastic bubble shell and sufficient paste viscosity [13].

Protection depends less on the total air content than on the distance between voids. Powers introduced the spacing factor, the maximum distance water travels to the nearest air void [14]. Recommended air-void parameters are given in Table 1.

Table 1 – Recommended air-void parameters of frost-resistant concrete

Parameter	Recommended value	Source
Spacing factor, mm	≤ 0.20	[6, 15]
Specific surface of voids, mm^{-1}	≥ 24	[4, 6]
Entrained air content, %	4–7 (depending on maximum aggregate size and exposure)	[6, 15]

[compiled by the authors]

The main drawback of air entrainment is the loss of strength: according to Neville, each percent of air reduces compressive strength by about 5 % [6]. This is partly offset because entrained air improves workability and allows the water content to be reduced [7, 10]. The review by Abbas and Muntean confirms this trade-off: air entrainment improves frost resistance at the cost of a slight reduction in strength [16].

An important conclusion was drawn in the meta-analysis by Matar et al.: no correlation was found between the chemistry of the air-entraining agent and the air-void parameters or the durability factor [17]. Frost resistance depends more on construction variables: mixing, placing, compaction and curing. Air-entraining agents also interact with other components of concrete; fly ash, for example, often causes air loss, and interactions with other chemical admixtures remain insufficiently studied [13]. The combined use with antifreeze admixtures belongs to this category.

3.3 Antifreeze admixtures

Antifreeze admixtures allow concrete to harden at sub-zero temperatures without heating by lowering the freezing point of the liquid phase and accelerating cement hydration [8, 9]. According to the classification of Ratinov and Rozenberg, there are two main groups [8]: electrolytes that act mainly by lowering the freezing point (sodium nitrite, sodium chloride), and setting accelerators with an antifreeze effect (calcium chloride, potash, calcium nitrate and calcium nitrite-nitrate). The main admixtures and their limitations are summarised in Table 2.

Table 2 – Main antifreeze admixtures and limitations of their use [7, 8, 9, 18, 19, 20]

Admixture	Lowest hardening temperature*, °C	Main limitations
Sodium nitrite (NN)	down to −15	efflorescence; risk of alkali–aggregate reaction; toxicity
Calcium chloride + sodium chloride (CC + SC)	down to −20	reinforcement corrosion; not permitted in reinforced concrete
Calcium nitrite-nitrate (CNN)	down to −20	high dosages required
Potash (P)	down to −25	rapid setting, loss of workability, lower final strength, efflorescence
Calcium nitrate	down to −20	dosages of about 6 % by mass of cement

* Indicative values; the actual limit depends on dosage and on the required critical strength.

Research in recent decades has focused on chloride-free compositions. At the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Korhonen and Cortez obtained good results for combinations of sodium nitrite with calcium nitrite and with potash at −5 and −10 °C [21]. In subsequent work the target was strength at −5 °C equal to that of plain concrete at +5 °C; dosages were 6–8 % by mass of cement, and chlorides were excluded because of corrosion [22].

Calcium nitrate is one of the most studied chloride-free admixtures. Karagöl et al. added it at 6 % by mass of cement and cured specimens at −5, −10, −15 and −20 °C [20]. Compared with the control, strength increased by 48–964 %, 50–721 %, 29–393 % and 24–183 %, respectively: the effect of the admixture weakens as the temperature decreases. Khan and Santha Kumar showed that a binary admixture of calcium nitrate and sodium thiocyanate gives a synergistic strength gain at −5 and −10 °C [23].

Antifreeze admixtures also protect fresh concrete exposed to freezing. In the study by Polat, after 28 freeze–thaw cycles the compressive strength of the control concrete decreased by 72 %, that of concrete with urea by 52.9 %, and that of concrete with calcium nitrate by 27.8 % (dosage 6 %) [24]. Concrete with calcium nitrate also had the lowest water absorption (5.8 %) and a denser microstructure.

3.4 Combined use of air-entraining and antifreeze admixtures

Combined use offers a potential mutual benefit. An accelerating antifreeze admixture increases early strength and may compensate the strength loss caused by air entrainment, while the air-entraining admixture provides the long-term frost resistance that an antifreeze admixture alone does not guarantee. In Russian practice, complex admixtures combining an electrolyte with an air-entraining component are regarded as a way to ensure both winter concreting and durability [5, 8].

The available data on compatibility are generally favourable. In the CRREL study, chloride-free antifreeze admixtures proved compatible with air-entraining agents: the spacing factor remained within acceptable limits and frost resistance was not reduced [22].

At the same time, electrolyte salts modify the air-void structure. Li, Ge and Yang found that sodium sulfate and sodium nitrite reduce the foaming capacity of an air-entraining agent (sodium abietate) but do not affect foam stability [25]. Both salts reduced the pore size; however, as the sodium sulfate dosage increased the spacing factor grew, whereas sodium nitrite had the opposite effect. In both cases a distinct shell formed on the void walls. The outcome of a combination therefore depends on the specific pair of admixtures and cannot be transferred from one mix to another.

Moreover, salts increase the concentration of the pore solution, which according to the osmotic model may intensify damage during subsequent freezing cycles [4, 7]. The review by Tunstall, Ley and Scherer explicitly identifies the interaction of air-entraining agents with other chemical admixtures as an insufficiently studied area [13].

3.5 Standards and climatic conditions of Kazakhstan

In Kazakhstan the use of admixtures and the assessment of frost resistance are governed by interstate (GOST) standards (Table 3).

Table 3 – Standards relevant to the subject of the review

Document	Scope
GOST 24211-2008 [26]	Classification of admixtures, including air-entraining and antifreeze admixtures, and general requirements
GOST 30459-2008 [27]	Methods and criteria for evaluating the efficiency of admixtures
GOST 26633-2015 [28]	Requirements for normal-weight concrete, including frost resistance grades and entrained air content
GOST 10060-2012 [29]	Basic and accelerated methods for determining frost resistance
SP RK 2.04-01-2017 [1]	Design climatic parameters

[compiled by the authors]

Most of the northern and central regions of Kazakhstan, including Astana, are characterised by long cold winters and large daily temperature fluctuations in the transitional seasons [1]. This places a double load on concrete: the construction season is shortened and antifreeze admixtures become necessary, while structures in service undergo many freeze–thaw cycles. Road and bridge structures are additionally exposed to de-icing salts [2].

ACI guides 201.2R and 306R give recommendations on air entrainment and cold weather concreting [15, 18]. They are useful for comparison with GOST requirements, but test methods and acceptance criteria differ. In particular, frost resistance under GOST 10060 is expressed as an F grade, whereas international studies more often use the durability factor and the spacing factor, which complicates direct comparison of results.

3.6 Research gaps and future directions

The review shows that the action of each type of admixture alone is well studied, whereas their combined use is studied much less. Four open questions can be identified:

1. **Compensation of strength loss.** The extent to which the accelerating effect of an antifreeze admixture compensates the strength loss caused by air entrainment at early and standard ages has not been quantified.
2. **Stability of the air-void system.** Data on the effect of electrolytes on the spacing factor are contradictory and depend on the type of salt [22, 25].
3. **Hardening at sub-zero temperature and subsequent frost resistance.** Most studies assess either strength gain under frost or the frost resistance of normally cured concrete; data on the frost resistance of concrete that gained strength at sub-zero temperature with a combination of admixtures are scarce.
4. **Local raw materials.** Systematic data for Kazakhstan-produced cements and aggregates and for commercial admixtures available on the local market are practically absent.

To address these questions, an experimental programme is proposed that includes a control mix, mixes with each admixture at two dosages and a combined mix at a constant water–cement ratio. The mixes should be tested under normal curing and at sub-zero temperature, with determination of air content, water absorption, compressive strength at 3, 7 and 28 days and the

frost resistance grade according to GOST 10060 [29], as well as the efficiency of the admixtures according to GOST 30459 [27].

4 CONCLUSIONS

1. Frost damage of concrete is described by the hydraulic and osmotic pressure models. The key factors of frost resistance are capillary porosity, the degree of saturation and the spacing of air voids.
2. Air-entraining admixtures remain the main means of increasing frost resistance. Their effectiveness is governed by the spacing factor (≤ 0.20 mm) and depends more on construction practice than on the chemistry of the admixture. The price of air entrainment is a strength loss of about 5 % per 1 % of air.
3. Antifreeze admixtures allow strength gain at temperatures down to −15…−25 °C depending on their type. The current trend is towards chloride-free compositions (calcium nitrate and nitrite, binary mixtures) that do not cause reinforcement corrosion.
4. The combined use of the admixtures is promising, but their mutual effect on the air-void system and strength depends on the specific combination and requires experimental verification with local materials.
5. For the conditions of Kazakhstan, research is needed on normal-weight concrete with a combination of air-entraining and antifreeze admixtures made with local raw materials, with assessment of early and standard strength, water absorption and frost resistance. The authors' further experimental work is devoted to this task.

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CONFLICT OF INTEREST

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Claude (Anthropic) was used to assist with structuring the manuscript, drafting text, searching for sources and translating the text into English, Kazakh and Russian. The authors checked all sources and data, edited the text and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

M.M. Balantayeva – conceptualization, literature search, writing – original draft. G.R. Baimenova – supervision, methodology, writing – review and editing.

A CONCEPTUAL MODEL OF A CRYPTOGRAPHIC PROTOCOL FOR SECURE PARAMETER EXCHANGE IN FEDERATED LEARNING BASED ON HOMOMORPHIC ENCRYPTION

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Abstract

Federated learning enables multiple participants to jointly train a machine learning model without centrally transferring their original training data. However, transmitted parameters and gradients may disclose information about participants' local data. Homomorphic encryption enables certain computations on encrypted values while preserving the confidentiality of the underlying data. Nevertheless, encryption alone does not specify how messages should be exchanged, validated, or handled when protocol rules are violated.

This paper aims to develop a conceptual model of a cryptographic protocol for secure parameter exchange in federated learning. The model defines system participants, a threat model, parameter states, transition rules, and an admissibility function for cryptographic operations. It also specifies the algorithmic sequence of parameter exchange, message verification, and conditions for accepting an aggregated result. The work presents a protocol design rather than a completed implementation or experimental evaluation.

Keywords: federated learning, homomorphic encryption, cryptographic protocol, secure parameter exchange, secure aggregation, threat model.

Introduction

Federated learning allows multiple participants to jointly train a model while retaining original data on local devices or within data-owning organizations. Participants send model updates to a server to construct a global model [1]. However, keeping the original data locally does not guarantee privacy: model gradients can reveal information about training examples [2].

Homomorphic encryption enables certain operations on ciphertexts without first disclosing plaintext values. Yet encryption alone does not ensure message authenticity, protection against replay, or verification that a participant's update is benign. A secure exchange therefore requires a complete protocol governing the process from message creation to acceptance of an aggregated result.

The objective of this study is to develop a conceptual model of a homomorphic-encryption-based cryptographic protocol for secure parameter exchange in federated learning. The tasks include defining the threat model, formalizing parameter states and transitions, specifying message-admissibility rules, and establishing a basis for subsequent security and performance evaluation.

Review of Existing Approaches

Existing studies address different aspects of secure parameter exchange in federated learning. BatchAgg uses gradient-vector packing and approximate homomorphic encryption to reduce computational and communication costs of encrypted aggregation [3]. VCSA combines symmetric homomorphic encryption with aggregation verification and considers resistance to collusion and participant dropout [6]. HP_FLAP combines homomorphic encryption with key-management and message-protection mechanisms; its authors identify authentication as an area for further development [5]. More recent research combines homomorphic encryption with decentralized identifiers and verifiable credentials [8].

Comparison of these approaches suggests that parameter confidentiality, homomorphic aggregation, key management, or authentication alone cannot be treated as sufficient scientific novelty. This work examines a narrower research question: how to formally determine whether an encrypted update may be admitted to aggregation in a particular training round, taking into account the participant identity, round number, global model version, message authenticity, and key admissibility. This is a preliminary research hypothesis; any claim of novelty requires further comparison with the full texts of related protocols.

Table 1. Literature-based comparison of research emphasis (not a formal feature audit).

Approach	Emphasis reported in cited work	Remaining issue for this proposal
BatchAgg [3]	Efficient encrypted aggregation	Round/message admission rules to specify
VCSA [6]	Verifiability and collusion resistance	Map verification to explicit state transitions
HP_FLAP [5]	Encrypted parameter aggregation	Specify authentication and key-state checks
Proposed concept	Round-, version-, and key-aware admission	Formal proof and implementation still required

System and Threat Model

The system consists of clients $C_1 \ldots C_n$, an aggregation server S, and a key-management component. Each client retains local data and computes a model update. The server coordinates training rounds and aggregates encrypted updates. The key-management mechanism creates, distributes, and governs the use of cryptographic keys.

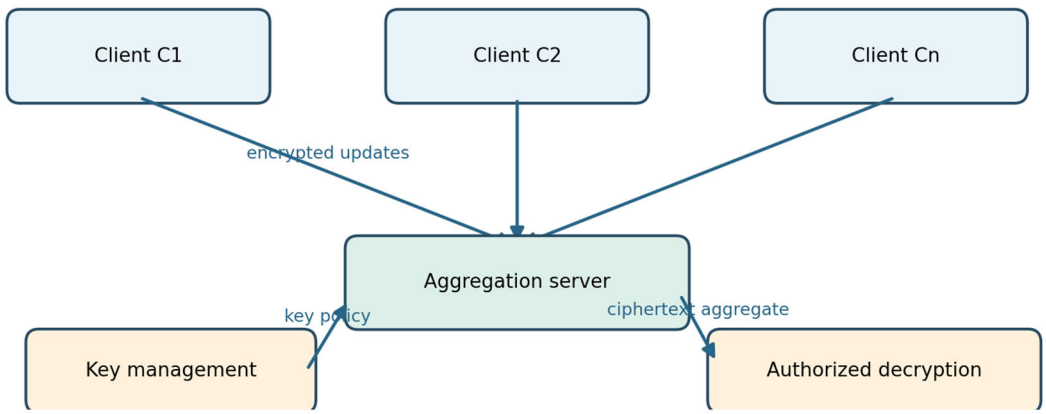


Figure 1. Conceptual architecture of the proposed secure parameter-exchange protocol.

The adversary is assumed capable of observing network traffic, replaying intercepted messages, modifying messages, or attempting to submit an update on behalf of a dishonest participant. A client may also disconnect before a round is completed.

Confidentiality of updates, authenticity and integrity of messages, and correctness of the protocol sequence must be distinguished. Homomorphic encryption alone does not guarantee protection against replay, model poisoning, or compromise of an endpoint.

Proposed Protocol and Mathematical Model

Basic Notation

Let w_t denote the global model parameters in round t, and let $\Delta_i^{(t)}$ denote the local update of participant C_i. The local model is defined as:

$$w_i^{(t+1)} = w_t + \Delta_i^{(t)} \quad (1)$$

Let $E_{pk}(m)$ denote encryption of message m with public key pk, and $D_{sk}(c)$ denote decryption of ciphertext c with secret key sk. For an additively homomorphic scheme, the following property holds:

$$D_{sk}(E_{pk}(a) \oplus E_{pk}(b)) = a + b \quad (2)$$

Here, $\oplus$ denotes an operation on ciphertexts. The equality is interpreted within the mathematical domain of the selected cryptosystem and under an appropriate encoding of model parameters.

If weights q_i are used, the aggregated update may be defined as:

$$\Delta^{(t)} = [\Sigma_i \in A_t \, q_i \, \Delta_i^{(t)}] / [\Sigma_i \in A_t \, q_i] \quad (3)$$

Here, A_t is the set of participants whose updates have been accepted in round t. Implementing a weighted average in encrypted form requires consideration of the supported operations, encoding of real-valued parameters, and normalization.

Parameter-State Model

The lifecycle of an update is represented by the tuple:

$$P_i^{(t)} = (id_i, t, v_i, s_i, c_i)$$

Here, id_i is the participant identifier; t is the round number; v_i is the version of the global model used to compute the update; s_i is its current state; and c_i is the plaintext or encrypted representation of the parameters.

For an individual update, define the state set $S_p = \{S_0, S_1, S_2, S_3, S_4, S_e\}$: S_0 — created; S_1 — encrypted; S_2 — transmitted; S_3 — verified; S_4 — included in aggregation; S_e — rejected. State S_4 does not imply that the global model has already been accepted.

States of the aggregated result are modeled separately: A_0 — aggregation initiated; A_1 — aggregate formed; A_2 — result verified; A_3 — result accepted; A_e — result rejected.

Transition Function

Let E be the set of protocol events, including encryption, message transmission, successful verification, and error detection. The transition function is defined as:

$$\delta : S_p \times E \rightarrow S_p \tag{4}$$

The principal transitions are $S_0 \rightarrow S_1$ upon successful encryption; $S_1 \rightarrow S_2$ upon transmission; $S_2 \rightarrow S_3$ after successful checks; $S_2 \rightarrow S_e$ when verification fails; and $S_3 \rightarrow S_4$ when an update is included in aggregation. A critical violation may move an unfinished state to S_e.

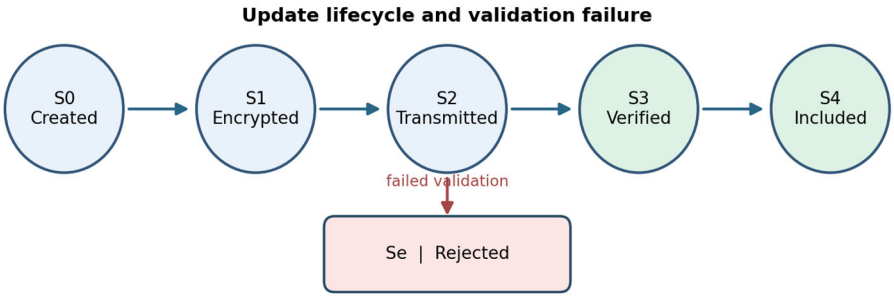


Figure 2. Update-state transitions and rejection path.

Transitions are permitted only when the specified conditions hold. Rejecting one message does not necessarily terminate the entire round; the action depends on the availability policy and the minimum permitted number of participants.

Operation-Admissibility Function

For message $m_i^{(t)}$ intended for round t, introduce the admissibility predicate:

$$\mathrm{Allow}(m_i^{(t)}, \Sigma_t) \in \{0, 1\}$$

Here, Σ_t denotes the current protocol state. In the initial model, an operation is permitted only if all five conditions are satisfied:

$$\mathrm{Allow} = V_1 \wedge V_2 \wedge V_3 \wedge V_4 \wedge V_5 \tag{5}$$

V_1 means that the participant is authorized for the round; V_2 that the round number matches the expected round; V_3 that the model version is admissible; V_4 that the message passes authenticity and integrity checks; and V_5 that the message has not already been accepted in this round. If any condition fails, the update is excluded from aggregation.

Table 2. Admission checks applied before aggregation.

Predicate	Acceptance condition	Failure response
V1	Client authorized for current round	Reject message
V2	Round identifier matches	Reject stale / wrong-round message
V3	Model version is admissible	Reject outdated update
V4	Authenticity and integrity verified	Reject altered / unauthenticated message
V5	Message not previously accepted	Reject replay
V6	Key authorized for operation and round	Reject invalid key use

Authenticity can be checked using a digital signature or another appropriate mechanism. Replay protection requires unique identifiers and persistent records of processed messages. Signature verification does not establish that a local update is benign.

4.5. Key State

The state of a cryptographic key is represented by the tuple:

$$K_j = (idK_j, stK_j, opK_j)$$

Here, idK_j is the key identifier; stK_j is its state; and opK_j is the set of permitted operations. The states are ACTIVE (permitted), SUSPENDED (temporarily prohibited), REVOKED (revoked), and EXPIRED (no longer valid).

$$V_6 = \mathrm{KeyAllowed}(K_j, op, t) \qquad (6)$$
$$\mathrm{Allow} *= \mathrm{Allow} \wedge V_6$$

Consequently, a message is not included in aggregation if the key is not authorized for the relevant operation or round. The implementation depends on the cryptographic scheme; under threshold encryption, aggregate decryption may require participation by multiple holders of secret-key shares.

Algorithmic Sequence

The protocol Π consists of five algorithmic components:

$$\Pi = (\mathrm{Setup}, \mathrm{Encrypt}, \mathrm{Verify}, \mathrm{Aggregate}, \mathrm{Finalize})$$

Setup: define cryptographic parameters, generate keys, distribute public keys, and establish rules for identifying rounds and accepting messages.

Encrypt: the client computes a local update, encodes the parameters, encrypts them, constructs a message containing participant, round, model-version, and message identifiers, and attaches information for authenticity and integrity verification.

Verify: the server checks the participant, round, model version, message authenticity and integrity, absence of duplicate processing, and key admissibility. The message is accepted only if all mandatory conditions are met.

Aggregate: the server checks participant-count requirements, performs supported homomorphic operations on accepted ciphertexts, and forms an encrypted aggregate.

Finalize: the aggregate is sent to an authorized entity for decryption. Following the prescribed checks, the aggregated update is applied to the global model; otherwise, the result is rejected.

This description is a conceptual-level specification. Cryptographic functions must be implemented using a selected, vetted cryptographic scheme.

