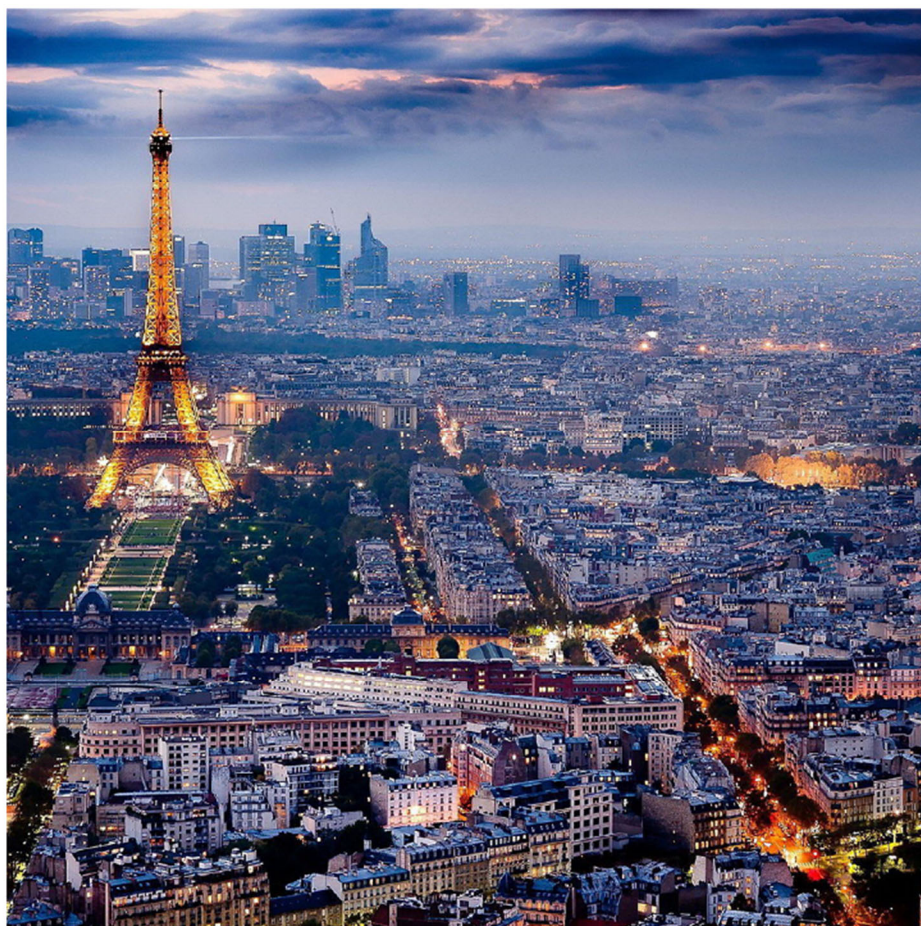


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## Psychological Sciences

# Developing Adolescents' Learning Motivation in the Context of Modern Education

**Ramazanova Kamala**

Sheki branch of Azerbaijan State Pedagogical University, Psychology teacher, Azerbaijan, Sheki, <https://orcid.org/0009-0004-5225-3779>

### ABSTRACT

The pedagogical and psychological analysis of adolescents' learning motivation demonstrates that motivation during this period is a complex and dynamic process shaped by individual psychological characteristics, social relationships, and the learning environment. During adolescence, identity formation, the search for personal identity, emotional changes, the development of self-regulation skills, and the increasing influence of peers may lead to changes in attitudes toward learning. These factors play an important role in determining adolescents' interest in learning, goal orientation, and level of participation in educational activities.

During this period, meeting adolescents' needs for competence, autonomy, and social relatedness is particularly important for strengthening intrinsic motivation. When students believe in their abilities, are able to make independent decisions, and feel valued in the learning process, they are more likely to participate actively in educational activities. At the same time, defining meaningful and realistic learning goals and taking students' interests and needs into account can contribute to maintaining their motivation.

Pedagogical factors also play an important role in the development of adolescents' learning motivation. Teachers' attitudes toward students, communication styles, teaching methods, assessment approaches, and the psychological climate created in the classroom directly influence students' engagement in learning. Supportive teacher behavior, a collaborative learning environment, differentiated instruction, and growth-oriented assessment strengthen students' self-confidence and interest in learning. In contrast, excessive criticism, assessment based solely on outcomes, and failure to consider individual characteristics may lead to decreased motivation.

Increasing activities that are meaningful and interesting to students, using problem-based and project-based tasks, and creating opportunities for independent thinking and creative activities support adolescents' active participation in lessons. In addition, strengthening cooperation among parents, teachers, and school psychologists enables motivation-related difficulties to be identified in a timely manner and appropriate support mechanisms to be implemented. Consequently, the sustainable development of adolescents' learning motivation requires not only individual psychological characteristics but also pedagogical approaches and the social environment to be considered comprehensively. Creating a purposeful, student-centered, and psychologically supportive learning environment makes an important contribution to improving adolescents' academic engagement, self-regulation skills, and learning outcomes.

**KEYWORDS:** Adolescence, learning motivation, intrinsic motivation, extrinsic motivation, teacher–student relationship, social influences

Adolescence is considered one of the most dynamic and complex stages of human development, and the formation of learning motivation during this period requires particular scientific and pedagogical attention. The intensive psychological, emotional, and social changes that occur during adolescence directly influence individuals' attitudes toward learning, learning behaviors, and academic achievement. Adolescents strive to understand themselves, seek greater independence, and experience a strong need for social acceptance. These developmental characteristics determine the content, stability, and direction of motivation within the learning process.

Learning motivation is closely associated with the opportunities created by the educational environment, teachers' attitudes, the teaching methods used, and the assessment system. A supportive teacher approach that respects students' opinions and creates a collaborative learning environment can increase adolescents' interest in learning. In contrast, strict and criticism-oriented pedagogical attitudes may lead to decreased motivation. From a psychological perspective, self-regulation skills, self-confidence, goal-setting abilities, and emotional stability are among the key mechanisms that determine adolescents' approaches to learning activities.

In this context, examining the pedagogical and psychological aspects of adolescents' learning motivation makes it possible to gain a deeper understanding of their educational activities and improve the effectiveness of the educational process. The relevance of the topic arises both from the changing learning needs of adolescents and from the need for modern education systems to develop strategies aimed at maximizing their individual potential. Therefore, studying the pedagogical and psychological mechanisms that influence adolescents' motivation creates opportunities for organizing the learning process in a more purposeful and student-centered manner.

Adolescence is one of the most complex and dynamic stages of human life, and the formation of learning motivation during this period is a highly sensitive pedagogical and psychological process. At this age, students experience rapid physical, psychological, and social changes, which directly influence their attitudes toward learning. As adolescents strive to understand their identity, gain independence, and find their place in society, motivation becomes closely connected with their internal emotional world. Therefore, learning activities are not limited to acquiring knowledge but are also related to needs such as self-expression, self-affirmation, and social acceptance.

One of the most important factors in the formation of learning motivation is students' range of interests. Adolescents tend to show greater interest in information that has practical value and is connected to everyday life. They consider it important to understand how the knowledge they acquire can be applied in real-life situations and what benefits it may provide in the future. Therefore, teachers should emphasize the practical aspects of subjects during the learning process and provide detailed and clear answers to adolescents' questions.

The family environment also plays an important role in the development of motivation. The support provided by parents, their expectations, and their attitudes toward their children contribute to the development of adolescents' self-confidence. Emotional encouragement from the family can increase students' interest in education, whereas excessive pressure may have the opposite effect. Therefore, the family environment is an important social factor that can have both positive and negative effects on the formation of motivation.

Another important factor is the teacher–student relationship. Adolescents are highly sensitive to teachers' emotional support, positive attitudes, objectivity, and fairness. A positive and democratic teacher–student relationship can increase students' enthusiasm for learning, whereas a strict, rude, or unfair approach may weaken their motivation. The most effective pedagogical approach is one that values the student as an individual, takes their questions seriously, and supports their initiative.

The social environment and peer group also play an important role in the formation of adolescents' learning motivation. At this age, students are particularly sensitive to their friends' opinions and attitudes. In some cases, the level of interest in education within a peer group, attitudes toward learning, and examples of academic success can directly influence an adolescent's behavior. While a positive peer environment can increase motivation to learn, a negative social environment may weaken learning outcomes.