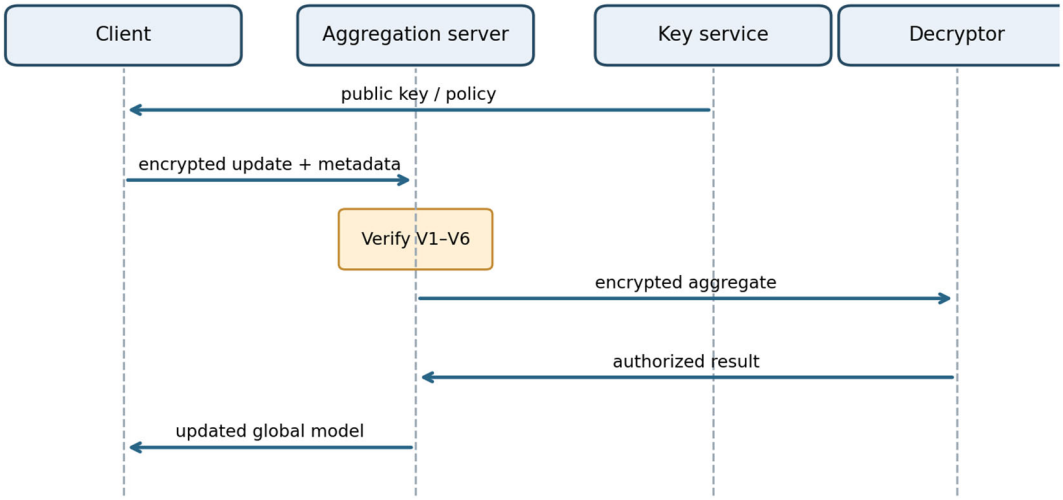


Figure 3. Protocol phases and verification gate (conceptual workflow).

The server binds each unique message identifier to the session, participant, and round identifiers. If a message has already been processed in the same context, including its update again is prohibited. A message associated with an earlier model version or a different round is rejected.

In a practical implementation, records of processed messages must survive server restarts. Storing identifiers only in volatile memory is insufficient for robust replay protection.

Security Requirements and Limitations

Update confidentiality depends on the selected cryptosystem and its assumptions. Message authenticity requires an authentication mechanism. Replay protection requires binding messages to the session and round. Correct aggregation requires including only messages that have passed the specified checks. Failure handling must define the minimum number of participants and round-completion conditions.

These requirements are not proven properties of an implemented system. Homomorphic encryption does not automatically prevent model poisoning, leakage through the global model, endpoint compromise, or misuse of decryption privileges.

Methodology for Subsequent Evaluation

To assess practical feasibility, the selected cryptographic scheme must be implemented and evaluated comparatively. Planned evaluation dimensions include functional correctness of homomorphic aggregation; key-generation, encryption, verification, aggregation, and decryption times; communication overhead; handling of client dropout; and resistance to the threats specified in the model.

Table 3. Planned evaluation criteria (no experimental measurements are claimed).

Security property	Formal criterion	Verification method
Correctness	Decrypted aggregation corresponds to the plaintext reference, subject to encoding precision	Algebraic analysis
Confidentiality	Individual model updates remain encrypted during transmission and aggregation	Cryptographic security analysis
Message authenticity	Only authenticated participants can submit admissible updates	Signature verification
Replay resistance	Previously accepted messages cannot be included again in the same training round	Message-ID and round validation
State consistency	Only updates with valid state transitions are admitted to aggregation	State-transition analysis
Key validity	Operations are permitted only for authorized and valid keys	Key-state verification

The comparison should include a baseline federated-learning implementation and at least one comparable secure-aggregation mechanism. Experimental settings and results should be reported only after measurements have actually been performed.

Discussion

The proposed concept connects the lifecycle of an individual update, key state, round identity, global-model version, and message verification to the decision to include a ciphertext in aggregation. The practical value of this formalization is that it makes permitted and prohibited transitions explicit and defines conditions for rejecting replayed or stale messages.

However, the presence of these mechanisms in a conceptual model does not itself prove scientific novelty or security of an implemented system. It remains necessary to determine which combinations of checks are already present in existing protocols, formally specify adversarial and trust assumptions, verify the claimed properties, and measure performance overhead. The model does not detect poisoned updates without an additional analysis mechanism.

Conclusion

This paper presents a conceptual model of a homomorphic-encryption-based cryptographic protocol for secure parameter exchange in federated learning. It identifies system participants, a preliminary threat model, individual-update states, transition rules, an operation-admissibility predicate, and an algorithmic exchange sequence.

The model provides a basis for further protocol formalization. The stated security properties remain requirements for the proposed system rather than outcomes of completed proofs or experimental verification. Future work will select a cryptographic scheme, perform formal security analysis, develop a prototype, and measure computational and communication costs.

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Psychological Sciences

PSYCHOLOGICAL FACTORS ASSOCIATED WITH PRIMARY HEALTHCARE PHYSICIANS' RECOMMENDATION OF HUMAN PAPILLOMAVIRUS VACCINATION

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Abstract

Human papillomavirus (HPV) vaccination is an important component of cervical cancer prevention, yet its implementation depends partly on how healthcare professionals communicate with patients and caregivers. This narrative review considers psychological factors that may be associated with primary healthcare physicians' recommendation of HPV vaccination, particularly vaccine confidence, perceived safety, professional self-efficacy, perceived social norms, and communication-related concerns. International guidance and studies involving healthcare professionals, including research from Kazakhstan, indicate that knowledge alone may not be sufficient: beliefs about vaccine safety, confidence in discussing HPV, and expectations about patient or community reactions may also be relevant to recommendation practices. The paper synthesizes these factors conceptually and identifies implications for professional support. It does not report new empirical data. Further local research should distinguish physicians' stated intention to recommend vaccination from their actual recommendation behaviour and assess psychological factors alongside organizational conditions.

Keywords: human papillomavirus; HPV vaccination; primary healthcare; physicians; vaccine confidence; self-efficacy; psychological factors.

Introduction

Human papillomavirus is associated with cervical cancer and several other anogenital and oropharyngeal cancers. HPV vaccination, delivered according to national recommendations, can substantially reduce the risk of HPV-related disease. The World Health Organization identifies vaccination of eligible girls as a central element of its strategy to eliminate cervical cancer as a public health problem [1, 2]. However, vaccine availability does not automatically ensure uptake. Recommendations from healthcare professionals can influence whether parents and eligible adolescents consider vaccination, seek reliable information, and proceed with vaccination.

Primary healthcare physicians are important because they provide preventive care, answer families' questions, and respond to concerns about vaccine safety and necessity. Their recommendation behaviour may not be determined by biomedical knowledge alone. Psychological factors—including confidence in the vaccine, perceived ability to explain its benefits,

anticipated resistance, and beliefs about professional expectations—may affect whether and how clearly vaccination is recommended.

Materials and methods

This paper is a narrative review of selected international guidance and published research on healthcare professionals' HPV vaccination recommendation practices and communication with patients or caregivers. Sources include World Health Organization guidance, a WHO communication resource, and peer-reviewed studies addressing healthcare professionals' knowledge, attitudes, barriers, and recommendation practices, including studies conducted in Kazakhstan [1–7]. The purpose is to organize relevant psychological factors into a practical conceptual framework, not to conduct a systematic review or estimate pooled effects. No new participant data were collected, and no original statistical analysis was performed.

Psychological factors relevant to recommendation behaviour

Vaccine confidence and perceived safety

Confidence in vaccine safety and effectiveness is a plausible psychological correlate of recommendation behaviour. A physician who trusts the evidence and feels comfortable explaining the benefit–risk balance may be more prepared to give a clear recommendation. Conversely, unresolved doubts, uncertainty about adverse events, or exposure to misinformation may lead to hesitant or qualified communication. Research among healthcare professionals in Kazakhstan has identified public mistrust, concerns about side effects, and insufficient professional knowledge among reported barriers to HPV vaccine communication [4]. These findings support examining confidence and safety beliefs as distinct constructs.

Professional self-efficacy and communication confidence

Self-efficacy refers to a person's belief in their ability to perform a particular task. Here, communication self-efficacy concerns a physician's confidence in explaining HPV-related disease, describing vaccine benefits and safety, responding to questions, and addressing misinformation respectfully. Physicians may support vaccination in principle but still feel unprepared to discuss it with hesitant parents. WHO communication guidance emphasizes practical, respectful conversations with caregivers, suggesting that communication skills should be supported alongside factual knowledge [3].

Anticipated resistance and perceived social norms

Physicians may anticipate that families will reject vaccination, interpret the recommendation negatively, or raise concerns about its relationship to sexual health. Such expectations can influence whether a recommendation is initiated and how firmly it is expressed. Perceived social norms—beliefs about whether colleagues, professional leaders, and the wider community support vaccination—may also shape professional behaviour. These mechanisms should be treated as factors to investigate, not as established explanations for every physician's decisions.

Trust, professional responsibility, and intention

A physician's sense of professional responsibility for preventive care may strengthen the intention to recommend vaccination. Trust operates in both directions: physicians need confidence in the evidence and must communicate in a way that helps families feel heard rather than judged. Recommendation intention, however, is not equivalent to actual practice. A questionnaire asking whether a physician intends to recommend HPV vaccination may overestimate behaviour if time constraints, unclear procedures, vaccine availability, or other organizational barriers intervene. Research should therefore measure both psychological determinants and a clearly defined indicator of recent recommendation practice.

Evidence and relevance to Kazakhstan

Studies conducted in Kazakhstan demonstrate that healthcare professionals' HPV-related knowledge, attitudes, and recommendation practices are relevant research issues. One study

reported gaps in knowledge and difficulties advising patients, alongside concerns about public mistrust and vaccine safety [4]. A separate study of primary care providers in Almaty examined knowledge, attitudes toward myths, and recommendation practice, reporting that these domains were not uniformly adequate across respondents [5]. These findings indicate that the local context warrants careful assessment; they do not, by themselves, prove that any single psychological factor causes recommendation behaviour.

For a focused study in primary healthcare, psychological variables could include vaccine confidence, perceived safety, confidence in discussing HPV vaccination, anticipated patient resistance, and perceived professional norms. These should be measured separately from factual knowledge, previous training, and organizational support. Where feasible, the outcome should capture actual recommendation behaviour over a defined period—for example, whether the physician recommended HPV vaccination to an eligible patient or caregiver during the previous three months. This approach would allow researchers to examine associations while avoiding causal claims from cross-sectional data.

Practical implications

Professional support should combine reliable information about HPV vaccination with opportunities to practise communication. Training can include responding to common questions, acknowledging uncertainty appropriately, explaining benefits and risks in plain language, and using a clear recommendation without dismissing caregiver concerns. WHO resources on caregiver communication and behavioural and social drivers of vaccination provide useful starting points [3, 6]. Clinics can also reinforce consistent preventive-care messages through accessible information materials and clear vaccination pathways. These measures are reasonable practice implications, but their effectiveness should be evaluated rather than assumed.

Future research in Kazakhstan should use clearly defined measures, pilot-test translated questionnaires, and distinguish intention from reported behaviour. It should account for professional characteristics and clinic-level conditions. If the design is cross-sectional, results should be reported as associations, not causal effects. Findings could inform locally tailored communication support and continuing professional education.

Conclusion

Psychological factors are a relevant, but not exclusive, part of understanding primary healthcare physicians' HPV vaccination recommendation practices. Vaccine confidence, perceived safety, communication self-efficacy, anticipated resistance, and perceived professional norms are suitable constructs for further investigation. Evidence from Kazakhstan highlights the importance of examining healthcare professionals' knowledge, attitudes, communication challenges, and recommendation practices in the local context. A focused empirical study should measure these constructs separately and assess their association with actual recommendation behaviour, while also considering organizational conditions. This narrative review presents a conceptual basis for such research and does not claim new empirical findings.

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Geographic Sciences

FACTOR-BASED AND METHODOLOGICAL FOUNDATIONS OF TOURISM DEMAND FORECASTING IN KAZAKHSTAN

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Abstract

The diversification of Kazakhstan's economy relies significantly on the strategic development of non-extractive sectors, notably tourism. A critical prerequisite for effective tourism planning, infrastructure investment, and sustainable destination management is the accurate forecasting of tourism demand. This article comprehensively investigates the theoretical, factor-based, and methodological foundations of tourism demand forecasting tailored to the unique economic and geographical context of Kazakhstan. Despite the growing importance of the tourism sector, a noticeable scientific gap exists in the systematic application of advanced predictive modeling for domestic and international tourist flows within Central Asia. The primary objective of this study is to develop a robust methodological framework for forecasting tourism demand in Kazakhstan by identifying the core determinants and evaluating applicable statistical and econometric models. Through a critical synthesis of existing literature, this study systematically classifies economic, demographic, geographical, institutional, and geopolitical factors influencing tourism. The study reviews a spectrum of forecasting methodologies, ranging from traditional time-series models (ARIMA) and econometric approaches (panel data, gravity models) to advanced machine learning techniques, comparing their predictive accuracy and suitability under conditions of data scarcity and structural volatility. An integrated, reproducible forecasting framework is proposed, delineating dependent variables, explanatory indicators, and data validation procedures. The findings emphasize that regional heterogeneity, extreme seasonality, and transitional institutional environments necessitate hybrid forecasting models. Practical recommendations are formulated for national tourism authorities, destination management organizations, and policymakers to improve data infrastructure, implement scenario-based planning, and optimize resource allocation. This research contributes to the academic discourse on tourism economics and provides actionable insights for enhancing the strategic management of Kazakhstan's tourism industry.

Keywords: tourism demand forecasting, Kazakhstan, tourism economics, forecasting models, tourism statistics, regional development, seasonality, predictive analytics.

1. Introduction

The global tourism industry has long been recognized as a powerful engine for economic growth, employment generation, and cultural exchange. For resource-rich nations in transition, such as the Republic of Kazakhstan, the development of the tourism sector represents a strategic imperative for economic diversification. Historically reliant on the export of hydrocarbons and minerals, Kazakhstan has increasingly prioritized the expansion of its non-oil economy to mitigate vulnerability to global commodity price fluctuations. In this context, tourism emerges as a sector with immense untapped potential, leveraging the country's vast geographic expanse, unique nomadic heritage, diverse landscapes ranging from the Tian Shan mountains to the Caspian Sea, and its geostrategic position along the historic Silk Road.

Effective planning, infrastructure development, and investment in the tourism sector require precise and reliable forecasts of tourism demand. Tourism demand forecasting serves as the foundation for strategic decision-making by both public and private stakeholders. National and regional authorities depend on accurate projections to allocate budgets, develop transport networks, manage destination capacities, and implement sustainable policies. Concurrently, private enterprises—such as hotel operators, airlines, and tour agencies—rely on these forecasts for yield management, pricing strategies, staffing, and marketing campaigns. However, forecasting tourism demand is inherently complex due to the industry's high sensitivity to a multitude of exogenous and endogenous factors, including economic cycles, geopolitical events, exchange rate volatility, and extreme seasonality.

Despite the critical need for robust predictive analytics in tourism planning, a significant scientific gap exists in the context of Kazakhstan and the broader Central Asian region. While tourism demand forecasting has been extensively researched in established markets (e.g., Western Europe, North America, and Southeast Asia), studies focusing on transitional economies with emerging tourism sectors remain limited. Existing planning documents often rely on simple trend extrapolations or target-driven scenarios that lack rigorous econometric validation. This deficiency can lead to overinvestment in infrastructure—resulting in stranded assets—or underinvestment, which throttles potential growth.

The primary objective of this article is to develop a comprehensive scientific framework examining the theoretical, methodological, statistical, economic, geographical, and institutional foundations of tourism demand forecasting in Kazakhstan. To achieve this objective, the research addresses the following questions: What are the distinct characteristics and determinants of tourism demand in Kazakhstan? How can theoretical and empirical models from international literature be adapted to account for the unique structural, geographic, and data constraints of the Kazakhstani market? Which methodological approaches offer the highest predictive reliability for domestic and inbound tourist flows?

The novelty of this study lies in its holistic approach, integrating economic geography, tourism economics, and predictive methodology tailored to a post-Soviet transitional economy. By systematically classifying the factors influencing demand and proposing an integrated methodological framework, this research provides both a theoretical contribution to tourism economics and practical tools for destination management in Kazakhstan. The resulting framework aims to enhance the resilience of the tourism sector against external shocks and foster sustainable regional development.

2. Theoretical Foundations of Tourism Demand Forecasting

The conceptualization of tourism demand forms the basis for any rigorous forecasting exercise. In economic theory, tourism demand is defined as the quantity of tourism products and services that consumers are willing and able to purchase at a given price over a specified period. However, in the context of tourism economics, demand is typically operationalized through aggregate macro-level indicators rather than individual consumption bundles. The United Nations

World Tourism Organization (UN Tourism) establishes the standard metrics for observed tourism demand, which primarily include tourist arrivals (inbound, outbound, and domestic), number of overnight stays (bed-nights), and total tourism expenditure (or receipts).

It is crucial to distinguish between observed demand (actual realized travel) and latent or potential demand. Observed demand is constrained by factors such as available income, time, and supply-side capacity (e.g., airline seats, hotel rooms). Latent demand represents individuals who possess the desire to travel but are impeded by various constraints, including financial limitations, lack of leave time, or visa restrictions. Forecasting models predominantly focus on observed demand, yet understanding latent demand is vital for policy interventions, such as the introduction of visa-free regimes or transport subsidies, which can rapidly convert latent demand into observed arrivals.

The theoretical approaches to analyzing tourism demand can be categorized into four primary perspectives: economic, geographical, behavioral, and destination competitiveness. The economic perspective, rooted in neoclassical consumer theory, treats tourism as an export commodity. Demand is modeled as a function of the consumer's disposable income, the price of tourism services in the destination relative to the origin country, transportation costs, and the prices of substitute destinations. Studies by foundational scholars in tourism forecasting (e.g., Song, Witt, Lim) emphasize that income elasticity and price elasticity are the core parameters governing tourism flows.

The geographical perspective introduces spatial dimensions, modeling tourism flows based on the distance between origin and destination (distance decay), spatial accessibility, and the distribution of natural and cultural attractions. Gravity models are frequently employed within this paradigm, positing that demand is directly proportional to the economic mass of the origin and destination and inversely proportional to the friction of distance. The behavioral perspective examines psychographic variables, consumer preferences, motivations, and cultural ties, recognizing that tourism is an experience good rather than a pure physical commodity. Finally, the destination competitiveness approach integrates supply-side factors, arguing that a destination's ability to attract tourists is contingent upon its comparative advantages (endowed resources) and competitive advantages (infrastructure, service quality, and management).

Table 1. Core concepts and indicators of tourism demand.

Indicator	Definition (UN Tourism context)	Unit of Measurement	Forecasting Application
Tourist Arrivals	Number of unique trips by visitors staying at least one night.	Persons / Trips	General volume forecasting, capacity planning.
Overnight Stays	Total number of nights spent by tourists in commercial or non-commercial accommodation.	Bed-nights	Hotel occupancy forecasting, yield management.
Tourism Receipts	Total expenditure by inbound visitors within the destination economy.	Currency (e.g., USD, KZT)	Economic impact, GDP contribution modeling.
Average Length of Stay	Total overnight stays divided by total tourist arrivals.	Days / Nights	Behavioral shifts, destination engagement.
Occupancy Rate	Percentage of available accommodation units occupied over a period.	Percentage (%)	Real estate investment, seasonal adjustment.

3. Tourism Development and Demand Characteristics in Kazakhstan

Kazakhstan's tourism geography is characterized by extreme spatial dispersion, a highly continental climate, and distinct regional clusters of tourism resources. As the ninth-largest country in the world, the sheer scale of the territory dictates that transport accessibility is a paramount determinant of both domestic and inbound tourism. The country's tourism development strategy has historically focused on specific spatial nodes to concentrate investment and infrastructure. The principal destinations include the Almaty mountain region (hub for eco-tourism, winter sports, and MICE), Astana (the capital, focusing on business and event tourism), Turkistan (the center for historical, cultural, and religious tourism), the Caspian Sea region in Mangystau (beach and unique desert landscapes), and the Shchuchinsk-Burabay resort area (the primary domestic nature resort).

An analysis of tourism demand in Kazakhstan reveals distinct structural characteristics. Firstly, domestic tourism significantly outpaces inbound international tourism in terms of volume. Following the COVID-19 pandemic, domestic tourism experienced a robust recovery, driven by the closure of international borders and subsequent governmental stimulus for local travel. International inbound tourism is heavily skewed toward neighboring countries, primarily the Russian Federation, Uzbekistan, and the Kyrgyz Republic, reflecting strong historical, linguistic, and economic ties (frequently captured by gravity model parameters). Non-CIS inbound tourism is comparatively small but yields higher per-capita expenditure, with source markets including China, Germany, Turkey, and India.

Seasonality is a defining constraint of Kazakhstan's tourism demand. The sharply continental climate restricts the operational window for many outdoor and nature-based

destinations. For instance, the beach season on the Caspian coast and the lakes of Burabay is limited to two to three months, leading to severe demand peaks that strain infrastructure and result in low annual average occupancy rates. Conversely, Almaty benefits from dual seasonality (summer trekking and winter skiing), offering a more balanced demand profile. These seasonal disparities necessitate the use of seasonal adjustment techniques and specialized time-series models (e.g., SARIMA) when forecasting.

Table 2. Regional characteristics of Kazakhstan's principal tourism destinations.