As these factors demonstrate, the formation of learning motivation among adolescents is a multidimensional process resulting not only from the educational process but also from the combined influence of psychological and social conditions. Appropriate guidance, emotional support, meaningful learning experiences, and opportunities for practical application contribute to the development of stable and sustainable motivation, which forms an important foundation for future educational success.

Pedagogical factors play an important role in the formation of adolescents' learning motivation and are directly related to the effective organization of the educational process, teachers' behavior, teaching methods, and assessment systems. These factors can either strengthen or weaken students' attitudes toward learning. Therefore, teachers should not act merely as providers of knowledge but also as guides who stimulate students' interests, encourage learning, and support their emotional development.

One of the pedagogical factors influencing motivation is the organization of the learning process. In modern education, the use of interactive and student-centered teaching methods is particularly important. Traditional lecture-based methods may reduce adolescents' interest because students at this age tend to prefer lessons that require active participation, encourage critical thinking, and provide opportunities to express their own ideas. Methods such as discussions, debates, project-based learning, and group activities can significantly improve adolescents' attitudes toward learning and increase their engagement in the educational process.

Another important factor is the teacher's personality and communication style. In addition to presenting lessons in an interesting and understandable manner, teachers should be able to empathize with students and make an effort to understand their difficulties. Adolescents tend to respond more positively to teachers who are fair, sincere, and demanding while maintaining a supportive and respectful attitude. Teachers' emotional support, encouraging words, and positive behavior can strengthen students' self-confidence, which in turn has a positive influence on learning.

Another important pedagogical factor is the content of the lesson and the way it is presented. Adolescents tend to prefer real-life examples and practical explanations to abstract information. Therefore, teachers should connect topics with real-life situations and provide explanations relevant to students' everyday experiences. Selecting content appropriate to students' developmental level, using visual materials such as pictures, diagrams, and videos, and integrating knowledge across different subjects can further strengthen learning motivation.

The assessment system is one of the most influential pedagogical mechanisms affecting motivation. Fair, transparent, and development-oriented assessment increases students' motivation. In contrast, a rigid system that focuses exclusively on results and fails to take individual differences into account may reduce students' interest in learning. Modern pedagogy increasingly emphasizes formative assessment, which involves identifying areas where students experience difficulties and providing guidance for further development.

Another important pedagogical factor is rewarding and feedback. When teachers praise students, recognize their progress, and express their appreciation openly, this can serve as a strong emotional stimulus for adolescents. Even a simple statement such as "Well done, you

have done better this time” can strengthen a student’s self-confidence and encourage them to make greater efforts. Constructive feedback, in particular, contributes to maintaining motivation over time.

It should also be noted that all pedagogical factors are interconnected, and their overall impact depends not on a single element but on how the educational environment is organized as a whole. An effective pedagogical approach creates conditions for the strong, sustainable, and purposeful development of learning motivation among adolescents. In such an environment, students not only acquire knowledge but also discover themselves, develop new skills, and approach their future with greater confidence.

Adolescence is one of the most critical stages of psychological development, and the psychological processes that emerge during this period directly influence students’ interest in learning and their motivation. Emotional changes, self-awareness, identity formation, and the search for social identity become particularly prominent at this age. For this reason, adolescents’ attitudes toward learning are not always stable and may change rapidly depending on both internal and external psychological influences. Psychological factors can have either a positive or negative effect on the stability and sustainability of motivation.

Self-confidence and self-esteem are among the most important psychological factors influencing learning motivation. Adolescents with a positive sense of self tend to approach the learning process with greater confidence, are less likely to avoid difficulties, and are more willing to set challenging goals. In contrast, students with low self-confidence may fear failure and consequently show less interest in acquiring new knowledge. Therefore, psychologists and teachers should emphasize students’ abilities and recognize even their small achievements. Such support can strengthen self-confidence and encourage adolescents to participate more actively in the learning process.

Emotional state also plays an important role in learning motivation. Since adolescents are psychologically sensitive, their emotions may fluctuate considerably. They may be highly motivated on one day and show little interest in the learning process on another. Stress, family tensions, conflicts with teachers, or difficulties in relationships with friends can significantly reduce interest in learning. In contrast, a positive emotional environment increases students’ interest in lessons because they feel safe, valued, and supported.