Tourism Destination	Primary Tourism Typology	Key Attractions / Resources	Seasonality Profile
Almaty & Region	Mountain, Eco, MICE, Winter	Ile-Alatau NP, Shymbulak, Charyn	Dual (Summer/Winter peaks)
Astana	Business, Event, Urban	Baiterek, EXPO site, Museums	Moderate (Year-round business)
Turkistan	Historical, Cultural, Pilgrim	Mausoleum of Khoja Ahmed Yasawi	Spring/Autumn peaks (Extreme summer heat)
Mangystau (Caspian)	Beach, Adventure, Desert	Aktau resorts, Bozzhyra tract	Summer peak (Short season)
Shchuchinsk-Burabay	Nature, Health, Recreation	Lakes, Pine forests, Sanatoriums	High Summer peak, minor winter activity

4. Factor-Based Foundations of Tourism Demand Forecasting

The accuracy of causal and structural forecasting models is entirely dependent on the correct identification and operationalization of demand determinants. In the context of Kazakhstan, these factors can be systematically classified into several interconnected groups.

4.1. Economic Factors: Economic variables are the most robust predictors of tourism demand. For inbound tourism, the Gross Domestic Product (GDP) per capita of the source country serves as a proxy for discretionary income. The relative exchange rate (e.g., KZT to USD, RUB, or EUR) determines destination affordability. A depreciation of the Tenge theoretically stimulates inbound tourism (making Kazakhstan cheaper) and domestic tourism (substitution effect, as outbound travel becomes prohibitive). Inflation, particularly the Consumer Price Index (CPI) for transport and hospitality sectors, alters the real cost of travel.

4.2. Demographic and Social Factors: Population growth in source markets mechanically increases potential demand. Furthermore, age structure impacts the type of tourism demanded; younger demographics may drive adventure tourism in Almaty, while older cohorts may favor health and wellness tourism in Saryagash or Burabay. Urbanization rates also correlate positively with the propensity to travel.

4.3. Geographical and Natural Factors: Geography acts as both an attraction and a barrier. The vast distances between Kazakhstan's cities create high internal friction of distance, necessitating expensive air travel or lengthy rail journeys. Climate variables, such as average temperature and snowfall, directly impact predictive models for specific resorts (e.g., snow depth for Shymbulak).

4.4. Transport and Infrastructure Factors: The availability of direct international flight routes is a leading indicator for non-CIS inbound tourism. Capacity constraints, such as the number of available hotel beds in a specific region, create a ceiling on observed demand, meaning forecasting models must sometimes utilize truncated or censored regression techniques when demand exceeds supply.

4.5. Institutional and Policy Factors: State interventions play a dominant role. The introduction of visa-free regimes (e.g., the 14-day visa-free regime for Chinese citizens, or the 30-day regime for OECD nations) acts as a structural break in time-series data, shifting demand curves outward. The 'Open Skies' aviation policy also dramatically alters accessibility variables.

4.6. External and Geopolitical Factors: Kazakhstan's tourism demand is highly sensitive to external shocks. Geopolitical instability in neighboring regions, border closures, global pandemics, and international sanctions can abruptly sever established tourist flows or create unexpected influxes (e.g., relocation flows from Russia in 2022).

4.7. Digital and Informational Factors: High-frequency data, such as Google Trends search indices for terms like 'Travel Kazakhstan' or flight booking queries, provide leading indicators that can improve short-term forecast accuracy before official statistical data is published.

Table 3. Classification of tourism demand determinants in Kazakhstan.

Category	Key Variables	Theoretical Effect on Demand	Data Source Example
Economic	Source GDP per capita, Exchange rates (KZT/USD), CPI	Higher income = higher demand. Cheaper destination = higher demand.	World Bank, National Bank of RK
Geographical	Distance, Climate indices, Spatial accessibility	Greater distance = lower demand (friction). Favorable climate = higher demand.	Kazhydromet, GIS mapping
Institutional	Visa policies (dummy variable), Tourism budgets	Liberalized entry = sudden demand spikes (structural break).	Ministry of Tourism and Sports RK
Infrastructure	Flight frequencies, Hotel bed capacity, Rail links	Increased capacity enables latent demand to become observed demand.	Bureau of National Statistics, Aviation admin
Digital	Search engine indices, Social media mentions	Higher search volume precedes physical arrivals (leading indicator).	Google Trends, Baidu Index

5. Methodological Approaches to Tourism Demand Forecasting

The scientific literature offers a wide array of methodological approaches for forecasting tourism demand. The selection of an appropriate method depends on the forecast horizon, data availability, and the specific objectives of the analysis (e.g., causal explanation vs. pure prediction).

Time-Series Models: Traditional time-series approaches, such as Autoregressive Integrated Moving Average (ARIMA) and Exponential Smoothing (ETS), model demand exclusively as a function of its own past values and error terms. These models are highly effective for short-term forecasting where historical patterns (trend and seasonality) are expected to continue. Seasonal ARIMA (SARIMA) is particularly suited for Kazakhstan's highly seasonal domestic data. However, they lack explanatory power, as they cannot account for changes in economic policies or price shocks.

Econometric Models: Econometric methods, including Autoregressive Distributed Lag (ARDL) models, Vector Autoregression (VAR), and panel data regression, incorporate causal

explanatory variables. These models are essential for understanding the elasticity of demand and performing policy simulations (e.g., 'What will happen to demand if the Tenge depreciates by 10%?'). Gravity models, a subset of econometrics, are optimal for predicting international inbound flows by utilizing panel data of bilateral flows between Kazakhstan and various origin countries.

Machine Learning and AI: In recent years, Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forests, and Gradient Boosting have gained prominence. These non-parametric methods excel at capturing complex, non-linear relationships and handling large volumes of unstructured data (e.g., search engine indices). However, they often act as 'black boxes', lacking the economic interpretability required by policymakers.

Hybrid Models: State-of-the-art forecasting increasingly relies on hybrid models that combine the strengths of different approaches. For example, an ARIMA-ANN model uses ARIMA to capture linear trends and ANN to model the non-linear residuals. Such combinations have consistently demonstrated superior predictive accuracy (lower MAPE and RMSE) in empirical tourism studies.

Table 4. Comparison of traditional and advanced tourism forecasting methods.

Methodology Group	Specific Models	Strengths	Limitations for Kazakhstan Context
Time-Series	ARIMA, SARIMA, ETS	Low data requirement, strong short-term accuracy.	Cannot explain causality, fails during structural breaks (e.g., COVID-19).
Econometric	ARDL, VAR, Panel Data, Gravity	High interpretability, estimates elasticities, allows scenario testing.	Requires long, stable historical datasets; vulnerable to multicollinearity.
Machine Learning	ANN, Random Forest, SVM	Captures non-linear patterns, handles big data effectively.	Black box nature, requires large sample sizes often missing in KZ stats.
Hybrid Approaches	ARIMA-ANN, Econometric-ML	Superior accuracy, robust to varying data patterns.	High computational complexity, difficult to implement for regional DMOs.

6. Proposed Methodological Framework for Kazakhstan

Given the specific constraints of the Kazakhstani tourism sector—namely, the presence of structural breaks, high seasonality, and sometimes limited historical data series—a singular forecasting model is insufficient. This study proposes an integrated, multi-tier methodological framework.

Step 1: Data Preparation and Variable Selection. The primary dependent variables (Y_t) should be monthly or quarterly tourist arrivals (domestic and inbound) and overnight stays, sourced from the Bureau of National Statistics (BNS). Explanatory variables (X_t) must include source-market GDP, real exchange rates, and transport capacity. Dummy variables must be constructed for structural breaks: D_covid (2020-2021), D_expo (2017 for Astana), and D_visa (policy shifts).

Step 2: Model Formulation. For short-term tactical planning (1-12 months), a Seasonal ARIMA model is recommended. The mathematical representation is SARIMA (p,d,q)(P,D,Q)s, where 's' represents the seasonal frequency (e.g., 12 for monthly data). For medium- to long-term strategic planning (1-5 years), where causal understanding is necessary, an ARDL boundary testing

approach is proposed. The ARDL framework is robust to variables integrated at different orders [I(0) and I(1)], which is typical for macroeconomic tourism data.

Step 3: Validation and Evaluation. The dataset must be divided into a training set (e.g., 2015-2023) and a testing set (e.g., 2024). Forecast accuracy should be evaluated using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). Mean Absolute Percentage Error (MAPE) should be used with caution, as regional data in off-peak months may approach zero, causing MAPE to distort toward infinity.

Table 5. Proposed variables for econometric tourism demand models.

Variable Name	Type	Definition & Specification	Expected Sign / Relationship
ARR_inbound	Dependent	Total quarterly international arrivals	N/A
ARR_dom	Dependent	Total quarterly domestic arrivals	N/A
INC_origin	Explanatory	Weighted real GDP index of top 5 source markets	Positive (+)
REL_PRICE	Explanatory	CPI of Kazakhstan / CPI of Origin * Exchange Rate	Negative (-)
AIR_CAPACITY	Explanatory	Available international airline seats per quarter	Positive (+)
D_VISA	Dummy	1 if visa-free regime active, 0 otherwise	Positive (+)
D_CRISIS	Dummy	1 during pandemic/border closures, 0 otherwise	Negative (-)

7. Empirical and Statistical Analysis

To operationalize the proposed framework, an empirical dataset must be assembled. According to the Bureau of National Statistics of the Republic of Kazakhstan, tourism data is collected through various statistical forms, including reports from accommodation facilities and border control data. While a full econometric estimation is beyond the scope of this methodological paper due to the real-time unavailability of finalized 2025 datasets and the necessity of extensive data cleaning, we present the structural outline of the empirical statistics that underpin the models.

Historical data (2015-2024) illustrates significant volatility. Prior to 2020, inbound tourism showed steady growth, heavily influenced by the 2017 EXPO in Astana, which created a definitive spike in arrivals. The 2020-2021 period represents a severe negative structural break due to the pandemic. The post-2022 recovery has been asymmetrical; domestic tourism rebounded rapidly, surpassing pre-pandemic levels as citizens substituted foreign holidays with local destinations like Almaty and Mangystau. Inbound tourism recovery has been complicated by regional geopolitical tensions, altering the traditional composition of source markets.

*Note: Data approximations based on historical Bureau of National Statistics trends for illustrative framework purposes.

Table 6. Official tourism indicators and structural events for empirical analysis framework.

Year	Domestic Arrivals (Millions)*	Inbound Arrivals (Millions)*	Accommodation Units	Key Statistical Event
2015	4.1	6.4	2,300	Baseline growth period
2017	4.6	7.7	2,900	EXPO-2017 in Astana (Peak)
2019	5.3	8.5	3,600	Pre-pandemic maximum
2020	2.1	1.7	3,500	COVID-19 structural break
2022	6.5	4.7	3,800	Strong domestic recovery, geopolitical shifts
2023	7.0	5.1	4,000	Visa-free regimes expanded (e.g., China)

8. Discussion

The integration of international forecasting methodologies into the Kazakhstani context presents both opportunities and challenges. The proposed methodological framework underscores that standard, 'off-the-shelf' models often fail when applied to transitional economies. High volatility, extreme seasonality, and frequent policy shifts (such as sudden changes to visa regimes or regional subsidies) generate non-stationary data that violate the assumptions of basic regression models.

A critical discussion point is the disparity in regional data quality. While metropolitan centers like Almaty and Astana possess relatively robust and frequent data collection mechanisms, remote regions (e.g., Ulytau, Abai) suffer from reporting lags and the informal economy. Shadow tourism—unregistered accommodations and informal transport—creates a discrepancy between observed statistical demand and actual physical demand. Consequently, forecasting models based solely on official statistics may systematically under-predict infrastructure requirements in rural areas.

Furthermore, the transferability of machine learning models to Kazakhstan is currently constrained by data volume. Deep learning algorithms require thousands of data points to train effectively. Given that reliable monthly tourism data in Kazakhstan generally spans only the last decade (yielding roughly 120-150 data points), simpler econometric models (ARDL) or time-series (SARIMA) remain statistically more reliable and less prone to overfitting.

Table 7. Forecast evaluation metrics and their applicability.

Metric	Formula / Concept	Advantage in KZ Context	Drawback in KZ Context
MAE (Mean Absolute Error)	Average of absolute errors	Robust to outliers (e.g., sudden spikes).	Doesn't heavily penalize large forecast misses.
RMSE (Root Mean Square Error)	Square root of average squared errors	Penalizes large errors, crucial for capacity planning.	Highly sensitive to extreme pandemic-era anomalies.
MAPE (Mean Absolute Pct Error)	Average of absolute percentage errors	Easy to interpret for non-technical policymakers.	Fails mathematically if observed arrivals drop near zero in off-season.

9. Practical Recommendations for Tourism Policy and Management

Based on the methodological findings and factor analysis, the following practical recommendations are proposed to enhance tourism demand forecasting and policy implementation in Kazakhstan:

1. Establishment of a Centralized Tourism Analytics Hub: The Ministry of Tourism and Sports, in collaboration with the BNS, should establish a dedicated predictive analytics unit. This unit would transcend descriptive statistics, utilizing the ARDL and SARIMA frameworks to generate quarterly rolling forecasts.

2. Integration of High-Frequency Digital Data: To overcome the lagging nature of official statistics, destination management organizations (DMOs) should incorporate digital footprints (e.g., flight search queries, mobile roaming data, and online booking aggregator trends) into short-term forecasting models as leading indicators.

3. Regionalized Forecasting Sub-Models: Due to stark geographic and climatic differences, a single national forecast is insufficient. Separate models must be estimated for distinct clusters (e.g., a winter-centric model for Almaty, a summer-centric model for Mangystau) to ensure accurate infrastructure allocation.

4. Scenario-Based Master Planning: Policymakers must move away from static target-setting. Forecasts should be presented as probabilistic ranges (optimistic, baseline, pessimistic) incorporating macroeconomic scenarios (e.g., fluctuations in oil prices impacting domestic income, or shifts in regional geopolitics).

Table 8. Institutional recommendations for tourism forecasting implementation.

Recommendation	Responsible Stakeholder	Timeframe	Expected Impact
Implement rolling SARIMA forecasts	Ministry of Tourism / BNS	Short-term (1 year)	Improved short-term resource allocation.
Integrate mobile roaming big data	Kazakh Tourism / Telecoms	Medium-term (2-3 years)	Capture shadow/informal domestic tourism volumes.
Develop regional ARDL models	Regional DMOs (Akimats)	Medium-term (2-3 years)	Understand specific local elasticities and climate impacts.
Scenario-based infrastructure planning	Ministry of Nat. Economy	Continuous	Prevent overinvestment and stranded assets in resorts.

10. Conclusion

Tourism demand forecasting is a vital, yet complex, component of strategic economic planning. For Kazakhstan, unlocking the potential of the tourism sector requires transitioning from reactive, purely descriptive data analysis to proactive, predictive modeling. This study has established a comprehensive theoretical and factor-based foundation for understanding tourism demand in the unique geographic and economic context of the country. By systematically classifying the economic, geographical, institutional, and infrastructural determinants, this research highlights the multifaceted nature of tourist flows in Central Asia.

The methodological review demonstrates that while traditional time-series models offer short-term utility, the high volatility and structural shifts inherent in Kazakhstan's transitional economy necessitate the use of causal econometric models (such as ARDL) and the exploration of hybrid methodologies. The proposed framework provides a rigorous, reproducible pathway for analysts and policymakers to generate reliable forecasts that account for extreme seasonality and external shocks.

The primary limitation of this research domain remains data quality and availability, particularly concerning latent demand and informal tourism activities. Future empirical research should focus on the application of machine learning techniques using big data (e.g., geospatial tracking and web search data) to complement official statistics. Ultimately, adopting advanced forecasting methodologies will enable Kazakhstan to optimize its tourism infrastructure, implement effective destination management, and secure sustainable growth in the non-oil economy.

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Table 9. Tourism demand forecasting scenarios and their assumptions.

Scenario	Underlying Economic Assumption	Expected Impact on Forecasting Trajectory
Baseline	Stable GDP growth (3-4%), constant real exchange rates.	Linear trend extrapolation, mild seasonal variations.
Optimistic	Visa liberalization expands, major transport subsidy launched.	Structural upward shift, exponential growth curve in short term.
Pessimistic	Regional geopolitical deterioration, inflation spikes.	Contraction in demand, heightened price sensitivity elasticity.
Climate Shock	Severe winter/summer anomalies shorten season.	Truncation of peak season volume, flat annual growth.

Table 10. Limitations and future research priorities regarding data constraints.

Data Source Constraint	Methodological Impact	Proposed Workaround
Short historical series (<10 years)	Prevents complex Machine Learning and VAR models.	Use parsimonious models (ARIMA, Simple Regression).
High frequency missing data	Interrupts time-series continuity.	Interpolation techniques, temporal disaggregation.
Informal accommodation sector	Underestimates true volume of tourist arrivals.	Incorporate proxy variables (e.g., waste generation, mobile data).

Table 11. Conceptual mathematical framework linking data collection and model estimation.

Model Component	Mathematical/Conceptual Framework	Application in Research
Dependent Variable (Y)	$Y_t = f(X_t) + e_t$	Capturing observed tourist arrivals (monthly/quarterly)
Elasticity Estimation	$\ln(Y_t) = B_0 + B_1*\ln(GDP) + B_2*\ln(Price) + u_t$	Measuring percentage change in demand relative to income/price
Seasonal Adjustment	Y_t = Trend * Seasonality * Irregular	Isolating structural growth from summer/winter fluctuations
Forecast Evaluation	Minimizing sum of squared residuals (e_t^2)	Comparing baseline ARIMA against advanced ARDL models

Journalism

ИНТЕРНЕТ-ЖАРНАМАДАҒЫ ВИЗУАЛДЫ КОММУНИКАЦИЯНЫҢ ЗАМАНАУИ ДИЗАЙН ТЕНДЕНЦИЯЛАРЫ

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Ғылыми жетекші:
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Аңдатпа (Аннотация)

Бұл мақалада интернет-жарнамадағы визуалды коммуникацияның заманауи дизайн тенденциялары, олардың жарнамалық өнімнің визуалды бейнесін қалыптастырудағы рөлі және коммуникациялық тиімділігі ғылыми тұрғыдан талданады. Зерттеудің негізгі мақсаты – цифрлық ортадағы графикалық дизайн шешімдерін жүйелеу және олардың аудитория назарын аударудағы қызметін бағалау. Зерттеу барысында визуалды-контенттік талдау, салыстыру және жүйелеу әдістері қолданылды. Мақалада типографика, түс, композиция, анимация және интерактивті элементтердің цифрлық жарнамадағы рөлі қарастырылып, дәстүрлі жарнамадан айырмашылықтары айқындалады. Әлеуметтік желілердегі, баннерлік және мобильді жарнама форматтарының визуалды ерекшеліктеріне салыстырмалы талдау жасалады. Сонымен қатар, Қазақстандық нарыққа тән визуалды коммуникацияны бейімдеу (көптілділік, ұлттық мәдени кодтар, кирилл қаріптері) мәселелері зерттелді. Зерттеу нәтижесінде жарнама дизайнерлері мен цифрлық маркетологтарға арналған интернет-жарнаманың визуалды бейнесін жобалаудың жүйелі практикалық ұсыныстары мен өлшемдері әзірленді. Ұсынылған жіктеулер мен модельдер цифрлық медиадағы жарнамалық коммуникацияның сапасын арттыруға негіз бола алады.

Түйін сөздер: интернет-жарнама, визуалды коммуникация, графикалық дизайн, цифрлық жарнама, визуалды бейне, типографика, дизайн тенденциялары, жарнамалық өнім.

Кіріспе

Қазіргі цифрлық дәуірде ақпаратты тұтыну үлгілерінің түбегейлі өзгеруі интернет-жарнаманың рөлін бұрын-соңды болмаған деңгейге көтерді. Ақпараттық шудың артуы және пайдаланушылардың назарын аудару үшін бәсекелестіктің күшеюі жағдайында визуалды коммуникация жарнамалық хабарламаны жеткізудің ең басты құралына айналып отыр. Осы ретте, интернет-жарнамадағы графикалық дизайн тек эстетикалық безендіру қызметін ғана емес, стратегиялық коммуникациялық мақсаттарды жүзеге асырудың қуатты тетігін білдіреді.

Зерттеудің өзектілігі цифрлық технологиялардың, соның ішінде мобильді құрылғылар мен әлеуметтік медиа платформалардың қарыштап дамуымен тікелей байланысты. Пайдаланушы тәжірибесі (user experience, UX) мен адаптивті дизайн (responsive design)

талаптарының күшеюі, сондай-ақ генеративті жасанды интеллекттің (ЖИ) контент жасау процесіне енуі визуалды бейнені қалыптастырудың дәстүрлі тәсілдерін қайта қарауды қажет етеді. Сондықтан, интернет-жарнаманың заманауи парадигмасы аясында жарнамалық өнімнің визуалды бейнесін зерттеу, дизайн тенденцияларын ғылыми негіздеу теориялық және практикалық тұрғыдан маңызды мәселе болып табылады.

Бұл мақала «Интернет-жарнаманың заманауи парадигмасы: жарнамалық өнімнің визуалды бейнесі» атты диссертациялық зерттеу аясында орындалған және оның негізгі теориялық-практикалық бағыттарын қамтиды. Зерттеудің нысаны – интернет-жарнамадағы визуалды коммуникация процесі. Зерттеу пәні – жарнамалық өнімнің визуалды бейнесін қалыптастыратын заманауи графикалық дизайн тенденциялары.