Another psychological factor that shapes adolescents’ interest in learning is the changing nature of their interests and the increasing complexity of their intellectual needs. During this period, students are often eager to explore new areas of knowledge. When learning activities are organized in accordance with these interests, motivation tends to remain high. Otherwise, monotonous and repetitive lessons can quickly lead to boredom and cause adolescents to direct their attention toward other areas.

Social comparison and peer influence are also important psychological factors. Adolescents tend to compare themselves with their peers. When their friends perform well academically, this may create a sense of competition and encourage the student to become more interested in learning. Conversely, negative peer influence, such as indifference toward lessons, irresponsibility, or devaluing education, may weaken adolescents’ motivation. Therefore, teachers should create a positive social environment in the classroom and encourage cooperation among students.

Another important factor is intrinsic and extrinsic motivation. Intrinsic motivation is associated with students’ genuine interest in learning and their desire to acquire knowledge. Extrinsic motivation, on the other hand, develops through external influences such as rewards, punishment, parental expectations, or high grades. Psychological research suggests that the most sustainable form of motivation among adolescents is associated with intrinsic interest. Therefore,

teachers should prioritize approaches that make learning engaging, respond to students' questions, and demonstrate that their opinions and ideas are valued.

In conclusion, psychological factors determine not only adolescents' attitudes toward learning but also their social behavior, self-expression, emotional stability, and perspectives on the future. Therefore, teachers and parents should pay close attention to adolescents' psychological well-being, respond sensitively to their needs, and create a positive psychological environment. Under such conditions, learning motivation among adolescents can develop in a more stable, strong, and purposeful manner.

The teacher–student relationship is one of the most influential pedagogical and psychological factors affecting adolescents' learning motivation. This relationship influences not only the organization of the learning process but also students' emotional well-being, self-confidence, and overall attitude toward education. During adolescence, young people need supportive adults whom they can consider role models and who value them as individuals. Therefore, the psychological climate created by the teacher in the classroom directly affects students' willingness to learn.

One of the main conditions for an effective teacher–student relationship is sincerity and mutual respect. Students are more likely to participate actively in lessons when teachers treat them respectfully, listen to their opinions, and recognize them as individuals. Such a relationship can foster a sense of “I can do it” and help adolescents believe in their own potential. In contrast, an excessively strict, overly demanding, or humiliating approach can lead to a significant decline in motivation.

The principle of fairness demonstrated by the teacher is particularly important for motivation. Adolescents are highly sensitive to perceived injustice during this period. If a teacher is not objective in assessment, shows preferential treatment toward certain students, or makes negative comments about a student's weaknesses, this can seriously reduce their interest in learning. Conversely, a teacher who treats students fairly and recognizes their efforts contributes to strengthening a motivating classroom environment.

Another important element of the teacher–student relationship is emotional support and empathy. Adolescents may experience emotional instability during this developmental stage and may interpret negative reactions as being directed personally at them. Simple acts of attention from the teacher—such as explaining a difficult question, approaching a student who is experiencing difficulties, or being willing to listen—can positively influence their attitude toward learning. Empathy builds trust between teachers and students, and this trust represents one of the fundamental foundations of learning motivation.

Another important pedagogical component for motivation is continuous and constructive feedback. When a teacher provides positively oriented feedback such as, “You have done this task well, but you can develop this part further,” it can strengthen students' self-confidence and encourage them to approach learning more responsibly. In contrast, harsh and humiliating criticism may create fear and withdrawal in adolescents, ultimately leading to decreased motivation.

Another factor that plays an important role in the teacher–student relationship is the teacher's exemplary behavior. Adolescents pay attention not only to what teachers say but also to how they behave. If a teacher demonstrates respect for their subject, behaves responsibly, and remains open to continuous learning, students may adopt these behaviors as positive models. When teachers present their subjects in an engaging manner and demonstrate energy and creativity during lessons, classroom motivation can increase considerably.