Мақаланың мақсаты – интернет-жарнамадағы визуалды коммуникацияның заманауи дизайн тенденцияларын жүйелі түрде талдау, олардың жарнамалық өнімнің визуалды бейнесін қалыптастырудағы рөлін анықтау және цифрлық ортада тиімді визуалды шешімдерді қолданудың негізгі қағидаларын негіздеу. Осы мақсатқа жету үшін визуалды коммуникация ұғымының теориялық негіздері талданады, графикалық элементтердің қызметі жүйеленеді, заманауи тенденциялар жіктеліп, әртүрлі жарнама форматтарының визуалды ерекшеліктеріне салыстырмалы баға беріледі.

Материалдар мен әдістер

Зерттеу барысында визуалды коммуникация, графикалық дизайн, жарнама психологиясы және цифрлық медиа салаларындағы отандық және шетелдік ғылыми әдебиеттерге сыни талдау жүргізілді. Негізгі ғылыми-теориялық база ретінде визуалды семиотика, когнитивтік психология және пайдаланушы интерфейсі (user interface, UI) теорияларына сүйенген іргелі еңбектер қарастырылды.

Интернет-жарнама форматтарының визуалды құрылымын зерттеу үшін визуалды-контенттік талдау әдісі қолданылды. Бұл әдіс жарнамалық өнімнің композициясы, түс шешімдері, типографикасы және анимациялық элементтері сияқты визуалды құрамдас бөліктерін функционалдық тұрғыдан бағалауға мүмкіндік берді. Түрлі платформалардағы (әлеуметтік желілер, веб-сайттар, мобильді қосымшалар) жарнамалық баннерлер мен бейнежарнамалардың визуалды иерархиясы сараланды.

Сонымен қатар, заманауи графикалық дизайн тенденцияларын жүйелеу және олардың коммуникациялық тиімділігін анықтау мақсатында салыстырмалы талдау және жіктеу әдістері пайдаланылды. Дәстүрлі визуалды шешімдер мен цифрлық дизайн тәсілдерін қарама-қарсы қоя отырып, интернет-жарнаманың эволюциялық даму векторлары айқындалды. Зерттеу логикасы дедуктивті сипатқа ие: жалпы теориялық тұжырымдардан бастап, нақты визуалды дизайн құралдарын бағалауға және Қазақстандық нарық жағдайына бейімделген практикалық ұсыныстарды әзірлеуге бағытталды.

Әдебиеттерге шолу

Визуалды коммуникация және оның жарнамадағы рөлі көптеген ғылыми пәндердің қиылысында зерттеліп келеді. Г. Кресс пен Т. ван Левеннің (Kress & van Leeuwen, 2020) «Оқу бейнелері: Визуалды дизайн грамматикасы» атты іргелі еңбегінде визуалды элементтердің мағынаны қалай құрылымдайтыны және көрерменмен визуалды диалогты қалай орнататыны семиотикалық тұрғыдан негізделген. Олардың тұжырымы бойынша, дизайн элементтері кездейсоқ орналаспайды, олар белгілі бір әлеуметтік және коммуникациялық қызметті атқаратын грамматикалық ережелерге бағынады.

Когнитивтік психология және пайдаланушы тәжірибесі (UX) бағытында Д. Норманның (Norman, 2013) зерттеулері айрықша маңызды. Ол визуалды дизайнның тек эстетикаға ғана емес, ең алдымен функционалдылыққа, жүйенің түсініктілігіне және пайдаланушының когнитивтік жүктемесін азайтуға бағытталуы тиіс екенін дәлелдейді. Бұл қағида интернет-жарнамадағы визуалды иерархия (visual hierarchy) ұғымын түсінудің негізін қалайды.

Сонымен бірге, Л. Манович (Manovich, 2013) өзінің «Программалық қамтамасыз ету билігі» еңбегінде цифрлық медиадағы визуалды бейнелердің бағдарламалық код арқылы басқарылатынын және олардың интерактивті табиғатын ашып көрсетеді.

Жарнама психологиясы мен тиімділігі тұрғысынан С. Мориарти және басқаларының (Moriarty et al., 2014) еңбектерінде визуалды коммуникацияның эмоциялық байланыс орнатудағы және брендті сәйкестендірудегі шешуші рөлі талданған. Цифрлық маркетинг мамандары Д. Чаффи мен Ф. Эллис-Чедвик (Chaffey & Ellis-Chadwick, 2019) интернет-жарнаманың дәстүрлі жарнамадан басты айырмашылығы оның дербестендірілуінде, өлшемділігінде (measurability) және форматтардың динамикалық түрде бейімделуінде екенін алға тартады.

Қазіргі ғылыми дискурста қозғалыс дизайнының (motion design), микроинтеракциялардың және генеративті жасанды интеллекттің визуалды мазмұн жасауға тигізетін әсері туралы мақалалар көбейіп келеді. Алайда, қазақстандық ғылыми кеңістікте интернет-жарнаманың нақты визуалды-дизайн тенденцияларын, әсіресе қазақ тіліндегі типографика және ұлттық визуалды кодтардың цифрлық ортадағы адаптациясын кешенді түрде қарастыратын зерттеулер әлі де аз. Бұл зерттеу осы олқылықтың орнын толтырып, жаһандық трендтер мен локальді ерекшеліктерді синтездеуге талпынады.

Зерттеу нәтижелері және талқылау

Визуалды коммуникацияның теориялық негіздері және элементтері

Визуалды коммуникация — бұл ақпаратты, идеяларды және эмоцияларды графикалық бейнелер, типографика, түс және кеңістік арқылы жеткізу процесі. Интернет-жарнама контекстінде оның басты қызметі — пайдаланушының назарын лезде аудару (көбінесе бірнеше секунд ішінде), хабарламаның мәнін жылдам жеткізу және мақсатты әрекетке (click, конверсия) итермелеу. Дәстүрлі баспа жарнамасына қарағанда, интернет-жарнама интерактивтілікке, мультимедиялылыққа және форматтардың экран өлшемдеріне қарай бейімделуіне (responsive design) негізделген.

Жарнамалық өнімнің визуалды бейнесі біртұтас коммуникациялық актіні құрайтын бірнеше негізгі элементтерден тұрады. Бұл элементтердің әрқайсысы белгілі бір когнитивтік және психологиялық жүктемені көтереді.

1-кесте. Интернет-жарнамадағы визуалды коммуникацияның негізгі элементтері және олардың функциялары

Визуалды элемент	Интернет-жарнамадағы негізгі функциясы	Психологиялық және когнитивтік әсері
Типографика (Қаріптер)	Мәтіндік ақпаратты құрылымдау, оқылымдылықты қамтамасыз ету, бренд дауысын (tone of voice) беру.	Мәтінді қабылдау жылдамдығын реттейді. Батыл қаріптер сенімділік ұялатса, серифті қаріптер дәстүр мен консерватизмді білдіреді.
Түс палитрасы	Назар аударту, визуалды контраст жасау, брендтің корпоративті стилін қолдау.	Эмоциялық реакция тудырады (мысалы, қызыл – акцент/шұғылдық, көк – сенімділік, жасыл – экология/өсу).
Иллюстрация / Фотография	Тауарды немесе қызметті визуалды түрде көрсету, контекст беру, визуалды метафора жасау.	Ассоциативті байланыс орнатады, эмпатия тудырады (әсіресе адам бейнелері пайдаланылғанда).
Композиция және кеңістік	Элементтердің орналасу ретін анықтау, бос кеңістікті (negative space) тиімді қолдану.	Когнитивтік жүктемені азайтады. Дұрыс композиция көздің қозғалу траекториясын бағыттайды.
Анимация / Қозғалыс	Динамика қосу, басты назарды қажетті элементке бұру (микроинтеракциялар).	Статикалық экранда қозғалыс адам назарын рефлекторлық түрде өзіне тартады.

Жарнамалық өнімнің визуалды бейнесін қалыптастыру

Жарнамалық өнімнің визуалды бейнесі жекелеген элементтердің жиынтығынан ғана емес, олардың өзара байланысын қамтамасыз ететін композициялық құралдардан тұрады. Визуалды иерархияны дұрыс құру – ақпаратты тұтыну процесін басқарудың кепілі. Пайдаланушы интернет парақшаны қарап шыққанда F-тәрізді немесе Z-тәрізді оқу паттерндерін қолданады. Дизайнерлер осы паттерндерге сүйене отырып, ең маңызды ақпаратты (бас тақырып, Call-to-Action батырмасы) стратегиялық нүктелерде орналастырады.

2-кесте. Жарнамалық өнімнің визуалды бейнесін қалыптастыратын композициялық құралдар

Композициялық құрал	Қолданылу сипаты	Коммуникациялық мақсаты
Визуалды иерархия	Өлшем, түс және орналасу арқылы элементтердің маңыздылық ретін көрсету.	Пайдаланушыға ақпаратты оқу кезегін (бас тақырып -> негізгі мәтін -> батырма) нұсқау.
Контраст	Фон мен мәтін, немесе әртүрлі визуалды блоктар арасындағы айырмашылықты күшейту.	Оқылымдылықты арттыру және басты элементтерді (мысалы, жеңілдік мөлшерін) ерекшелеу.
Бағыттаушы сызықтар	Графикалық элементтер немесе кейіпкердің жанары арқылы көрінбейтін сызықтар құру.	Аудиторияның назарын тікелей мақсатты әрекет батырмасына (CTA) немесе өнімге бағыттау.
Бос кеңістік (Negative space)	Элементтер арасындағы дем алатын бос орындарды қалдыру.	Ақпараттық шуды азайтып, басты визуалды хабарламаның қабылдануын жеңілдету.

Заманауи дизайн тенденцияларының талдауы

Интернет-жарнама дизайны үнемі трансформацияға ұшырап отырады. Бұл өзгерістер тек эстетикалық талғамның ауысуымен емес, технологиялық мүмкіндіктердің (интернет жылдамдығының артуы, экран ажыратымдылығының жақсаруы) және пайдаланушы психологиясының өзгеруімен (назар ұстау уақытының қысқаруы) негізделеді.

Қазіргі таңда мынадай негізгі дизайн тенденциялары үстемдік етуде: минимализм, батыл типографика, қозғалыс дизайны (motion design), үшөлшемді (3D) графика және генеративті жасанды интеллект арқылы жасалған контент. Минимализм когнитивтік жүктемені азайтуға бағытталса, динамикалық типографика бейнежарнамаларда дыбыссыз ойнату режимінде де ақпараттың жетуін қамтамасыз етеді.

3-кесте. Заманауи графикалық дизайн тенденцияларының салыстырмалы сипаттамасы

Дизайн тенденциясы	Визуалды сипаттамасы	Интернет-жарнамадағы артықшылықтары мен шектеулері
Минимализм және визуалды ықшамдау	Шектеулі түс палитрасы, көп бос кеңістік, артық детальдардан бас тарту.	Артықшылығы: хабарлама өте тез оқылады, мобильді құрылғыларда жақсы көрінеді. Шектеуі: тым қарапайым болып, назар тартпай қалуы мүмкін.
Батыл типографика (Bold typography)	Өте ірі, әдеттен тыс немесе анимацияланған қаріптердің басты визуалды элементке айналуы.	Артықшылығы: суретсіз-ақ күшті визуалды соққы жасайды. Шектеуі: мәтін ұзақ болса, оқылымдылығы төмендейді.
Қозғалыс дизайны (Motion design)	Графикалық элементтердің, мәтіннің немесе интерфейстің үздіксіз, жұмсақ қозғалысы.	Артықшылығы: баннерлік соқырлықты (banner blindness) жеңуге көмектеседі. Шектеуі: файл көлемін үлкейтіп, сайттың жүктелуін баяулатуы ықтимал.
Үшөлшемді (3D) графика	Тереңдігі, көлемі және шынайы текстурасы бар объектілер немесе кейіпкерлер.	Артықшылығы: жоғары эстетикалық құндылық, өнімді шынайы көрсету. Шектеуі: өндіріс уақыты мен құны жоғары.
ЖИ арқылы жасалған визуал (Generative AI)	Midjourney, DALL-E сияқты нейрожелілер арқылы генерацияланған бірегей суреттер.	Артықшылығы: жылдамдық, шексіз креативті нұсқалар. Шектеуі: авторлық құқық мәселелері және кейде жасанды немесе 'пластик' көрінуі.

Жарнамалық форматтардың визуалды ерекшеліктері

Интернет-жарнама бірнеше негізгі форматтарға бөлінеді, және олардың әрқайсысы дизайнға өзіндік талаптар қояды. Әлеуметтік желілердегі жарнама (Instagram, TikTok) көбінесе тік (vertical) форматқа және алғашқы 3 секундта назар аударуға негізделген. Ал дәстүрлі баннерлік жарнама статикалық немесе шектеулі анимациялы болып, негізгі акцентті мәтінге (Copywriting) және CTA батырмасына қояды.

4-кесте. Жарнама форматтарының визуалды ерекшеліктерін салыстыру

Жарнама форматы	Композициялық құрылымы мен визуалды ерекшелігі	Аудитория назарын ұйымдастыру тәсілі
Әлеуметтік желі (Таспа / Feed)	Шаршы (1:1) немесе тік (4:5) формат, бейресми стиль, органикалық контентке ұқсастық.	Қолданушының лентаны айналдыруын тоқтату үшін контрастты сурет немесе күтпеген ракурс қолданылады (thumb-stopping).
Әлеуметтік желі (Stories / Reels)	Тік формат (9:16), динамикалық, мәтіннен гөрі визуал мен дыбысқа басымдық беріледі.	Экранды толық жабу арқылы иммерсивті тәжірибе жасау, қысқа әрі жылдам кадр алмасу.
Веб-баннерлер (Display Ads)	Стандартты өлшемдер (мысалы, 300x250, 728x90), шектеулі кеңістік, статикалық немесе GIF.	Тікелей хабарлама, көзге түсетін ірі батырма, фоннан айқын ерекшеленетін жақтау немесе контраст.
Бейнежарнама (YouTube Pre-roll)	Көлденең (16:9), жоғары сапалы өндіріс, хикаялау (storytelling) элементі.	Алғашқы 5 секундта басты визуалды ілмек (hook) және брендті көрсету, көруді жалғастыруға интрига жасау.

Дәстүрлі және цифрлық дизайн тәсілдерінің айырмашылығы

Дәстүрлі жарнамалық визуал (газет, журнал, билборд) статикалық, бір бағытты коммуникацияны білдіреді. Онда қателіктерді жөндеу қиын және дизайн өзгеріссіз қалады. Цифрлық жарнама дизайны икемді, адаптивті және көп нұсқалы. A/B тестілеу арқылы дизайнерлер түрлі визуалды шешімдердің (мысалы, қызыл батырма мен жасыл батырманың) қайсысы аудиторияға көбірек әсер ететінін нақты деректер негізінде анықтай алады.

5-кесте. Дәстүрлі визуалды шешімдер мен заманауи цифрлық дизайн тәсілдерінің салыстырмасы

Өлшем / Сипат	Дәстүрлі визуалды шешімдер (Баспа/Сыртқы)	Заманауи цифрлық дизайн тәсілдері
Икемділік	Статикалық, басып шығарылғаннан кейін өзгермейді.	Адаптивті (түрлі құрылғыларға бейімделеді), кез келген уақытта жаңартылады.
Интерактивтілік	Пассивті қабылдау (тек қарау).	Белсенді қатысу (басу, айналдыру, анимациямен әрекеттесу).
Дербестендіру	Жалпы масс-маркетке арналған бірыңғай дизайн.	Пайдаланушы деректеріне негізделген динамикалық визуал (динамикалық ретаргетинг).
Нәтижені өлшеу	Тікелей өлшеу мүмкін емес немесе өте қиын.	Әрбір басу (click), қарау уақыты нақты бағаланады.

Визуалды дизайн тиімділігін бағалау көрсеткіштері

Ғылыми тұрғыдан алғанда, жарнама дизайнының тиімділігі тек оның эстетикалық тартымдылығымен өлшенбейді. Өте әдемі, күрделі дизайн коммерциялық тұрғыдан сәтсіз болуы, ал қарапайым, контрастты дизайн жоғары нәтиже беруі мүмкін. Сондықтан визуалды коммуникацияның тиімділігі нақты сандық көрсеткіштермен бағаланады.

6-кесте. Визуалды дизайн тиімділігін бағалау көрсеткіштері және олардың қолданылу аясы

Метрика (Көрсеткіш)	Анықтамасы	Визуалды дизайнмен байланысы
Басу коэффициенті (CTR - Click-Through Rate)	Жарнаманы көргендердің оны басқандарға шаққандағы пайызы.	Визуалды иерархия мен CTA батырмасының контрасты мен тартымдылығын тікелей көрсетеді.
Конверсия коэффициенті (Conversion Rate)	Жарнаманы басып өтіп, мақсатты әрекетті (сатып алу, тіркелу) орындағандар пайызы.	Сайттағы визуалды дизайнның жарнама үәдесіне (visual consistency) қаншалықты сәйкес келетінін бағалайды.
Көріну деңгейі (Viewability)	Жарнаманың пайдаланушы экранында нақты көріну пайызы мен уақыты.	Дизайнның парақша фонынан қаншалықты дұрыс ерекшеленіп тұрғанын көрсетеді.
Қарау ұзақтығы (View-Through Rate)	Бейнежарнаманы соңына дейін немесе белгілі бір уақытқа дейін көргендер үлесі.	Алғашқы кадрлардың (визуалды ілмек) қаншалықты сәтті жасалғанын, анимация сапасын білдіреді.

Қазақстан жағдайындағы визуалды коммуникация ерекшеліктері

Қазақстандық интернет-жарнама нарығы өзіне тән визуалды, лингвистикалық және мәдени ерекшеліктерге ие. Ең басты фактор – көптілділік (қазақ және орыс тілдері). Дизайнерлер мәтіндік блоктарды жобалау кезінде екі тілдегі мәтін көлемінің әртүрлі болатынын ескеруі қажет (қазақ тіліндегі мәтін көбінесе орыс тіліндегі баламасынан 15-20%-ға ұзағырақ болуы мүмкін). Сонымен қатар, кирилл қаріптерінің, әсіресе қазақ әріптерінің (қ, ұ, ғ, і, ә) сапалы типографиялық нұсқаларын таңдау маңызды мәселе болып табылады.

Соңғы жылдары қазақстандық брендтер жарнамада ұлттық мәдени кодтарды (ою-өрнектердің заманауи интерпретациясы, дәстүрлі түстер, көшпелі мәдениетке сілтеме жасайтын визуалды метафоралар) белсенді қолдана бастады. Бұл тек патриоттық сезімге ғана емес, сонымен бірге жаһандық біртекті контент арасында локальді аудиторияның назарын аударудың тиімді тәсіліне айналуда.

7-кесте. Қазақстандық интернет-жарнамада визуалды коммуникацияны бейімдеу қағидалары

Бейімдеу бағыты	Қазақстандық нарықтағы ерекшелігі	Дизайнға қойылатын талаптар
Типографика және тіл	Қос тілді коммуникация, қазақ тіліне тән әріптердің болуы.	Гарнитура таңдағанда толық кирилл (қазақша) қолдауын тексеру, екі тілді мәтіндерге теңдей визуалды кеңістік қалдыру.
Ұлттық мәдени код	Дәстүрлі элементтердің цифрлық кеңістікте қолданылуы.	Ою-өрнектерді көшірмелемей, заманауи минималистік немесе 3D форматта қайта ойластыру (стилизация).
Визуалды метафора	Локальді әзілдер, мемдер немесе жергілікті танымал тұлғаларды пайдалану.	Мақсатты аудиторияның мәдени контекстін терең түсіну, инклюзивтілікті сақтау.
Түс қабылдау	Климаттық және табиғи ландшафтқа байланысты түс ассоциациялары.	Жергілікті аудиторияға жақын жылы немесе ұлттық реңктерді (көк, сары, алтын) орынды пайдалану.

Интернет-жарнаманың визуалды дизайнын жетілдіру бойынша практикалық ұсыныстар

Зерттеу нәтижелерін қорытындылай келе, интернет-жарнаманың визуалды бейнесін жобалаудың жүйелі алгоритмін ұсынуға болады. Бұл ұсыныстар дизайнерлер мен маркетологтарға процесті оңтайландырып, түпкілікті өнімнің коммуникациялық сапасын арттыруға бағытталған.

8-кесте. Интернет-жарнаманың визуалды дизайнын әзірлеу кезеңдері мен сапаны бағалау критерийлері

Жобалау кезеңі	Орындалатын негізгі әрекеттер	Сапаны бағалау критерийлері
1. Зерттеу және мақсат қою	Мақсатты аудиторияның мінез-құлқын зерттеу, платформаны анықтау (Мис: TikTok немесе веб-сайт).	Коммуникациялық мақсаттың (сату, брендті таныту) нақтылығы.
2. Визуалды архитектура құру	Визуалды иерархияны бекіту, ақпараттық блоктарды (бас тақырып, сурет, батырма) орналастыру.	5 секунд ережесі: басты хабарлама бірден оқыла ма?
3. Дизайн трендтерін қолдану	Типографиканы, түсті таңдау, қажет болса анимация немесе 3D элементтерін қосу.	Эстетиканың функционалдылыққа кедергі келтірмеуі (жүктелу жылдамдығы, оқылымдылық).
4. Мобильді бейімдеу	Смартфон экрандары үшін дизайнды тексеру, 'Dark mode' (қараңғы режим) үшін бейімдеу.	Мәтіннің кішкентай экранда оқылуы, батырмалардың басуға ыңғайлы өлшемі.
5. Тестілеу және өлшеу	A/B тестілеу жүргізу, CTR, Viewability метрикаларын бақылау, қажет болса дизайнды өзгерту.	Деректерге негізделген (Data-driven) шешім қабылдау.

Қорытынды

Интернет-жарнамадағы визуалды коммуникация – бұл жай ғана сурет пен мәтіннің жиынтығы емес, аудиториямен стратегиялық қарым-қатынас орнатудың күрделі құралы. Жүргізілген зерттеу интернет-жарнаманың визуалды бейнесін қалыптастырудағы заманауи дизайн тенденцияларының маңыздылығын толықтай растайды.

Зерттеу барысында анықталғандай, минимализм, батыл типографика, қозғалыс дизайны және генеративті жасанды интеллект сияқты тенденциялар тек эстетикалық жаңаруды емес, ең алдымен ақпараттық шу жағдайында пайдаланушының назарын ұстап тұру қажеттілігін бейнелейді. Типографика, түс, контраст және визуалды иерархия сияқты элементтер когнитивтік психология заңдылықтарына сүйене отырып, коммуникацияның тиімділігін қамтамасыз етеді.

Дәстүрлі жарнамадан айырмашылығы, цифрлық жарнама форматтары (әлеуметтік желілер, баннерлер, бейнежарнама) икемділікті, дербестендіруді және нақты сандық бағалауды (CTR, конверсия) қажет етеді. Сондай-ақ, Қазақстандық нарық жағдайында екі тілділік пен ұлттық мәдени кодтарды визуалды дизайнға дұрыс интеграциялау маңызды артықшылық болып табылады.

Бұл зерттеудің ғылыми жаңалығы – заманауи дизайн тенденцияларын жүйелеп, олардың визуалды коммуникациядағы қызметін нақты жарнамалық форматтар негізінде жіктеуінде. Мақалада ұсынылған практикалық кезеңдер мен бағалау критерийлері дизайнерлер мен цифрлық маркетологтарға күнделікті жұмыста қолдануға арналған ғылыми

негізделген құрал бола алады. Болашақ зерттеулер нейромаркетингтік құралдарды (мысалы, eye-tracking) пайдалана отырып, қазақстандық пайдаланушылардың интернет-жарнаманы визуалды қабылдау ерекшеліктерін эмпирикалық түрде өлшеуге бағытталуы мүмкін.

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Цифрлық медиа кеңістіктің жаңа парадигмасы және фактчекинг мәселесі

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Аннотация: Цифрлық технологиялардың қарқынды дамуы журналистиканың институционалдық құрылымын, ақпарат өндіру тәсілдерін және аудиториямен байланыс орнату тетіктерін түбегейлі өзгертті. Дәстүрлі редакциялық сүзгілердің рөлі әлсіреп, әлеуметтік желілер, видеохостингтер, мессенджерлер мен цифрлық платформалар ақпарат таратудың негізгі арнасына айналды. Бұл процесс ақпарат өндірушілер санын арттырғанымен, жарияланатын мазмұнның тексерілу деңгейін біркелкі етпеді. Генеративті жасанды интеллект пен дипфейк технологиялары визуалды және аудиалды шынайылықты бұрынғыдан жоғары деңгейге көтерді, соның нәтижесінде аудиторияның сенімді дереккөз бен манипуляциялық контентті ажырату қабілеті сынаққа ұшырады.

Мақалада цифрлық медиа кеңістіктің жаңа парадигмасы теориялық тұрғыдан сипатталады, Қазақстандық ақпараттық кеңістіктегі нақты дипфейк кейстері талданады, фактчекинг құралдары қызметіне қарай жіктеледі, әр құралдың мүмкіндіктері мен шектеулері ғылыми тұрғыдан бағаланады. Сонымен қатар қазақстандық редакциялар үшін кешенді тексеру моделі ұсынылады. Эмпирикалық зерттеу нәтижелері келтіріліп, медиасауаттылықты жүйелі түрде дамыту қажеттілігі негізделеді. Зерттеу қорытындысында фактчекингтің тек жалған ақпаратпен күресу құралы ғана емес, қоғамдық сенімді сақтаудың негізгі тетігі екені дәлелденеді.

Түйін сөздер: жасанды интеллект, фактчек, дипфейк, контент, цифрлы журналистика, инфографика.

Кіріспе

Қазіргі кезеңде цифрлық технологиялардың дамуы журналистиканың өндірістік, тарату және қабылдау процестерін қайта құрды. Дәстүрлі медиа жүйесінде ақпаратты іріктеу, тексеру және жариялау негізінен редакция арқылы жүзеге асатын. Журналист материал дайындап, редактор тексергеннен кейін ғана ол аудиторияға ұсынылатын. Ал цифрлық ортада бұл тізбек бұзылды. Кез келген пайдаланушы әлеуметтік желіге мәтін, фотосурет немесе бейнежазба жариялап, оны қысқа уақыт ішінде кең аудиторияға жеткізе алады. Осылайша ақпарат тарату ортасы демократияланып, қоғамдық коммуникацияның қатысушылары күрт көбейді. Алайда өндірушілер санының артуы жарияланатын мәліметтердің барлығы бірдей тексерілген дегенді білдірмейді. Керісінше, кәсіби журналистік материалдар, жеке пікірлер, жарнамалық жарияланымдар және әдейі бұрмаланған ақпарат бір ақпараттық кеңістікте қатар таралады. Олардың сыртқы формасы ұқсас болғандықтан, аудитория сенімді дереккөз бен манипуляциялық контенттің арасындағы айырмашылықты анықтауда қиындыққа тап болады. Сондықтан цифрлық медиа

жағдайында ақпараттың қолжетімділігімен қатар оның шығу тегін, дәлелділігін және қоғамдық маңызын бағалау мәселесі өзекті бола түсті.

Цифрлық трансформацияның тағы бір маңызды көрінісі – конвергентті журналистиканың дамуы. Қазіргі редакциялар бір оқиғаны бірнеше форматта ұсына алады: ақпараттық мақала, қысқа бейнеролик, подкаст, инфографика, әлеуметтік желіге арналған карточка немесе тікелей эфир. Мұндай тәсіл аудиторияның әртүрлі ақпарат тұтыну дағдыларына бейімделуге мүмкіндік береді. Сонымен қатар журналистен тек мәтін жазу қабілетін ғана емес, мультимедиалық контент әзірлеу, визуалды ақпаратты түсіндіру және цифрлық платформалардың ерекшеліктерін ескеру дағдыларын да талап етеді.

Дегенмен контент формаларының көбеюі ақпараттың мазмұндық сапасын автоматты түрде арттырмайды. Керісінше, бір ақпараттың бірнеше форматқа бейімделуі барысында бастапқы контекстің жоғалуы, тақырыптың әсіреленуі немесе маңызды мәліметтердің қысқартылуы мүмкін. Мысалы, ұзақ сұхбаттан алынған қысқа бейнежазба спикердің сөзін бастапқы мағынасынан өзгеше етіп көрсетуі ықтимал. Демек, цифрлық журналистикадағы сапа өлшемі материалдың көрнекілігімен немесе таралу жылдамдығымен ғана емес, мазмұнның дәлдігімен және контекстің сақталуымен де анықталуы керек. Осы үдерістермен қатар жасанды интеллект технологиялары журналистік өндірістің жаңа құралы ретінде қалыптасып келеді. Генеративті ЖИ мәтіннің бастапқы нұсқасын әзірлеуге, көлемді құжаттарды жүйелеуге, аудиожазбаларды транскрипциялауға, аударма жасауға және графикалық материалдар дайындауға көмектеседі. Ал сөйлеуді тану және синтездеу технологиялары аудио мен бейнематериалдарды өңдеу мүмкіндіктерін кеңейтеді. Мұндай құралдар редакцияның уақытын үнемдеп, күнделікті техникалық жұмыстарды жеңілдетуі мүмкін. Алайда олардың тиімділігі қолданылатын деректердің сапасына, тапсырманың ерекшелігіне және алынған нәтижені адамның тексеруіне тікелей тәуелді.

Қазақстандық медиада бұл өзгерістерді телевизиялық өндіріс мысалынан байқауға болады. ЖИ технологияларын редакциялық үдерістерге енгізу тәжірибесі мәтінді дыбыстау, аудио мен бейнені мәтінге айналдыру, графикалық материалдар әзірлеу және монтаж жұмыстарына көмек көрсету сияқты бағыттарды қамтиды. Бұл технологиялардың қолданылуы телевизиядағы контент дайындаудың кейбір кезеңдерін автоматтандыруға мүмкіндік береді. Сонымен бірге автоматтандыру журналистің рөлін жоймайды: ақпаратты іріктеу, оның қоғамдық маңызын бағалау, дереккөздің сенімділігін анықтау және жарияланатын материалдың жауапкершілігін өз мойнына алу редакцияның кәсіби міндеті болып қала береді. Жасанды интеллектінің журналистикаға ықпалын бағалағанда, оны тек тиімділікті арттыратын технология ретінде қарастыру жеткіліксіз. ЖИ жүйелері қате мәлімет ұсынуы, бастапқы дереккөздің мағынасын бұрмалауы немесе шынайы көрінетін, бірақ негізсіз ақпарат құрастыруы мүмкін. Егер мұндай материал редакциялық тексерусіз жарияланса, технологияның жылдамдығы қателіктің де жылдам таралуына жағдай жасайды. Сондықтан цифрлық ортада журналистік жауапкершілік тек материалдың мазмұнына емес, оны әзірлеу кезінде қолданылған технологиялар мен тексеру рәсімдеріне де қатысты қарастырылуы қажет.

Осы тұрғыдан алғанда, цифрлық медиа кеңістіктің жаңа парадигмасы үш өзара байланысты өзгеріс арқылы сипатталады. Біріншіден, ақпарат өндіру мен тарату мүмкіндіктері кәсіби редакциялардан тыс кеңейді. Екіншіден, мультимедиалық және автоматтандырылған құралдар журналистік жұмыстың тәсілдерін өзгертті. Үшіншіден, ақпараттың шынайылығын тексеру мен аудитория сенімін сақтау бұрынғыдан да маңызды кәсіби міндетке айналды. Соңғы өзгеріс әсіресе генеративті жасанды интеллект арқылы жасалған синтетикалық контент пен дипфейктердің таралуы жағдайында айқын көрінеді.

Негізгі бөлім

Генеративті жасанды интеллектінің дамуы цифрлық медиа кеңістікте бұрынғыдан да шынайы көрінетін мәтіндер, фотосуреттер, аудио және бейнематериалдар жасауға мүмкіндік берді. Бұл технологиялар шығармашылық өндірісте, білім беру мен коммуникацияда қолданылуы мүмкін болғанымен, оларды жалған ақпарат тарату, қоғамдық пікірді манипуляциялау немесе алаяқтық әрекеттерді жүзеге асыру мақсатында пайдалану қаупі де бар. Осы жағдайда журналистика үшін негізгі мәселе технологияның өзін жоққа шығару емес, оның көмегімен жасалған контенттің шынайылығын, мақсатын және таралу контекстін анықтау болып отыр. Бұл мәселені түсіну үшін ЖИ көмегімен жасалған контент пен дипфейк ұғымдарын ажырата қарастырған жөн. Жасанды интеллект арқылы жасалған кез келген материал міндетті түрде дипфейк бола бермейді. Мысалы, нейрожелі көмегімен әзірленген инфографика немесе иллюстрация синтетикалық контентке жатуы мүмкін, бірақ ол нақты адамның бейнесін не дауысын қолдан жасап, оның атынан жалған мәлімдеме таратуды көздемеуі ықтимал. Ал дипфейк көбіне адамның бет-әлпетін, дауысын немесе қимыл-қозғалысын имитациялау арқылы көрерменді белгілі бір оқиғаға не мәлімдемеге қатысты жаңылыстыру мүмкіндігімен ерекшеленеді.

Дипфейктің ақпараттық қаупі оның көрнекі шынайылығымен байланысты. Көрермен белгілі бір адамның бейнесін көріп, дауысын естігенде, материалды тікелей дәлел ретінде қабылдауы мүмкін. Бұрын аудио немесе бейнематериал оқиғаның болғанын растауға көмектесетін маңызды деректердің бірі саналса, қазіргі жағдайда визуалды сәйкестікке ғана сүйену жеткіліксіз. Технология адамның бұрынғы бейнесін пайдаланып, оның айтпаған сөзін айтқандай көрсетуі немесе белгілі бір әрекетке қатысқандай әсер қалдыруы мүмкін. Нәтижесінде жалған ақпарат аудиторияның эмоциясына әсер етіп, шешім қабылдауына ықпал етуі ықтимал.

Қазақстандық ақпараттық кеңістікте мұндай қауіптің нақты көріністері бірнеше рет тіркелді. 2025 жылғы 6 мамырда Factcheck.kz порталы Димаш Құдайбергеннің бейнесі пайдаланылған жалған инвестициялық жарнама туралы материал жариялады [1]. Тексеру барысында әлеуметтік желіде тараған видеода әнші «Қазатомпром» инвестициялық платформасын жарнамалап, қысқа мерзімде табыс табуға болатынын айтқандай көрсетілгені анықталды. Видео да, ұсынылған инвестициялық жоба да жалған болған. Алаяқтар әншінің бұрынғы бейнежазбасын пайдаланып, жасанды интеллект көмегімен оның атынан жарнамалық мәлімдеме жасаған. Кейінірек 2025 жылдың қазан айында ұқсас дипфейктер қайта пайда болды, олардың кейбірі миллиондаған қаралым жинады [2].

Бұл кейс дипфейктің танымал адамның бейнесін қолдан жасап қана қоймай, сол адамның қоғамдық беделін жалған ақпараттың сенімділігін арттыру құралы ретінде пайдалануы мүмкін екенін көрсетеді. Аудитория танымал тұлғаға деген сенімін оның жарнамалаған өніміне немесе қызметіне ауыстыруы ықтимал. Мұндай жағдайда жалған бейнежазба эмоционалды сендіру құралына айналып, пайдаланушыны қаржылық шешім қабылдауға итермелеуі мүмкін. Демек, дипфейк мәселесі тек бейненің түпнұсқалығын анықтаумен шектелмейді: оның қандай мақсатта жасалғанын, кімнің мүддесіне қызмет ететінін және аудиторияға қандай әрекет ұсынатынын да талдау қажет.

Дипфейктің таралуы журналистикаға да ерекше жауапкершілік жүктейді. Әлеуметтік желіде көп қаралым жинаған видео редакция үшін назар аударуға тұрарлық ақпараттық себеп болуы мүмкін, алайда оның танымалдығы шынайылықтың көрсеткіші емес. Егер журналист күмәнді материалды бастапқы дереккөзін анықтамай, ресми органдардан нақтыламай немесе тәуелсіз тексеруден өткізбей жарияласа, ол жалған ақпараттың таралу ауқымын кеңейтуі ықтимал. Сондықтан редакция үшін мұндай материалды жариялауға асықпау – ақпараттық үдерістен қалып қою емес, кәсіби тексеру стандартын сақтау.

Мұндай жағдайда фактчекингтің міндеті жалған контентті анықтаумен ғана шектелмейді. Ол материалдың шығу тегін зерттеуді, оның бастапқы нұсқасын іздеуді, видеодағы мәлімдемелерді сенімді деректермен салыстыруды және пайдаланылған тұлғаның не мекеменің ресми ұстанымын анықтауды қамтиды. Егер материал қаржылық қызметті немесе мемлекеттік қолдауды жарнамаласа, оның артында тұрған ұйымның нақты бар-жоғын, қызметтің заңды негізін және ресми байланыс арналарын тексеру маңызды. Дипфейкті анықтау үшін техникалық құралдар да қолданылады. Арнайы жүйелер бейнедегі бет қимылын, ерін қозғалысын, жарық пен көлеңкенің сәйкестігін немесе аудиодағы ерекшеліктерді талдауы мүмкін. Алайда мұндай құралдардың нәтижесін абсолютті дәлел ретінде қабылдауға болмайды. Бір детектор материалды жасанды деп бағаласа, екіншісі керісінше қорытынды ұсынуы ықтимал. Бұған бейненің сапасы, қысқартылуы, қайта кодталуы және қолданылған генерация әдісі әсер етуі мүмкін. Сондықтан техникалық талдау бастапқы дереккөзді зерттеу, мәлімдемелерді салыстыру және контексті тексеру сияқты журналистік әдістермен толықтырылуы қажет.

Осылайша дипфейктердің таралуы цифрлық медиада сенімділік мәселесін күрделендіреді. Ақпаратты тек оның сыртқы көрінісіне қарап бағалау мүмкіндігі шектелген жағдайда журналистикада дереккөздерді тексеру, контексті қалпына келтіру және дәлелдерді салыстырудың маңызы арта түседі. Бұл фактчекингті қосымша редакциялық қызмет деңгейінен ақпараттың шынайылығын қамтамасыз ететін негізгі кәсіби тетік деңгейіне көтереді.

Осыған байланысты журналистік верификация бірнеше әдістің үйлесіміне негізделуі керек. Алдымен материалдың бастапқы дереккөзі анықталады: оны кім жариялаған, бастапқы нұсқасы қайда орналасқан және ол ресми аккаунттарда бар ма? Одан кейін бейненің уақыты мен контексті тексеріледі. Мысалы, танымал тұлғаға қатысты жарнамалық мәлімдеме тараса, оның ресми сайтында немесе расталған әлеуметтік желідегі парақшаларында осы ақпараттың бар-жоғын салыстыруға болады. Егер мемлекеттік органның атынан үндеу жасалса, ұйымның атауын ресми мемлекеттік ресурстардан тексеру қажет. Бұдан кейін мәлімдеменің мазмұны тәуелсіз дереккөздермен және қолжетімді құжаттармен салыстырылады. Техникалық детекторлардың қорытындысы осы тексеру нәтижелерін толықтырушы дәлел ретінде пайдаланылуы мүмкін.

Фактчекингтің маңызы дәл осы жерде көрінеді. Ол тек жалған видеоны әшкерелеу немесе ақпаратты «рас» және «жалған» деп жіктеу ғана емес, мәлімдеменің қандай негізде жасалғанын және аудиторияны жаңылыстыратын қандай белгілер бар екенін түсіндіруді де қамтиды. Кәсіби фактчекинг оқырманға тек қорытындыны емес, сол қорытындыға қалай келгенін де көрсетуі керек. Бұл аудиторияның ақпаратты сыни бағалау дағдысын қалыптастырып, журналистік жарияланымның дәлелділігін арттырады.

Сонымен қатар дипфейк туралы ақпарат тарату кезінде журналистің өзі де жауапкершілік танытуы қажет. Жалған бейнені әшкерелеу мақсатында жариялау кезінде оның толық нұсқасын немесе зиянды сілтемесін қайта тарату міндетті емес. Материалдың негізгі мазмұнын түсіндіріп, оның жалған екені туралы ресми деректерді көрсету және аудиторияны алаяқтық сілтемелерге өтпеуге шақыру әлдеқайда орынды. Мұндай тәсіл жалған контенттің қайта таралу қаупін азайтуға көмектеседі. Генеративті жасанды интеллект пен дипфейк технологиялары цифрлық медиа кеңістікте ақпараттың шынайылығын бағалаудың жаңа талаптарын қалыптастырып отыр. Қазақстандағы танымал тұлғаның бейнесін пайдаланған инвестициялық жарнама және мемлекеттік орган қызметкерінің бейнесімен жасалған жалған роликтер ақпараттық манипуляцияның нақты мысалдары болып табылады. Бұл жағдайларда сенімділік адамның бейнесі, қоғамдық бедел немесе ресми сипаттағы белгілер арқылы қалыптастырылған. Алайда сыртқы шынайылық ақпараттың мазмұндық дұрыстығына кепіл бола алмайды.

Сондықтан қазіргі журналистикада ақпараттың бастапқы көзін анықтау, визуалды материалдың контекстін тексеру, мәлімдемелерді тәуелсіз деректермен салыстыру және техникалық тексеру құралдарын сыни тұрғыдан қолдану ерекше маңызға ие. Жасанды интеллект журналистік жұмысты жеңілдететін құрал бола алады, бірақ оның көмегімен жасалған контенттің дұрыстығын бағалау кәсіби жауапкершіліктен тыс қалмауы тиіс. Осы тұрғыдан алғанда, фактчекинг цифрлық медиа кеңістіктегі жалған ақпаратпен күресудің ғана емес, журналистикаға деген қоғамдық сенімді сақтаудың да маңызды тетігі болып табылады.

Цифрлық медиа кеңістікте жалған ақпараттың таралуы фактчекингтің әдістері мен құралдарын жетілдіру қажеттілігін арттырды. Қазіргі журналистикада ақпаратты тексеру тек ресми дереккөзге жүгінумен шектелмейді. Ол мәтіннің мазмұнын салыстыруды, фото мен бейненің бастапқы нұсқасын іздеуді, жарияланған уақытын анықтауды, аудиоматериалдың түпнұсқалығын бағалауды және ақпараттың қандай контексте таралғанын зерттеуді қамтиды. Әсіресе генеративті жасанды интеллект арқылы жасалған контент жағдайында осы әдістердің өзара байланыста қолданылуы маңызды. Фактчекинг құралдарын олардың атқаратын қызметіне қарай бірнеше топқа бөлуге болады. Бірінші топқа ақпараттың бастапқы нұсқасын іздеуге арналған кері сурет іздеу жүйелері жатады. Екінші топқа фото мен бейненің техникалық сипаттамаларын зерттейтін цифрлық құралдары кіреді. Үшінші топты әлеуметтік желілердегі ақпараттың таралу тарихын және дереккөздердің байланысын анықтайтын сервистер құрайды. Төртінші топқа ЖИ арқылы жасалған немесе өзгертілген контенттің ықтимал белгілерін анықтайтын арнайы детекторлар жатады. Мұндай жіктеу журналистке нақты ақпараттық жағдайға сәйкес құрал таңдауға мүмкіндік береді.