An effective teacher–student relationship is one of the important predictors of students' academic success, emotional well-being, and learning motivation. A humanistic, student-centered approach characterized by attention, support, and objectivity can contribute to the development

of long-term motivation and positively influence adolescents' learning activities. When such a relationship is established, students not only acquire knowledge but also enjoy the learning process, develop as individuals, and prepare for the future with greater confidence.

Organizing lessons in an interactive and participation-oriented manner is one of the main strategies for increasing adolescents' learning motivation. At this age, students may show limited interest in monotonous lessons based solely on teacher explanations. Instead, they tend to prefer learning activities in which they can express their opinions and participate actively. Therefore, group work, debates, project-based tasks, observations, experiments, and creative activities can encourage students to participate more actively in the learning process. Such methods not only facilitate learning but also strengthen students' social skills, cooperation abilities, and sense of responsibility.

Connecting lesson topics with real-life examples is important for helping students answer the question, "What is the practical value of what I am learning?" When adolescents understand the practical benefits of acquired knowledge, their level of interest and attention tends to increase considerably. For example, when mathematical problem-solving is presented through real-life situations or when the relevance of environmental issues in biology is explained in relation to everyday life, students are more likely to engage enthusiastically in lessons. The use of technology and visual materials, including pictures, videos, and interactive diagrams, can make lessons more engaging and interesting while helping maintain adolescents' attention for longer periods.

Individualized teacher support and continuous constructive feedback also play an important role in strengthening motivation. Recognizing and encouraging even small achievements can increase students' self-confidence and create a desire to achieve greater success. In addition, selecting tasks according to students' interests and abilities enables them to participate more actively in the learning process. Thus, when interactive lessons, real-life examples, technology, and individualized approaches are applied together, they can contribute to the development of strong and sustainable intrinsic motivation among adolescents and encourage active and responsible participation in learning.

Creating a positive emotional environment in the classroom is essential for strengthening adolescents' learning motivation. When students feel safe, valued, and accepted, their interest and enthusiasm for learning tend to increase. A sincere, understanding, and supportive attitude from the teacher creates a sense of trust and comfort among adolescents. At the same time, fair and objective assessment plays an important role in maintaining motivation, as students at this age are particularly sensitive to perceived injustice. Teachers should consider students' strengths and weaknesses and provide tasks that correspond to their individual pace of development.

One of the main psychological factors that strengthens motivation is supporting students in defining their own goals. When adolescents understand that what they learn can be useful in the future, their interest in learning increases. Teachers should help them clarify their goals, connect lessons with their interests and aspirations, and provide positive reinforcement and constructive feedback. This approach not only strengthens learning motivation but also contributes to the development of students' sense of responsibility and initiative.

Emotional support and respect for students' initiatives also contribute to the sustainability of motivation. Teachers should recognize and encourage students' achievements, support those who experience difficulties, and take their opinions seriously. This approach strengthens adolescents' intrinsic motivation and develops a lasting interest in learning. Consequently, when a positive psychological environment, individualized approach, fair assessment, constructive feedback, and emotional support are implemented together, adolescents' learning motivation can develop in a stable and sustainable manner, encouraging them to participate actively and responsibly in the learning process.

## CONCLUSION

The analysis demonstrates that strengthening adolescents' learning motivation requires not only consideration of psychological mechanisms but also the systematic organization of the pedagogical environment. Motivation is closely associated with adolescents' emotional state, self-confidence, goal-setting abilities, and social relationships, and it can be further strengthened through supportive, transparent, and individualized teacher approaches. The implementation of cooperation, dialogue, formative assessment, and creative activities in the educational process creates favorable conditions for the development of adolescents' intrinsic motivation. Therefore, adolescents' learning motivation can be strengthened through pedagogical approaches that correspond to their stage of psychological development. Such a systematic approach can make a significant contribution to their academic achievement, engagement in learning, and development of long-term learning habits.