Фактчекингтің алғашқы кезеңдерінің бірі – тексерілетін материалдың бастапқы нұсқасын табу. Әлеуметтік желілерде фотосуреттер мен бейнекадрлар бастапқы оқиғадан бірнеше күн, ай немесе жыл өткеннен кейін басқа контексте жариялануы мүмкін. Кейде ескі сурет жаңа оқиғаға қатысты сияқты көрсетіледі немесе нақты фотосуретке жалған түсіндірме беріледі. Мұндай жағдайда кері сурет іздеу құралдары материалдың интернетте бұрын жарияланған-жарияланбағанын анықтауға көмектеседі.

Google Lens – сурет арқылы іздеу жүргізуге мүмкіндік беретін құрал. Журналист тексерілетін фотосуретті немесе бейнекадрдың скриншотын жүктеп, сол суретке ұқсас материалдарды, оның интернеттегі ықтимал нұсқаларын және суретте көрінетін объектілер туралы ақпаратты іздей алады. Мысалы, әлеуметтік желіде Қарағандыда болғаны айтылған оқиғаның фотосы тараса, Google Lens арқылы суретті іздеу оның басқа қаладағы немесе бұрынғы оқиғаға қатысты жарияланымдарда кездесетінін анықтауға көмектесуі мүмкін. Google Lens-тің басты артықшылығы – қолдануға жеңіл болуы және суретпен қатар ондағы визуалды объектілерді іздеу мүмкіндігі. Дегенмен іздеу нәтижелерінің болмауы суреттің жалған екенін дәлелдемейді. Фотосурет интернетке алғаш рет жарияланған болуы, іздеу жүйесінің индексіне енбеуі немесе елеулі өзгертілуі мүмкін. Сондықтан табылған нәтижелерді жарияланымның датасымен, авторымен және басқа дереккөздермен салыстыру қажет.

TinEye – суреттің интернеттегі басқа нұсқаларын іздеуге арналған кері сурет іздеу жүйесі. Ол суреттің атауына немесе метадеректеріне ғана сүйенбей, кескіннің өзін тану технологиясын пайдаланады. Қызмет суреттің қиылған, өлшемі өзгертілген немесе белгілі бір дәрежеде өңделген нұсқаларын да табуы мүмкін. Осы арқылы журналист фотосуреттің бұрын жарияланған нұсқасын және оның интернеттегі қолданылу тарихын салыстыра алады. TinEye-дің Google Lens-тен айырмашылығы – оның негізгі міндеті суреттің сәйкестігін және бұрын кездескен нұсқаларын іздеу. Google Lens суреттегі объектілер мен визуалды ұқсастықтар бойынша кеңірек іздеу жүргізе алады, ал TinEye нақты кескіннің өзгертілген көшірмелерін анықтауға бағытталған. Екі құралды қатар пайдалану іздеу нәтижелерін

толықтыруы мүмкін. Алайда TinEye де интернеттегі барлық суретті қамтымайды және кескіннің авторын немесе оқиғаның шынайылығын өздігінен анықтамайды.

Кері сурет іздеудің журналистикадағы маңызы дипфейктерді тексеру кезінде де байқалады. Мысалы, танымал тұлғаның бейнесі инвестициялық жарнамада пайдаланылса, оның бастапқы сұхбатын немесе бұрынғы бейнежазбасын іздеу қажет. Егер бастапқы материалда басқа мазмұн айтылғаны анықталса, бұл жарияланған видеодағы мәлімдеменің контексті өзгертілген болуы мүмкін екенін көрсетеді. Дегенмен бастапқы видеоны табудың өзі дыбыстың қалай өзгертілгенін толық дәлелдемейді. Ол үшін аудионы бөлек тексеріп, мәлімдемені ресми дереккөздермен салыстыру қажет.

Фактчекинг саласындағы маңызды құралдардың бірі – InVID-WeVerify Verification Plugin. Бұл браузерге қосылатын кеңейтім журналистерге әлеуметтік желілерде таралған фото мен бейнені тексеруге арналған бірнеше функцияны бір ортада ұсынады [6]. Оның мүмкіндіктеріне бейнені жеке кадрларға бөлу, кадрларды кері сурет іздеуге жіберу, медиафайлдың метадеректерін қарау, суреттегі ықтимал өзгерістерді зерттеу және бұрын тексерілген материалдарды іздеу жатады [7]. Құралдың маңызды функциясы – бейнені негізгі кадрларға бөлу. Журналист ұзақ видеоны түгелдей қараумен шектелмей, ондағы маңызды сәттерді жеке суреттер ретінде шығарып ала алады. Кейін сол кадрларды Google, Bing, TinEye немесе басқа қолжетімді іздеу жүйелері арқылы тексеруге болады.

InVID-WeVerify құралдарында суретті үлкейту, кейбір техникалық белгілерін зерттеу, метадеректерді қарау және белгілі бір манипуляцияларды анықтауға көмектесетін функциялар да бар. Кейбір нұсқаларында әлеуметтік желілердегі ақпаратты іздеу, бұрын тексерілген материалдарды табу және аудионың жасанды өзгертілуін анықтауға арналған қосымша мүмкіндіктер қарастырылған. Бұл құралдың басты артықшылығы – бірнеше тексеру әдісін бір жұмыс үдерісіне біріктіруі. Алайда InVID-WeVerify барлық дипфейкті автоматты түрде анықтайтын әмбебап детектор емес. Ол журналистің тексеру жұмысын жеңілдететін құралдар жиынтығы ретінде қарастырылуы керек. Мәселен, бейненің кадрларын іздеу бастапқы видеоны табуға көмектескенімен, кадрлардың өзінен адамның дауысы шынайы ма, әлде жасанды түрде өзгертілген бе деген сұраққа әрдайым жауап ала алмаймыз.

Фотосуреттің техникалық өзгерістерін зерттеу үшін Forensically және WeVerify Image Verification Assistant сияқты құралдар қолданылады. Олар суреттегі ықтимал өңдеу белгілерін зерттеуге мүмкіндік береді. Мұндай талдау фотосуреттегі белгілі бір бөліктің көшіріліп қойылғанын, кескіннің кейбір аймақтарының басқаша өңделгенін немесе сурет құрылымында ерекшеліктер бар-жоғын анықтауға көмектесуі мүмкін.

Forensically қызметінде Error Level Analysis (ELA), клондау белгілерін анықтау, шу деңгейін талдау, үлкейту және метадеректерді қарау сияқты функциялар бар. Мысалы, фотосуреттің бір бөлігі басқа суреттен көшіріліп, бастапқы кескінге енгізілген болуы мүмкін. Клондау белгілерін зерттеу қайталанатын аймақтарды табуға көмектеседі. Ал ELA кескіннің әртүрлі аймақтарындағы сығылу ерекшеліктерін салыстыру арқылы ықтимал өңделген бөліктерге назар аударуға мүмкіндік береді.

Дегенмен мұндай белгілерді бірден қолдан жасалған суреттің дәлелі ретінде қабылдауға болмайды. Кәдімгі редакциялау, суретті қайта сақтау, өлшемін өзгерту немесе әртүрлі сападағы сығу да кескіннің техникалық сипаттамаларын өзгерте алады. Сондықтан ELA нәтижесінде белгілі бір аймақтың ерекшеленуі оның міндетті түрде жалған екенін білдірмейді. Нәтижені бастапқы фотосуретпен, басқа ракурстармен және жарияланымның контекстімен салыстыру қажет.

WeVerify Image Verification Assistant бірнеше алгоритм арқылы суреттегі ықтимал манипуляция белгілерін талдайды. Оның кейбір әдістері кескіндегі күмәнді аймақтарды визуалды түрде көрсетуге мүмкіндік береді. Бұл зерттеушіге суреттің қай бөлігін қосымша тексеру керегін анықтауға көмектеседі. Алайда мұндай талдау да суреттің мазмұны

шындыққа сәйкес келе ме деген сұраққа тікелей жауап бермейді. Техникалық өзгерістерді анықтау мен ақпараттың шынайылығын дәлелдеу – өзара байланысты болғанымен, екі бөлек міндет.

Фото мен бейнені тексерудің тағы бір бағыты – олардың метадеректерін зерттеу. Метадеректер файлдың жасалған уақыты, құрылғысы, кейбір өңдеу әрекеттері және кей жағдайларда географиялық координаттары туралы ақпаратты қамтуы мүмкін. Мұндай деректер журналистке материалдың пайда болу тарихын зерттеуге көмектеседі.

Бұл міндетті орындау үшін ExifTool сияқты бағдарламалар қолданылады. ExifTool суреттердің, аудионың және бейненің көптеген форматтарындағы метадеректерді оқуға және талдауға арналған. Егер фотосуретте географиялық координаттар сақталған болса, оларды картадағы орналасумен салыстыруға болады. Мысалы, белгілі бір көшеде түсірілді деп жарияланған суреттегі нысандар мен ықтимал орналасу орнының сәйкестігін зерттеу оқиғаның контекстін тексеруге көмектеседі.

Алайда метадеректердің болмауы суреттің жалған екенін білдірмейді. Әлеуметтік желілер файлды қайта өңдеу кезінде бастапқы метадеректердің бір бөлігін немесе барлығын алып тастауы мүмкін. Сонымен қатар файлдағы уақыт пен құрылғы туралы ақпаратты өзгертуге болады. Сондықтан метадеректерді жалғыз дәлел ретінде пайдаланбай, оларды басқа дереккөздермен салыстыру керек.

Геолокациялық тексеруде Google Maps, Google Earth және Street View сияқты сервистер де пайдалы болуы мүмкін. Олар кадрдағы ғимараттарды, жолдарды, көше белгілерін және ландшафт ерекшеліктерін салыстыруға мүмкіндік береді. Егер видео белгілі бір жерде түсірілген деп көрсетілсе, кадрдағы нысандардың сол орынмен сәйкестігін зерттеу арқылы жарияланған мәліметтің дұрыстығын бағалауға болады.

Бұл әдіс дипфейкті тікелей анықтамаса да, видеодағы оқиғаның контекстін тексеруге көмектеседі. Мәселен, бейнежазбада адамның беті мен дауысы жасанды өзгертілмеген болуы мүмкін, бірақ материалдың өзі басқа уақытта немесе басқа жерде түсіріліп, жалған түсіндірмемен таралуы ықтимал. Сондықтан журналистік тексеру кезінде контенттің техникалық түпнұсқалығы мен оқиға туралы мәлімдеменің дұрыстығы қатар қарастырылуы керек.

Кері сурет іздеу және цифрлық құралдары материалдың шығу тегін, контекстін немесе ықтимал өңдеу белгілерін зерттеуге көмектеседі. Ал арнайы дипфейк детекторлары аудио, бейне немесе суреттегі синтетикалық контентке тән белгілерді машиналық оқыту модельдері арқылы талдайды. Мұндай жүйелердің жұмысы контенттің белгілі бір түрлерін анықтауға бейімделгендіктен, әр құралдың нені анықтай алатынын және қандай шектеулері бар екенін ажырату маңызды.

Deepware Scanner – адамның бет-әлпеті өзгертілген немесе басқа адамның бетімен алмастырылған бейнематериалдарды анықтауға бағытталған құрал. Қызметтің ресми түсіндірмесіне сәйкес, жүйе видеодағы адамның бетіне қатысты манипуляция белгілерін талдайды. Ол бет алмастыру арқылы жасалған дипфейктерді анықтауға арналғанымен, өзгертілген дауысты тексермейді және кез келген жасанды интеллект арқылы жасалған бейнематериалды анықтайтын әмбебап жүйе болып саналмайды.

Deepware Scanner-дің артықшылығы – журналистке күмәнді видеоны бастапқы тексеруден өткізуге мүмкіндік беруі. Мысалы, әлеуметтік желіде белгілі бір саясаткердің немесе қоғамдық тұлғаның бейнесі тараса, құрал видеоның бет-әлпетіне қатысты ықтимал манипуляция белгілерін бағалауға көмектеседі. Бірақ нәтиже адамның дауысы түпнұсқа ма, мәлімдеме рас па немесе бейне қандай контексте түсірілген деген сұрақтарды шешпейді. Deepware-дің ресми FAQ бөлімінде де нәтиженің абсолютті кепілдік бермейтіні көрсетілген [8]. Қызмет дипфейк мәселесі толық шешілген сала емес екенін және оның бағасын

ықтималдық ретінде қарастыру қажеттігін түсіндіреді. Демек, «дипфейк анықталмады» деген нәтиже материалдың міндетті түрде түпнұсқа екенін білдірмейді.

Hive – сурет, бейне, аудио және мәтін сияқты әртүрлі форматтағы контентті талдауға арналған ЖИ-құралдарын ұсынатын платформа. Оның қызметтері арасында толықтай жасанды интеллект көмегімен жасалған визуалды материалдарды анықтау және адамның бет-әлпеті басқа адамға ауыстырылған дипфейктерді талдау функциялары бар. Hive жүйесінің ерекшелігі – ЖИ жасаған кескінді анықтау мен дипфейкті анықтауды бөлек міндет ретінде қарастыруы. Мысалы, генеративті модель арқылы жасалған пейзаж толықтай синтетикалық сурет болуы мүмкін, бірақ ол нақты адамның бейнесін ауыстыруға негізделген дипфейк емес. Ал шынайы түсірілген видеоның ішіндегі адамның беті өзгертілсе, мәселе басқа сипатқа ие болады. Осы екі жағдайды ажырату редакциялық тексеру үшін маңызды.

Платформаның API құжаттамасында визуалды контентке қатысты модельдер нәтижені сенімділік көрсеткішімен бірге беретіндігі көрсетілген. Бұл журналистке немесе контент модерациясымен айналысатын маманға ықтимал күмәнді материалдарды іріктеуге көмектеседі. Дегенмен көрсетілген пайыз немесе сенімділік ұпайы нақты материалдың жалған екеніне қатысты абсолютті статистикалық кепілдік емес. Нәтиженің мағынасы қолданылған модельге, материалдың түріне және тексеру жағдайына байланысты.

Hive-дің маңызды артықшылығы – бірнеше форматқа арналған құралдардың болуы. Ал шектеуі – оның кейбір қызметтері API арқылы немесе ақылы модельдер түрінде ұсынылады, сондықтан жеке журналист үшін қолжетімділік пен шығын мәселесін алдын ала қарастыру қажет.

Reality Defender – аудио, бейне және суреттегі синтетикалық контентті анықтауға арналған кәсіби платформа. Оның технологиялары жазылған аудиодағы немесе тікелей сөйлесу кезіндегі дауыстың жасанды жасалғанына, бейнедегі бет пен кадрлардың өзгертілуіне және кескіндегі синтетикалық белгілерге қатысты талдау жүргізе алады. Reality Defender-дің басты ерекшелігі – бірнеше медиа түрін бір жүйеде қарастыруы. Мысалы, жалған видеода адамның беті шынайы көрінгенімен, оның дауысы басқа жүйе арқылы синтезделген болуы мүмкін. Мұндай жағдайда тек бет-әлпетке арналған детектор жеткіліксіз. Аудио мен видеоны қатар талдау күмәнді белгілерді жан-жақты бағалауға мүмкіндік береді. Платформа ұйымдарға, медиа компанияларға және алаяқтыққа қарсы жұмыс істейтін құрылымдарға бағытталған. Ол нәтижелерді API арқылы басқа жүйелерге біріктіруге мүмкіндік береді. Сондықтан Reality Defender-ді күнделікті қарапайым тексеруге арналған қосымша ретінде емес, үлкен көлемдегі контентті талдауға арналған кәсіби шешім ретінде қарастырған дұрыс.

Дегенмен бірнеше модальдылықты тексеру мүмкіндігі материалдың мазмұны рас екенін өздігінен дәлелдемейді. Жүйе синтетикалық белгілерді бағалағанымен, видеодағы мәлімдеменің шындыққа сәйкестігін, ұйымның заңдылығын немесе оқиғаның контекстін журналист бөлек тексеруі керек.

Sensity AI – дипфейктерді және басқа да синтетикалық медианы анықтауға арналған кәсіби шешім. Оның құжаттамасында видео, сурет және аудионы бір API арқылы тексеру мүмкіндігі көрсетілген. Платформа бет-әлпетті өзгерту, толықтай жасанды контент жасау, дауысты клондау және файлдың техникалық сипаттамаларына қатысты бірнеше тексеру түрін біріктіреді. Sensity-дің артықшылығы – тек бір ғана визуалды белгіні емес, әртүрлі талдау нәтижелерін біріктіріп бағалауға бағытталуы. Мысалы, бейнежазбада бет-әлпеттің өзгертілу белгілері анықталса, жүйе аудио мен файл сипаттамаларын да бөлек талдай алады. Бұл әсіресе бірнеше түрлі манипуляция қолданылған күрделі материалдар үшін пайдалы.

Алайда платформаның нәтижесі де түпкілікті фактчекингтің орнына жүрмейді. Егер жүйе материалды күмәнді деп белгілесе, журналист оның бастапқы дереккөзін, жариялану тарихын және мазмұнын тексеруі керек. Ал файл күмәнді деп белгіленбесе, бұл оның

шынайылығына абсолютті кепілдік бермейді. Платформаның кәсіби бағытта ұсынылуы оның кез келген пайдаланушыға тегін әрі шектеусіз қолжетімді екенін білдірмейді.

SynthID – Google DeepMind әзірлеген технология. Ол қолдау көрсетілетін ЖИ жүйелері жасаған кейбір сурет, видео және аудиоматериалдарға адам көзіне көрінбейтін цифрлық белгі енгізуге арналған. Мұндай белгі контенттің белгілі бір ЖИ жүйесімен жасалғанын немесе өңделгенін анықтауға көмектеседі. 2026 жылғы 7 қазанда Google DeepMind SynthID Detector қызметіне қолжетімділікті кеңейту туралы хабарлады [3]. Компанияның мәліметінше, құрал Google немесе серіктес жүйелердің қолдау көрсетілетін технологиялары арқылы жасалған контенттен SynthID белгісін іздеуге арналған. Бұл тәсілдің маңызды ерекшелігі – ол барлық дипфейкті жалпы әдіспен іздеуден гөрі, белгілі бір технологиялар енгізген цифрлық белгілерді тексеруге сүйенеді. SynthID-дің артықшылығы – қолдау көрсетілетін контентте арнайы белгі сақталған болса, оның шығу тегін анықтауға қосымша дәлел ұсына алуы. Алайда бұл құрал барлық ЖИ жүйесі жасаған материалды анықтайды деген сөз емес. Егер материал басқа жүйеде жасалса, белгі енгізілмесе немесе тексерілетін нұсқада қажетті белгі сақталмаса, нәтиже контенттің түпнұсқалығын толық анықтай алмайды. Сондықтан SynthID Detector-ді жалпы дипфейк детекторы емес, белгілі бір ЖИ жүйелеріне қатысты шығу тегін тексеретін технология ретінде сипаттау дұрыс. Оның нәтижесін де бастапқы дереккөзбен және басқа тексеру әдістерімен салыстыру қажет.

Дипфейкпен күресте маңызды бағыттардың бірі – контенттің қалай жасалғанын және қандай өзгерістерден өткенін тіркейтін цифрлық шығу тегі жүйелері. Осы бағыттағы белгілі стандарттардың бірі – C2PA (Coalition for Content Provenance and Authenticity). Ол Content Credentials деп аталатын цифрлық мәліметтер арқылы материалдың жасалу тарихы, қолданылған құралдар және енгізілген өзгерістер туралы ақпаратты тіркеуге мүмкіндік береді [4].

C2PA-ның негізгі ерекшелігі – суреттің немесе видеоның шынайылығын сыртқы көрінісіне қарап болжаудың орнына, оның шығу тегі туралы тексерілетін мәліметтерді пайдалануы. Егер файл қолдау көрсететін құрал арқылы жасалып, тиісті цифрлық деректер сақталса, тексеру жүйесі сол материалдың қандай бағдарламамен жасалғаны немесе өзгертілгені туралы ақпаратты көрсете алады.

Бұл журналистика үшін пайдалы, себебі редакция материалды тек «жалған» немесе «шынайы» деп жіктемей, оның жасалу тарихын да қарастыра алады. Мысалы, фотосуреттің белгілі бір редакциялау бағдарламасында өңделгені туралы мәлімет сақталса, журналист оны бастапқы нұсқамен салыстырып, қандай өзгерістер енгізілгенін зерттей алады.

Алайда C2PA-ның да маңызды шектеуі бар [5]. Оның ресми түсіндірмесінде контенттің шығу тегі туралы мәлімет материалдың ішіндегі ақпараттың шындыққа сәйкестігін өздігінен дәлелдемейтіні көрсетілген. Сонымен қатар метадеректерді сақтамайтын бағдарлама арқылы өңдеу кезінде шығу тегі туралы мәліметтер жоғалуы мүмкін. Сондықтан Content Credentials табылмаса, бұл файлдың міндетті түрде жалған екенін білдірмейді. Ал мәліметтер табылған жағдайда да олардың мазмұнын, қолтаңбасын және материалдың контекстін тексеру қажет. Жоғарыда қарастырылған құралдар бірдей міндет атқармайды. Бір бөлігі адамның бет-әлпетіндегі өзгерістерді анықтауға бағытталса, екіншілері толықтай ЖИ көмегімен жасалған суреттерді, аудионы немесе бейнені талдайды. Ал SynthID мен C2PA сияқты технологиялар контенттің шығу тегін анықтауға арналған цифрлық белгілер мен метадеректерге сүйенеді.