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## Medical Sciences

# USE OF COMPUTER SOFTWARE IN PRECLINICAL PHARMACOLOGICAL RESEARCH: NEW APPROACHES TO MODELING AND REDUCING EXPERIMENTAL BURDEN

**Khaitova Malika**

PhD, Associate Professor of pharmacology department, Asfendiyarov Kazakh National Medical University, Almaty, Kazakhstan

### Abstract

Currently, the role of modern digital technologies in preclinical pharmacological research has increased. Software for molecular modeling, including docking, molecular dynamics, and QSAR analysis tools, is reviewed, enabling early virtual screening and selection of promising compounds. Particular attention is paid to programs for predicting pharmacokinetics and toxicity, which provide assessment of ADMET profiles and improve the accuracy of experimental planning. The importance of digital predictions for optimizing dose selection prior to studies in animal models is emphasized, thereby contributing to risk reduction and a decrease in experimental burden. Existing challenges in integrating digital platforms into laboratory practice are noted, including the need for algorithm validation, infrastructure adaptation, and researcher training.

**Keywords:** digital technologies; molecular modeling; ADMET prediction; preclinical studies; virtual screening; dose optimization; laboratory digitalization.

### Introduction.

The relevance of the widespread use of digital technologies and computer software at the preclinical research stage is driven by the growing need to improve the efficiency and reproducibility of preclinical pharmacological studies. The integration of digital technologies, including molecular modeling and predictive approaches, makes it possible to optimize the selection of biologically active compounds, reduce the experimental burden, and minimize the risk of failure during experimental studies.

### Computer software in preclinical pharmacological research.

Software for molecular modeling combines sets of tools for docking, molecular dynamics, free-energy calculations, and QSAR, which make it possible to reproduce the structure and conformational changes of protein–ligand complexes and to perform virtual screening of large compound libraries. Computational modeling serves as an important complement to experimental data, effectively bridging the gap between atomic-level properties and whole-organism function—a task that cannot be accomplished using any single method. For efficient collection of information across biological scales, the optimal approach is to combine several computational methods covering a broad range of time intervals and spatial scales [1].

Classical implementations include AutoDock/AutoDock Vina for rapid assessment of binding poses and binding energies, demonstrating a good balance between speed and quality, as well as major molecular dynamics packages (GROMACS, Desmond) for evaluating the dynamics and stability of complexes [2].

Programs for predicting pharmacokinetics and toxicity (ADMET tools) include web services and machine-learning models—SwissADME, pkCSM, and similar platforms—which provide rapid estimates of absorption, distribution, metabolism, excretion, and potential toxicity based on structural features and trained datasets. A key advantage of the SwissADME platform is its comprehensive toolkit for assessing drug-likeness. This toolkit includes the application of multiple filters (including the Lipinski, Ghose, Egan, and Veber rules), as well as calculations using the BOILED-Egg model, which visualizes the probability of gastrointestinal absorption and blood–brain barrier permeability. In addition, built-in filters for PAINS motifs and structural “alert fragments” (Brenk alerts) provide preliminary toxicological screening, substantially improving the quality and reliability of early selection of promising candidates. These tools are widely used for the early filtering of candidate compounds and are supported by validation publications [3].

A validated computational platform, pkCSM, is available for predicting the pharmacokinetic and toxicological properties of small molecules. The tool is based on the analysis of graph-based signatures, in which the structural representation of a molecule is transformed into a set of topological descriptors reflecting spatial and electronic characteristics. This approach, trained on extensive experimental data, provides high predictive accuracy [4].

Quantitative structure–activity relationship (QSAR) analysis is a fundamental method of ligand-based drug design. For more than five decades, QSAR has remained a highly effective tool for constructing mathematical models. The purpose of these models is to establish statistically significant correlations between chemical structure and biological or toxicological properties (including binary outcomes—active/inactive) using regression and classification methods. Over recent decades, the methodology has undergone substantial transformation, evolving both in terms of the dimensionality of molecular descriptors and the diversity of algorithms used to identify structure–function relationships. Modern research approaches can combine virtual docking, QSAR, and molecular dynamics calculations. These approaches include multiscale assessments of binding energy, free energies, conservation of contacts, and appropriate validation [5].

The role of digital predictors in experimental planning lies in the early filtering of unsuccessful candidate compounds, selection of targets, and prioritization of dose ranges. This reduces the number of required *in vivo* studies and helps focus resources on the most promising molecules. Numerous publications demonstrate the successful use of *in silico* assessments for candidate selection before preclinical stages [6]. Risk reduction and optimization of dose selection prior to animal studies are achieved through the integration of predictions and computational models. Model-informed approaches make it possible to narrow dose ranges and plan experimental designs while reducing the number of animals and dose levels required [7,8].

One stage in the digitalization of experimental work is the use of an electronic laboratory notebook (ELN). The implementation of an ELN is a key step in optimizing workflow. Use of this resource reduces the time required to complete primary documentation, standardizes data through the creation of standardized templates for analytical methods, and enables rapid retrieval of necessary information. In addition, server-based backup functionality ensures reliable preservation and identification of all primary experimental data [9].

### Conclusions.

Challenges associated with the integration of digital platforms into laboratories include technical incompatibility, the need for algorithm validation, staff training, and institutional support for software. It is necessary to develop algorithms for implementing computer platforms, as well

as strategies for addressing problems that arise during their use and overcoming existing barriers [10].

Thus, modern digital technologies substantially expand the capabilities of preclinical pharmacology by enabling virtual screening, prediction of pharmacokinetic profiles, and optimization of experimental design; however, they require reliable validation and adaptation of laboratory infrastructure.

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# THE SCIENTIFIC DISCOURSE ON PHARMACOLOGY, MECHANISMS OF ACTION, PHARMACOLOGICAL SAFETY, SIDE EFFECTS, AND TOXICITY OF ANTICANCER MEDICATIONS IN MODERN ONCOLOGY: PHARMACOVIGILANCE AND INTEGRATED APPROACHES TO EVIDENCE-BASED PHARMACOTHERAPY, PHARMACOGENOMICS, PERSONALIZED MEDICINE, AND THERAPEUTIC DRUG MONITORING STRATEGIES

## **Nodar Sulashvili**

MD, PhD, Doctor of Pharmaceutical and Pharmacological Sciences In Medicine, Professor of Faculty of Medicine at Georgian International University GIU; Professor of Pharmacology of Faculty of Medicine at Georgian National University SEU; Professor of Medical and Clinical Pharmacology of Faculty of Medicine at BAU International University Batumi, Invited Professor/Lecturer of Scientific Research-Skills Center at Tbilisi State Medical University; Invited Lecturer of Clinical Pharmacology Department at Tbilisi State Medical University; Scientific Researcher, Best, Top Academic Scientist, Georgia, Europe, Worldwide; Associate Professor of Biochemistry and Pharmacology Direction of School of Health Sciences at The University of Georgia; Tbilisi, Georgia; Scientific Researcher of Yerevan State Medical University After Mk. Heratsi, Yerevan, Republic of Armenia; Former Clinical Pharmacologist of London Lewisham University Hospital, London, England, United Kingdom of Great Britain and Northern Ireland; <https://orcid.org/0000-0002-9005-8577>

## **Margarita Beglaryan**

MD, PhD, Doctor of Pharmaceutical Sciences, Academician, Professor of Yerevan State Medical University After Mkhitar Heratsi, Head of the Department of Pharmaceutical Management of Yerevan State Medical University After Mkhitar Heratsi; Yerevan, Republic of Armenia; <https://orcid.org/0000-0003-3697-6390>

**Maka Buleishvili**

MD, PhD, Doctor of Medical Sciences, Professor of Faculty of Medicine at Georgian International University GIU, Dean of Faculty of Medicine at Georgian International University GIU, Professor of Faculty of Medicine at Georgian National University SEU, Professor of Faculty of Medicine at European University, Professor of Faculty of Medicine at Caucasus International University, Professor of Faculty of Medicine at Georgian-American University, Invited Lecturer of Tbilisi State Medical University, Tbilisi, Georgia; Professor of Faculty of Medicine at BAU International University Batumi, <https://orcid.org/0009-0004-2657-8473>

**Mariam Darbaidze**

MD, PhD, Doctor of Biological Sciences, Professor of Georgian International University GIU, Vice Rector of Georgian International University GIU; Professor of Georgian National University SEU; Tbilisi, Georgia; <https://orcid.org/0009-0005-0275-4222>

**Nana Gorgaslidze**

MD, PhD, Doctor of Pharmaceutical Sciences, Academician, Professor of Tbilisi State Medical University, Head of The Department of Social and Clinical Pharmacy, Tbilisi, Georgia. <https://orcid.org/0000-0002-4563-5224>