Сондықтан детекторларды салыстыру кезінде олардың атауына немесе жарнамалық сипаттамасына ғана назар аудару жеткіліксіз. Негізгі өлшемдерге тексерілетін файл түрі, қандай манипуляцияларды анықтайтыны, нәтижені қалай ұсынатыны, қолжетімділік деңгейі және жалған оң не жалған теріс нәтиже беру ықтималдығы жатады.

Мысалы, Deepware Scanner бет-әлпет алмастыру арқылы жасалған видеоларды тексеруге бағытталған. Hive сурет пен видеоның ЖИ арқылы жасалғанын және дипфейк белгілерін бөлек бағалай алады. Reality Defender және Sensity бірнеше медиа түрін талдауға арналған кәсіби жүйелер ұсынады. SynthID Detector қолдау көрсетілетін ЖИ жүйелерінің цифрлық белгілерін іздейді, ал C2PA контенттің жасалу және өңделу тарихын тексеруге көмектеседі. Осы айырмашылықтарды ескере отырып, бір құралдың нәтижесіне сүйеніп, материалды түпкілікті «жалған» немесе «шынайы» деп жариялау дұрыс емес. Мысалы, бет-әлпетті анықтайтын жүйе дауысты клондау арқылы жасалған манипуляцияны байқамауы мүмкін. Керісінше, белгілі бір ЖИ белгісінің табылмауы контенттің басқа технологиямен жасалмағанын дәлелдемейді. Ал шығу тегі туралы цифрлық мәліметтер материалдың кім жасағанын немесе қалай өңделгенін көрсетуі мүмкін, бірақ оның ішіндегі мәлімдемелердің рас екенін растауға жеткіліксіз.

Осыдан журналистік практика үшін маңызды қорытынды шығады: детекторлардың міндеті – күмәнді белгілерді табу және қосымша тексеруге бағыт беру. Ал ақпараттың шынайылығы туралы қорытынды бірнеше дереккөзді салыстыру, бастапқы контекстті қалпына келтіру және дәлелдерді кешенді бағалау арқылы жасалуы керек.

Қазақстандық медиада ЖИ құралдарын қолдану кеңейген сайын редакцияларда контенттің шынайылығын тексерудің тұрақты тәртібін қалыптастыру маңызды. Мұндай тәртіп тек дипфейк пайда болған жағдайда іске қосылатын шара емес, ақпаратты жариялаудың жалпы редакциялық стандарты болуы керек.

Бірінші кезеңде журналист ақпараттың бастапқы көзін анықтауы қажет. Материал кімнен шыққан, алғашқы жарияланымы қайда орналасқан және оны таратқан аккаунттың ресми мәртебесі бар ма деген сұрақтар қарастырылады. Екінші кезеңде жарияланымның мазмұны мен контексті тексеріледі: оқиға қашан және қай жерде болған, видеоның бастапқы нұсқасы бар ма, мәлімдеме басқа сенімді дереккөздерде расталған ба? Үшінші кезеңде фото, аудио немесе видеоға қатысты техникалық талдау жүргізіледі. Бұл кезеңде кері сурет іздеу, кадрларды бөлу, метадеректерді зерттеу және қажет болған жағдайда арнайы детекторларды пайдалану мүмкін. Төртінші кезеңде алынған нәтижелер өзара салыстырылады. Егер техникалық детектор материалды күмәнді деп бағаласа, журналист бұл нәтижені басқа деректермен толықтыруы керек. Мысалы, видеода мемлекеттік органның қызметкері ретінде көрсетілген адамның бейнесі қолданылса, органның ресми сайты мен ресми әлеуметтік желілеріндегі мәліметтер тексеріледі. Егер танымал тұлға инвестициялық жобаны жарнамалап тұрғандай көрсетілсе, оның ресми арналарындағы мәлімдемелер және жобаның заңды тіркелуі туралы ақпарат зерттеледі. Бесінші кезеңде редакция жарияланымның формасын анықтайды. Егер материал жалған екені дәлелденсе, оны тексеру нәтижелерімен бірге түсіндіруге болады. Ал дәлелдер жеткіліксіз болса, материалды бірден дипфейк деп атаудың орнына, оның түпнұсқалығы тәуелсіз расталмағанын көрсету қажет. Мұндай тәсіл ғылыми дәлдік пен журналистік жауапкершілікке сәйкес келеді.

Кешенді тексеру моделі журналистің жұмысын күрделендіру үшін емес, ақпараттық тәуекелді азайту үшін қажет. ЖИ құралдары техникалық жұмыстың бір бөлігін автоматтандырғанымен, олардың нәтижесін түсіндіру және жарияланатын материал үшін жауап беру редакцияның кәсіби міндеті болып қала береді.

Зерттеу аясында Қазақстанның әртүрлі өңірлерінен отыз тұрғынға шағын сауалнама жүргізілді. Қатысушылар арасында әртүрлі жас топтары мен кәсіби сала өкілдері болды. Сауалнаманың мақсаты – қарапайым азаматтардың фактчекинг туралы хабардарлық деңгейін және оны қолдану дағдыларын анықтау.

Нәтижелер мынадай болды: отыз адамның жиырмасы (66,7 %) фактчекинг әдістерін белгілі бір деңгейде білетіндерін және кейбір жағдайларда қолданатындарын айтты. Олар

кері сурет іздеуді, ресми дереккөздермен салыстыруды немесе күмәнді видеоларды тексеру үшін қарапайым құралдарды пайдалануды атап өтті. Ал он адам (33,3 %) фактчекинг ұғымының өзімен таныс еместігін, оның не екенін білмейтінін мәлімдеді.

Бұл деректер медиасауаттылықтың әлі де жеткіліксіз екенін көрсетеді. Үштен бір бөлігінің негізгі ұғымды білмеуі – ақпараттық қауіп-қатерлердің алдын алуда елеулі олқылық. Сондықтан болашақта фактчекинг дағдыларын барлық азаматқа үйрету қажет. Әр мекеме, әр қызметкер, әр студент пен оқушы бұл негізгі құзыретті меңгеруі тиіс. Себебі жалған ақпарат тек журналистика саласына ғана емес, қаржылық шешімдерге, денсаулыққа, сайлау процестеріне және қоғамдық тұрақтылыққа тікелей әсер етеді.

Сауалнама нәтижелері фактчекингті тек кәсіби журналистердің міндеті ретінде қарастыру жеткіліксіз екенін дәлелдейді. Ол қоғамдық медиасауаттылықтың ажырамас бөлігі болуы керек. Мектептерде, жоғары оқу орындарында, мемлекеттік және жеке ұйымдарда арнайы тренингтер, онлайн курстар мен практикалық сабақтар ұйымдастыру арқылы бұл олқылықты жоюға болады.

Қорытынды

Цифрлық медиа кеңістікте фактчекинг пен дипфейкті анықтау құралдарының дамуы журналистиканың технологиялық мүмкіндіктерін кеңейтеді. Google Lens және TinEye сияқты кері сурет іздеу жүйелері материалдың бұрын жарияланған нұсқасын табуға көмектессе, InVID-WeVerify видеоны кадрларға бөлу, метадеректерді қарау және контексті зерттеу үдерісін жеңілдетеді. Forensically және WeVerify Image Verification Assistant суреттегі ықтимал өзгерістерді талдауға мүмкіндік береді. Deepware Scanner, Hive, Reality Defender және Sensity сияқты жүйелер синтетикалық контенттің белгілі бір түрлерін анықтауға бағытталған. Ал SynthID және C2PA контенттің шығу тегі туралы цифрлық белгілер мен мәліметтерді тексеруге көмектеседі.

Дегенмен бұл құралдардың ешқайсысын барлық жалған ақпаратты анықтайтын мінсіз жүйе ретінде қарастыруға болмайды. Әр құрал белгілі бір файл түріне, технологияға немесе тексеру міндетіне бейімделген. Сондықтан олардың нәтижелері бастапқы дереккөздерді іздеу, контексті қалпына келтіру, тәуелсіз мәліметтермен салыстыру және редакциялық бағалау сияқты әдістермен толықтырылуы тиіс. Осы тұрғыдан алғанда, цифрлық журналистикадағы фактчекинг – бір ғана қосымшаны пайдалану емес, өзара байланысты тексеру әдістерінің жүйесі. Технологиялық детекторлар күмәнді материалдарды анықтауға көмектеседі, ал журналистік талдау олардың мағынасын, шығу тегін және қоғамға ықтимал әсерін бағалайды. Ақпараттық сенімділікті сақтау үшін осы екі бағыттың үйлесуі қажет.

Сауалнама нәтижелері көрсеткендей, қоғамның бір бөлігі әлі де фактчекинг ұғымымен таныс емес. Сондықтан оны барлық азаматқа, әр мекеме мен әр қызметкерге үйрету – болашақтағы басым міндеттердің бірі. Тек осындай кешенді тәсіл арқылы цифрлық медиа кеңістіктегі сенімділікті сақтауға және қоғамдық ақпараттық қауіпсіздікті нығайтуға болады.

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Kabus Şəhərlər Və Tərk Edilmiş Coğrafiyalar: İnsan Çəkildikdən Sonra Təbiətin Dönüşü

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Xülasə: İqtisadi tənəzzül, ekoloji fəlakətlər və nüvə qəzaları səbəbindən insanların tamamilə tərk etdiyi kabus şəhərlər bəşəriyyətin təbiət üzərindəki kövrək dominantlığını nümayiş etdirir. İnsan amili aradan qalxdıqdan sonra yerli ekosistemlərin necə sürətlə bərpa olunduğu, beton konstruksiyaların meşələrə çevrildiyi və təbiətin öz ərazilərini necə geri aldığı bu məqalədə elmi və sosioloji prizmadan təhlil olunur.

1. Giriş: İnsanın Kövrək İzi və Təbiətin Səssiz Gücü

Müasir sivilizasiya planetin relyefini, iqlimini və ekosistemlərini öz ehtiyaclarına uyğun olaraq formalaşdıran ən böyük qüvvə kimi görünür. İri meqapolislər, nəhəng sənaye obyektləri və beton magistrallar insanın təbiət üzərindəki qəti qələbəsinin simvolları hesab olunur. Lakin bu dominantlıq əslində çox kövrək bir müvazinətə əsaslanır. Tarix və müasir coğrafiya sübut edir ki, insanın hər hansı bir məkandan səs-küylü və ya səssiz gedişi həmin ərazidə dramatik və sürətli bir bioloji transformasiyanın başlanğıcını qoyur.

"Kabus şəhərlər" (Ghost towns) – iqtisadi, ekoloji və ya texnogen qəzalar səbəbindən əhalisi tərəfindən tamamilə tərk edilmiş yaşayış məskənləridir. İnsan ayağı çəkilən andan etibarən, sivilizasiyanın illərlə böyük zəhmətlə qoruyub saxladığı süni sərhədlər dərhal çökməyə başlayır. Təbiət heç bir ideoloji fərq qoymadan, beton çatlarından baş qaldıran kiçik otlardan tutmuş, boşalmış binaları bürüyən sıx meşələrə qədər hər bir qarış torpağı sürətlə öz ağuşuna alır. Bu proses, insan sonrakı dünyanın necə görünə biləcəyinə dair bizə canlı bir laboratoriya təqdim edir.

2. Şəhərləri Kabusa Çevirən Səbəblər: Üç Əsas Faktor

Bir coğrafi məkanın tərk edilməsi adətən qəfil və ya tədricən baş verən böhranların nəticəsidir. Bu səbəbləri ümumi şəkildə üç böyük qrupda təsnif etmək mümkündür:

Nüvə və Texnogen Qəzalar: Ən qorxulu və qəfil tərk edilmə ssenarileridir. Radiasiya və ya kimyəvi çirklənmə insan həyatını qeyri-mümkün etdiyi üçün minlərlə kvadrat kilometrlik ərazilər bir neçə saat ərzində boşaldılır.

İqtisadi Tənəzzül və Resursların Tükənməsi: Müəyyən bir təbii resursun (məsələn, kömür, qızıl, neft) hasilatı üzərində qurulmuş şəhərlər, həmin resurs bitdikdə və ya iqtisadi əhəmiyyətini itirdikdə sürətlə tənəzzülə uğrayır və sənaye kabusuna çevrilir.

Ekoloji və İqlim Dəyişiklikləri: Torpaqların şorlaşması, su mənbələrinin quruması və ya ardıcıl təbii fəlakətlər insanları daha təhlükəsiz və məhsuldar bölgələrə köçməyə məcbur edir.

3. Tarixin Canlı Şahidləri: Tərk Edilmiş Tanınmış Məkanlar

3.1. Çernobıl və Pripyat (Ukrayna) – Atomun Kölgəsində Yaşıl Revalüasiya

1986-cı ildə Çernobıl Atom Elektrik Stansiyasında baş verən qəza bəşəriyyət tarixinin ən böyük texnogen fəlakəti idi. Stansiyanın yaxınlığında yerləşən və 50 minə yaxın əhalisi olan gənc, müasir Pripyat şəhəri bir neçə gün ərzində tamamilə boşaldıldı. İnsanlar radiasiya səbəbindən hər şeyi geridə qoyub getdilər. Elm adamları bu zonanın əsrlər boyu ölü bir səhraya çevriləcəyini proqnozlaşdırırdılar.

Lakin hadisədən keçən onilliklər tamamilə fərqli bir mənzərə ortaya qoydu. İnsan amilinin (ovçuluq, kənd təsərrüfatı, tikinti, sənaye səs-küyü) ortadan qalxması təbiət üçün radiasiyanın

mənfi təsirlərindən daha böyük bir xilas oldu. Bu gün Pripyatın mərkəzi meydanları, stadionları və binaların damları sıx meşəliklərlə örtülmüşdür. Çernobıl Qapalı Zonası Avropanın ən böyük vəhşi təbiət sığınacaqlarından birinə çevrilib. Radiasiyaya baxmayaraq, ərazidə canavarlar, qonur ayılar, vaşaqlar, marallar və nəsli kəsilməkdə olan Prjevalski atları sürətlə artır. Bu fenomen sübut edir ki, təbiət üçün ən böyük fəlakət radiasiya deyil, insanın gündəlik fəaliyyətidir.

3.2. Haşima Adası (Yaponiya) – Beton və Dəmirin Səssiz Çürüməsi

Nizami binaları və uzaqdan hərbi gəmiyə bənzəməsi səbəbindən "Kreyser adası" (Gunkanjima) adlandırılan Haşima, XIX əsrin sonlarında dənizaltı kömür mədənlərində işləyən fəhlələr üçün salınmışdı. Cəmi 6.3 hektarlıq bu süni adada 1960-cı illərdə 5000-dən çox insan yaşayırdı və bura dünyanın ən sıx məskunlaşmış yerlərindən biri idi. Adanın hər qarışı çoxmərtəbəli beton binalar, məktəblər və xəstəxanalarla örtülmüşdü.

1974-cü ildə Yaponiyanın kömürdən neft enerjisinə keçməsi ilə mədənlər bağlandı və ada bir neçə həftə ərzində tamamilə tərk edildi. Aradan keçən müddətdə dəniz dalğaları, duzlu küləklər və tayfunlar beton konstruksiyaları daxildən və xaricdən parçaladı. Heç bir torpaq qatının olmadığı bu beton yığınında belə, quşların gətirdiyi toxumlar və rütubət sayəsində binaların divarlarından yaşıl bitkilər və sarmaşıqlar boy verməyə başladı. Haşima, insanın tikdiyi ən möhkəm strukturların belə baxımsız qaldıqda dəniz və bitki örtüyü qarşısında necə aciz olduğunu göstərən vizual bir abidədir.

3.3. Naqoro (Yaponiya) – İnsanların Yerini Alan Kuklalar və Təbiət

Siyahımızdakı digər məkanlardan fərqli olaraq, Naqoro kəndi qəfil bir fəlakətlə deyil, qocalma və demoqrafik böhran səbəbindən səssizcə tərk edilən coğrafiyalara nümunədir. Sikoku adasındakı bu dağ kəndinin gənc əhalisi iş tapmaq üçün böyük şəhərlərə köçmüş, yaşlılar isə zamanla vəfat etmişdir. Kənddə demək olar ki, heç kim qalmadıqda, yerli sakin Ayano Tsukimi itkin düşən qonşularının və köçənlərin xatirəsini yaşatmaq üçün insan ölçüsündə parça kuklalar tikməyə başladı.

Bu gün Naqoroda cəmi bir neçə canlı insan, lakin yüzlərlə kukla "yaşayır". Bu müddət ərzində kənd təsərrüfatı sahələri, bağlar və yollar meşəliklər tərəfindən udulur. Dağlıq ekosistem, insanın əsrlər boyu kəsib təmizlədiyi sahələri sürətlə geri qaytarır, evləri isə mamırlar və vəhşi bitkilərlə örtür.

4. Bioloji Transformasiyanın Xronologiyası: Təbiət Ərazini Necə Geri Alır?

İnsan bir sahəni tərk etdikdən sonra ekoloji proseslər təsadüfi deyil, müəyyən bir elmi ardıcıllıq (suksesiya) ilə baş verir. Bu transformación xronoloji mərhələlərini aşağıdakı kimi xarakterizə etmək olar:

1. Birinci Dalğa (İlk Bir Neçə İl): Kommunal xidmətlərin (su, elektrik, isitmə) dayanması ilə binaların daxilində rütubət artır. Şaxtalı qışlar və isti yaylar beton və asfaltda kiçik çatlar yaradır. Küləyin və quşların gətirdiyi toz və toxumlar bu çatlara dolur. İlk olaraq mamırlar, şibyələr və aqressiv alaq otları (məsələn, gicitkən, qanqal) asfalta meydan oxuyur.

2. İkinci Dalğa (5-15 İl): Beton çatları böyüyür, yollar yaşıl xalçalara çevrilir. Kiçik kol bitkiləri və sürətlə böyüyən ağac növləri (məsələn, tozağacı, söyüd) kök ataraq yeraltı infrastrukturu (kanalizasiya, borular) parçalayır. Pəncərə şüşələri sınaraq binaların içərisinə yağış və torpağın daxil olmasına şərait yaradır. Evlərin içində kiçik ekosistemlər – göbələklər və həşərat koloniyaları qurulur.

3. Üçüncü Dalğa (25+ İl): Süni drenaj sistemləri sıradan çıxdığı üçün çökəklik ərazilər bataqlıqlara çevrilir. Damların çökməsi ilə binaların daxili tamamilə meşə zəminina çevrilir. Böyük yırtıcılar (canavarlar, tülkülər, ayılar) şəhər küçələrini öz ov əraziləri kimi istifadə etməyə başlayırlar. Artıq bura 'tərk edilmiş şəhər' deyil, içində beton skeletləri olan vəhşi bir meşədir.

5. Nəticə: İnsansız Dünyanın Dərsləri

Kabus şəhərlər bəşəriyyətə təkəbbürdən uzaq durmağı öyrədən ən böyük vizual dərslikdir. Biz elə hesab edirik ki, təbiəti tamamilə ram etmişik və yaratdığımız sivilizasiya əbədidir.

Lakin Pripyat, Haşima və digər tərk edilmiş coğrafiyalar göstərir ki, təbiətin bizi 'silməsi' üçün sadəcə bizim oradan çəkilməyimiz kifayətdir. Təbiət insan olmadan da mükəmməl şəkildə yaşaya, özünü bərpa edə və çiçəklənə bilər; lakin insan təbiət olmadan mövcud ola bilməz.

Bu ərazilərin bizə verdiyi digər bir mühüm mesaj isə planetin regenerasiya (bərpa) potensialının nə qədər güclü olmasıdır. Ən ağır nüvə çirklənməsinə məruz qalmış zonalar belə, insan təzyiqi olmadıqda bir neçə onillik ərzində yaşıl cənnətə çevrilə bilir. Bu, ekoloji böhranlarla mübarizə aparan müasir dünya üçün həm bir xəbərdarlıq, həm də böyük bir ümid mənbəyidir.

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An Event-Based Comparative Analysis of the 2024 Parliamentary Election and the Subsequent Political Crisis

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Abstract

This article examines the dynamics of political media polarization in Georgia during the 2024 parliamentary election and the political crisis that followed. The study combines an event-based comparative framing analysis of major Georgian media outlets with existing quantitative and qualitative media-monitoring evidence. The empirical sample includes Georgian Public Broadcaster (First Channel), Imedi, Rustavi 2, TV Pirveli, Mtavari Arkhi, Formula, the Georgian Service of Radio Free Europe/Radio Liberty, and Netgazeti. The observation period is divided into four stages: the pre-election campaign; the post-election dispute over electoral legitimacy; the 17–25 November period of opposition protest and the first sitting of the newly elected parliament; and the political escalation following the 28 November announcement concerning the postponement of EU accession negotiations. The analysis identifies four principal frames—institutional legitimacy, electoral legitimacy, conflict, and European integration/sovereignty—and examines how their relative salience changed across events and outlets. OSCE/ODIHR monitoring provides a quantitative baseline demonstrating substantial asymmetries in the amount and tone of campaign coverage, while the Georgian Charter of Journalistic Ethics provides independent qualitative evidence of a highly polarized television environment. Event-level analysis shows that polarization intensified as the political conflict moved from electoral competition to a dispute over institutional legitimacy and subsequently to a broader confrontation over Georgia's European trajectory. The findings suggest that media polarization in Georgia is better understood as a dynamic process of competing political meaning-making than as a static division between pro-government and opposition media. The article also emphasizes that the communicative construction of the crisis cannot be reduced to a single political narrative: government institutions, opposition actors, protesters, police and media organizations all became competing and sometimes conflicting sources of political meaning.

Keywords: political communication; media polarization; framing; Georgia; 2024 parliamentary elections; political legitimacy; protest; European integration; political journalism

1. Introduction

The parliamentary election held in Georgia on 26 October 2024 was followed by one of the most consequential periods of political and communicative confrontation in the country's recent history. The election itself took place in an environment that international observers described as highly polarized, while the weeks after the vote were marked by competing claims concerning the legitimacy of the results, the legitimacy of the newly elected parliament, the right to protest, the conduct of law-enforcement agencies and, ultimately, the direction of Georgia's relationship with the European Union. In this environment, news media became not only channels through which political actors communicated with the public but also important arenas in which the meaning of events was constructed and contested.

The media dimension of the Georgian crisis deserves particular attention because the country has a strongly polarized television environment in which different outlets frequently present substantially different interpretations of the same political event. This does not mean that every difference in emphasis constitutes misinformation or intentional manipulation. Rather, polarization can operate through selection, source attribution, terminology, headline construction, ordering of facts, emotional language and the relative visibility given to competing explanations.

Existing monitoring provides strong evidence of this environment. OSCE/ODIHR monitored the media during the 2024 election campaign and identified significant differences in the amount and tone of coverage devoted to political actors. The Georgian Charter of Journalistic Ethics, using a separate qualitative methodology, likewise reported a heavily polarized television environment and examined ten television channels during the election period. These studies establish the background against which the present research examines the subsequent political crisis.

The purpose of this article is therefore not to determine which political side was correct in the disputes that followed the election. Nor is it to reproduce the existing binary classification of Georgian media into government-oriented and opposition-oriented outlets. Instead, the study asks how the political meaning of key events was constructed across different media environments and how those constructions changed as the crisis evolved.

The principal research question is: How did major Georgian media outlets frame the key political events surrounding the 2024 parliamentary election and the subsequent political crisis, and how did these frames differ and change across the main stages of the conflict?

Three subsidiary questions guide the analysis. First, how did the pre-election media environment shape the communicative context in which the election results were interpreted? Second, how were electoral and parliamentary legitimacy constructed by different media outlets after the election? Third, how did media framing change following the 28 November announcement on EU accession negotiations and the subsequent escalation of street protests?

2. Theoretical Framework

The study draws primarily on framing theory and the literature on political polarization and partisan media. Framing is understood here as the process by which communicators select and emphasize particular aspects of reality in order to promote a specific interpretation of an issue, event or actor. In a politically polarized environment, framing is particularly consequential because competing political actors seek not simply to describe events but to establish the appropriate definition of reality: who possesses legitimate authority, who is responsible for conflict, what constitutes democratic behavior, and what political future should be considered desirable.

The study operationalizes framing through four dimensions. The institutional legitimacy frame emphasizes constitutional procedure, parliament, state institutions and continuity. The electoral legitimacy frame concerns the validity of the election, allegations of violations, the mandate of elected representatives and claims that the results should or should not be recognized. The conflict frame foregrounds confrontation, protest, police action, arrests, violence, barricades and political antagonism. Finally, the European integration/sovereignty frame emphasizes the European Union, Georgia's European trajectory, external pressure, national sovereignty and competing interpretations of geopolitical orientation.

This framework is intentionally symmetrical. It allows the researcher to identify government-oriented and opposition-oriented frames without assuming in advance that one side is necessarily the sole source of polarization. A government statement describing protest as destabilization, for example, is coded as a political claim and examined for attribution and editorial treatment; an opposition statement describing the parliament as illegitimate is treated under the same principle. The analytical question is whether the media outlet adopts, contests, contextualizes or balances the claim.

3. Research Design and Methodology

3.1. Research approach

The study uses a mixed-source, event-based comparative design. It combines (1) secondary quantitative evidence from OSCE/ODIHR media monitoring, (2) independent qualitative monitoring by the Georgian Charter of Journalistic Ethics, (3) temporal evidence from the ISET Media (de)Polarization Index, and (4) a purposive sample of publicly accessible media reports concerning a set of politically decisive events. The design is intended to provide both contextual measurement and close analysis of political framing.

3.2. Media sample

Outlet	Medium	Analytical role
Georgian Public Broadcaster / First Channel	Television and online	Public-service reference point
Imedi	Television and online	Government-oriented comparison
Rustavi 2	Television and online	Government-oriented comparison
TV Pirveli	Television and online	Opposition-oriented comparison
Mtavari Arkhi	Television and online	Opposition-oriented comparison
Formula	Television and online	Opposition-oriented comparison
RFE/RL Georgian Service	Radio and online	Independent international-service comparison
Netgazeti	Online	Independent digital comparison

The six television outlets correspond closely to the television sample used in OSCE/ODIHR monitoring: First Channel, Formula, Imedi, Mtavari Channel, Rustavi 2 and TV Pirveli. Netgazeti and RFE/RL are treated as a separate digital/radio comparison rather than being statistically merged with the television sample. The Georgian Charter of Journalistic Ethics monitored a broader television sample of ten channels and eight online outlets, making its findings useful as independent contextual evidence.

3.3. Periodization

Phase	Period	Political context	Analytical focus
I	18 September–26 October 2024	Election campaign	Visibility, tone and electoral competition
II	27 October–16 November	Post-election dispute	Electoral legitimacy
III	17–25 November	Opposition protest and first parliamentary session	Institutional legitimacy and protest
IV	28 November–December	EU announcement and prolonged protests	European integration, sovereignty and conflict

3.4. Coding procedure

Each selected media item is coded for: outlet; date; political event; dominant frame; tone; principal actor; attribution of claims; conflict intensity; delegitimization; source balance; and emotional language. The dominant frame is the frame that organizes the largest proportion of the item's narrative emphasis. A report may contain more than one frame, but one is designated

dominant for comparative purposes. Political claims are not automatically coded as facts: the coding distinguishes between a claim attributed to a source and an editorial assertion presented without qualification.

Because the current manuscript is being developed from publicly accessible material rather than a complete archive of every broadcast segment, the study does not claim exhaustive statistical coverage of all media output. Numerical findings drawn from OSCE/ODIHR and ISET are explicitly identified as secondary data. The event-level findings are presented as comparative qualitative evidence unless a complete count has been independently verified.

4. Pre-election Media Environment: Empirical Baseline

The pre-election environment provides an essential baseline because the post-election crisis did not emerge in a communicative vacuum. OSCE/ODIHR's media monitoring for 18 September–25 October 2024 identified pronounced differences in both the volume and tone of political coverage. Georgian Dream accounted for 82% of campaign coverage on Imedi, 80% on Rustavi 2, 61% on First Channel, 56% on Formula, 52% on Mtavari Channel and 51% on TV Pirveli. The tone of Georgian Dream coverage also differed sharply: 80% of its coverage on Imedi was positive or neutral compared with 20% negative, while the corresponding negative figures were 89% on Formula, 90% on Mtavari Channel and 91% on TV Pirveli. cite turn0search0

Outlet	GD share of campaign coverage	Critical/negative GD tone	Positive/neutral GD tone
First Channel	61%	—	ODIHR reports 89% positive/neutral overall tone
Imedi	82%	20%	80%
Rustavi 2	80%	32%	68%
Formula	56%	89%	11%
Mtavari Channel	52%	90%	10%
TV Pirveli	51%	91%	9%

These data should not be interpreted as proof that every individual news item on a particular channel was partisan. They instead demonstrate systematic differences in the communicative environment. The contrast between Imedi and TV Pirveli is especially pronounced: the former devoted a larger share of campaign coverage to Georgian Dream and evaluated that coverage predominantly positively or neutrally, whereas the latter devoted a smaller share to the party but overwhelmingly negative treatment. cite turn0search0

Independent qualitative monitoring by the Georgian Charter of Journalistic Ethics reinforces the broader conclusion. Its 2024 election monitoring covered the main news programmes of ten television channels from 27 August to 26 October and concluded that the television environment remained highly polarized; it also noted an increase in hate speech and discriminatory language compared with previous years.

5. The Election and the Emergence of a Legitimacy Conflict

The 26 October election shifted the central political question from electoral competition to competing interpretations of legitimacy. The governing Georgian Dream party treated the result as a mandate to form government and proceed with parliamentary institutions. Opposition parties rejected the results and questioned the legitimacy of the newly elected parliament. International observers, while recognizing the existence of political choice, also described the election environment as marked by entrenched polarization and concerns relating to pressure on voters and other aspects of the electoral process.

For media analysis, the distinction between an allegation and an established fact is crucial. The phrase 'claims of electoral theft', for example, represents a strong political interpretation when used by an opposition actor; the research question is whether the media presents it as a quotation,

challenges it, contextualizes it or adopts it as its own narrative. The same principle applies to government claims concerning destabilization, radicalism or external interference.

The result was a classic legitimacy contest in which the same institutional outcome—the formation of a new parliament—could be represented either as constitutional continuity or as the institutionalization of a disputed electoral result. This contest became the dominant background to the protests that began in mid-November.

6. 17–25 November: Protest, Resistance and Parliamentary Legitimacy

The night of 17–18 November marked a new phase. Opposition supporters and activists began a continuing protest campaign, while media narratives diverged over its purpose, scale and legitimacy. The difference was visible at the level of terminology. Government-oriented coverage could describe the participants as a radical minority and emphasize disruption or damage to infrastructure. Opposition-oriented coverage more often emphasized resistance, protection of electoral choice and the demand for new elections.

This divergence is analytically significant because it demonstrates that framing does not require contradictory factual reporting. Two reports may both acknowledge that demonstrators blocked a road while assigning radically different meanings to the action: one can define it as unlawful disruption, another as civil resistance. The frame is therefore located not only in the event description but in the causal and normative relationship established between facts.

6.1. The 25 November parliamentary session as a comparative case

The first sitting of the newly elected parliament on 25 November is one of the clearest comparative cases in the study. First Channel emphasized the institutional opening of parliament while separately covering the protest outside the building. Imedi focused on the formal institutional basis of the session and the registration of 89 deputies. Netgazeti foregrounded the fact that only Georgian Dream deputies were present in the chamber. Opposition-oriented coverage emphasized the disputed legitimacy of the parliament and framed the protest as a response to an allegedly claims of electoral theft.

The event therefore generated at least three competing frames: institutional continuity, parliamentary legitimacy dispute and democratic resistance. The disagreement was not merely about what happened on 25 November; it was about what the event meant. This is precisely the type of communicative polarization that event-based framing analysis can capture.

The case also illustrates why a simple ‘pro-government versus pro-opposition’ variable is insufficient. A media outlet may accept that parliament legally convened while simultaneously highlighting the political absence of opposition deputies. Another outlet may emphasize constitutional procedure while minimizing the political dispute. A third may foreground the dispute and treat the parliamentary procedure as secondary.

7. 28 November: European Integration and Sovereignty Become the Central Frame

On 28 November, Prime Minister Irakli Kobakhidze announced that Georgia would not put the opening of EU accession negotiations on the agenda until 2028 and would reject EU budgetary grants until then. The announcement immediately changed the political context and triggered a new wave of demonstrations. The ISET Media (de)Polarization Index identifies 28 November as the historical maximum of media polarization, associating the peak with the suspension of EU accession talks and the ensuing protests. cite turn0search6

The dominant communicative question consequently changed. Electoral legitimacy remained important, but the conflict was increasingly articulated through two competing frames. In one, the government’s position was associated with sovereignty, national decision-making, resistance to external pressure and the protection of state interests. In the other, the opposition and protesters interpreted the decision as a departure from Georgia’s European trajectory and as a challenge to the country’s declared integration objective.

This transformation is important because it explains why media polarization increased even after the election itself had ended. Political communication was no longer organized primarily around the distribution of parliamentary seats. It was organized around competing visions of the state's future and competing definitions of legitimate political action.

8. 29 November: Escalation and the Conflict Frame

The following night intensified the conflict frame. News reports increasingly centered on police dispersal, water cannon, arrests, injuries, barricades, pyrotechnics and reported attacks on journalists. Yet the selection and sequencing of these elements varied by outlet.

First Channel reported the use of water cannon and also reported protesters' use of pyrotechnics and other objects. Rustavi 2 similarly reported a tense situation involving both police action and protesters' construction of barricades and fires. TV Pirveli placed greater emphasis on the detention and alleged beating of peaceful citizens and on injuries to journalists. Netgazeti foregrounded the dispersal of the protest and the implications for freedom of assembly. RFE/RL coverage emphasized the force used during the dispersal and arrests. The same physical confrontation was therefore embedded in different causal narratives.

This is a central finding of the study: conflict framing is not equivalent to reporting that conflict occurred. It is the organization of conflict around actors, responsibility, victims, threats and justification. The choice of whether the headline begins with police action, protester action, injuries, arrests or political demands can substantially affect the audience's interpretation of the same event.

9. Journalists as Actors and Targets

The political crisis also affected the media themselves. Journalists and camera operators covering the protests were among those subjected to physical attacks, obstruction and damage to equipment. The Georgian Charter of Journalistic Ethics documented incidents involving media representatives during the protest period, while individual outlets reported injuries to their own staff. The result was a feedback loop: polarized politics shaped media coverage; polarized media became targets of political conflict; and those attacks subsequently became news events that further reinforced divergent narratives.

This phenomenon is especially relevant to media polarization because journalists were no longer merely observers of a political conflict. They became participants in the conflict environment, whether willingly or unwillingly, and their institutional affiliations could themselves become part of the political narrative.

10. Comparative Results

The combined evidence produces five principal findings.

Finding 1 - Polarization preceded the post-election crisis. The pre-election monitoring data demonstrate that major outlets already differed substantially in the amount and tone of their coverage. The post-election crisis therefore developed on top of an already polarized media structure.

Finding 2 - The principal object of polarization changed over time. During the campaign, competition centered on political actors and electoral choice. After the election, the main object became legitimacy: the validity of the results and the legitimacy of the new parliament.

Finding 3 - The 25 November parliamentary session produced competing institutional narratives. The same event was framed as constitutional institutional continuity, evidence of a disputed parliament, or an occasion for democratic resistance. This makes the parliamentary session a particularly strong comparative case.

Finding 4 - 28 November transformed the conflict into a European/sovereignty dispute. The announcement concerning EU accession negotiations shifted the dominant political frame from electoral legitimacy toward European integration, sovereignty and external pressure. The ISET

index independently identifies this date as the historical peak of media polarization. cite turn0search6

Finding 5 - The conflict frame became dominant during the 29 November escalation. Coverage increasingly centered on police, protesters, arrests, injuries, barricades and journalists. However, outlets differed substantially in which actor's behavior they foregrounded and how responsibility was attributed.

11. Discussion

The findings support the proposition that media polarization in Georgia during the 2024 political crisis was dynamic rather than static. The ideological orientation of individual outlets mattered, but the more important analytical development was the transformation of the political object being framed. The media environment moved through a sequence of interconnected disputes: who should govern, whether the election was legitimate, whether the parliament was legitimate, whether protest was legitimate, and what Georgia's European future should be.

This sequence helps explain why polarization intensified after the election rather than declining once voting was over. Elections normally provide a mechanism for resolving political competition. In this case, however, the result itself became the object of political disagreement. When one side recognized the electoral outcome and another rejected it, the media were forced to interpret not simply political preferences but the status of the state institutions that emerged from the election.

The 28 November announcement created another transformation. The conflict was no longer limited to domestic institutional legitimacy. European integration became a symbolic and strategic object around which both sides organized political meaning. Government-oriented narratives could frame resistance to EU pressure as a defense of sovereignty, while opposition narratives could frame the same decision as a departure from the country's declared European integration objective. The result was a high-polarization environment in which the same factual event acquired incompatible normative meanings.

The analysis also cautions against treating polarization as a phenomenon generated exclusively by one political camp. The evidence reveals reciprocal delegitimization. Government actors and aligned media delegitimized opposition mobilization through concepts such as radicalism and destabilization; opposition actors and aligned media delegitimized government institutions through claims concerning electoral theft, illegitimacy and authoritarianism. These narratives were not necessarily symmetrical in factual content or consequences, but they were structurally similar in their effort to establish one side as legitimate and the other as fundamentally illegitimate.

This finding does not mean that all media outlets were equally biased or that all political claims were equally supported by evidence. Rather, it means that a rigorous analysis should distinguish between factual verification, political attribution and editorial framing. Such differentiation prevents the study from becoming an extension of either government or opposition discourse.

12. Conclusion

The 2024 parliamentary election and subsequent political crisis in Georgia provide a particularly valuable case for examining the relationship between political conflict and media polarization. The evidence demonstrates that polarization was already pronounced during the election campaign, but its communicative form changed substantially after election day.

The first transformation occurred when electoral competition became a dispute over legitimacy. The second occurred when the legitimacy dispute was translated into a confrontation over the newly elected parliament and the right to protest. The third occurred after 28 November, when the political crisis became increasingly organized around competing interpretations of Georgia's European trajectory, sovereignty and the relationship between domestic political authority and external actors.

The study's central conclusion is that media polarization is best understood as a process of competing political meaning-making. The most consequential differences between outlets did not always consist in the factual events they reported. They often consisted in which facts were made salient, which actors were given explanatory authority, how responsibility was attributed, which terminology was used, and whether competing interpretations were contextualized or marginalized.

At the same time, the analysis does not support a one-sided narrative in which only one political camp produced polarization. Government institutions, opposition parties, protesters, law-enforcement agencies and media organizations all operated within a highly adversarial communicative environment. The media reflected this conflict, amplified some of its dimensions and, in some cases, became direct participants or targets of it.

The Georgian case therefore demonstrates that political polarization and media polarization can reinforce one another through a cumulative process. Once political legitimacy becomes contested, every subsequent event—including parliamentary procedure, protest, police action, European integration and reported attacks on journalists—can be interpreted through the pre-existing political divide. The result is not simply a divided media market but a divided interpretive environment in which citizens may receive fundamentally different answers to the question of what is happening in their country.

Future research should extend the present event-based design by building a larger machine-readable corpus of television transcripts and online articles, applying intercoder reliability testing and measuring frame prevalence quantitatively over time. Such an approach would allow researchers to distinguish more precisely between stable editorial orientation and short-term polarization produced by particular political shocks.

13. Limitations

Several limitations should be acknowledged. First, the event-level sample is purposive rather than exhaustive. Publicly accessible archives do not preserve every television broadcast item, and availability varies across platforms. Second, qualitative frame coding involves interpretive judgment; a future expanded study should use at least two independent coders and report intercoder reliability statistics such as Cohen's kappa. Third, the study combines different types of media -television, radio and online media - so these should not be treated as statistically interchangeable. Finally, secondary monitoring data and the present study's own event-level observations answer somewhat different questions and are therefore used in complementary rather than interchangeable ways.

14. Data and Source Strategy for Replication

For replication, the final submission should preserve the original URL, publication date, headline and access date for every event-level item. The coding sheet should contain the full text or transcript where legally and technically possible, the dominant frame, secondary frames, main source, tone, delegitimization indicator and balance indicator. The quantitative OSCE/ODIHR figures should remain identified as secondary data rather than being merged into the researcher-generated corpus.

The present manuscript is therefore a full journal-style research draft, but it should undergo one final empirical audit before submission: every event-level coding entry should be checked against the original source page and, where possible, the corresponding video. No numerical claim should be added unless the denominator and coding rule are explicit.

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Appendix A. Preliminary Event-Level Coding Matrix

Outlet	Date	Event	Dominant frame	Tone	Conflict	Delegitimization	Main actor	Balance
Imedi	18 Nov	Protest	Conflict / radicalism	Critical/negative	2	Yes	Opposition	Low
RFE/RL	18 Nov	Protest	Resistance / electoral legitimacy	Mixed	1	No	Opposition	Medium
First Channel	25 Nov	Parliament session	Institutional legitimacy	Mixed	2	Attributed	Parliament	Medium
Imedi	25 Nov	Parliament session	Institutional legitimacy	Positive/neutral	1	Attributed	Government	Low
Netgazeti	25 Nov	Parliament session	Legitimacy dispute	Critical	2	Yes	Parliament/Opposition	Medium
TV Pirveli	25 Nov	Parliament session	Delegitimization	Critical/negative	3	Yes	Government	Low
First Channel	29 Nov	Protest	Law enforcement / conflict	Mixed	3	No	Police + protesters	Medium
Rustavi 2	29 Nov	Protest	Conflict / both sides	Mixed	3	No	Police + protesters	Medium
TV Pirveli	29 Nov	Protest	Use of force by police	Critical/negative	3	Yes	Police	Low
Netgazeti	29 Nov	Protest dispersal	Use of force by police / assembly rights	Critical/negative	3	Yes	Police	Medium

Appendix B. Submission Checklist

Confirm the target journal's aims and scope and adapt the title, abstract and reference style.
Replace preliminary event-level coding with audited source-by-source coding.
Add at least two independent coders for the final quantitative corpus and calculate intercoder reliability.
Verify every URL, publication date and quotation against the original source.
Prepare 2–4 publication-quality figures from the final coded dataset.
Ensure the abstract matches the final numerical results.
Apply the target journal's reference style and word limit.
Add author information, affiliation, ORCID and funding/conflict-of-interest statements if required.
Submit only after the empirical tables and references have been independently checked.



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