**Nato Alavidze**

MD, PhD, Doctor of Pharmaceutical Sciences, Professor of Akaki Tsereteli State University, Faculty of Medicine, Department of Pharmacy, Kutaisi, Georgia; Professor, Head of The Medical Doctor Degree Program of Faculty of Healthcare Sciences at East European University, Tbilisi, Georgia. <https://orcid.org/0000-0001-6695-5924>

**Irina Imerlishvili**

PhD, Doctor of Law, Professor, Rector of BAU International University Batumi; Professor of BAU International University Batumi; Professor at the International Black Sea University, Batumi-Tbilisi, Georgia; <https://orcid.org/0009-0008-6862-7025>

**Naira Chichoyan**

MD, PhD, Doctor of Pharmaceutical Sciences, Professor of Yerevan State Medical University after Mk. Heratsi; Head of the Department of Pharmacognosy at Yerevan State Medical University after Mk. Heratsi; Yerevan, Republic of Armenia. <https://orcid.org/0000-0003-3905-3372>

**Marika Sulashvili**

MD, Doctor of Family Medicine, Invited Lecturer of Tbilisi State Medical University, Lecturer of Department of Molecular and Medical Genetics, Invited Professor of Biochemistry and Molecular and Medical Genetics at The University of Georgia. Tbilisi, Georgia. <https://orcid.org/0000-0002-6338-4262>

**Lasha Tchelidze**

MD, PhD Candidate, Tbilisi State Medical University, Director of the Georgian Association of Allergology and Clinical Immunology, Tbilisi, Georgia.

**Marina Giorgobiani**

MD, PhD, Doctor of Medical Sciences, Academician, Professor of Tbilisi State Medical University, Faculty of Public Health; Department of Hygiene and Medical Ecology, Tbilisi, Georgia. <https://orcid.org/0000-0003-0686-5227>

**Ada (Adel) Tadevosyan**

MD, PhD, Doctor of Medical Sciences, Academician, Professor of Yerevan State Medical University, Academician and Full Member of the International Academy of Sciences of Ecology and Life Safety (MANEB), Academician of the Republic Armenia Law Academy, Member of the Association of Psychiatrists of Armenia, World Association of Psychiatrists, International Association for Traumatic Stress, World Association for Biological Psychiatry, International Association "Stress and Behavior", Licensed Psychiatrist, Psychotherapist, Public Health Organizer; Tbilisi-Georgia, Yerevan-Armenia, Los Angeles-USA;

**Igor Seniuk**

PhD, Doctor of Pharmaceutical Sciences, Dean of faculty of Pharmacy at National University of Pharmacy of Ukraine, Associate Professor of Biological Chemistry Department at National University of Pharmacy, Kharkiv, Ukraine. <https://orcid.org/0000-0003-3819-7333>

**David Aphkhazava**

PhD, Doctor of Biological Sciences, Professor of Biochemistry at The University of Georgia, Tbilisi, Georgia. Orcid: <https://orcid.org/0000-0001-6216-6477>

**Vira Kravchenko**

MD, PhD, Doctor of Biological Sciences, Academician, Professor, Head of The Biological Chemistry Department at National University of Pharmacy of Ukraine, Kharkiv, Ukraine. <https://orcid.org/0000-0001-6335-2490>

**Magda Davitashvili**

PhD, Doctor of Biological Sciences, Professor, Academician, Georgian Academy of Ecological Sciences, Program Coordinator of Quality Assurance Office at Iakob Gogebashvili Telavi State University (TeSaU), Telavi, Georgia. <https://orcid.org/0009-0005-4213-6533>

**Olga Shapoval**

MD, PhD, Doctor of Pharmaceutical Sciences, Associate Professor of Department of Pharmacology and Medical Prescription at Kharkiv State Medical University, Kharkiv, Ukraine; <https://orcid.org/0000-0002-1971-2863>

**Natia Kvizhinadze**

MD, PhD, Doctor of Pharmaceutical Sciences, Professor of Tbilisi State Medical University, Department of Social and Clinical Pharmacy; Tbilisi, Georgia.

**Nino Abuladze**

MD, PhD, Doctor of Pharmaceutical Sciences, Academician, Professor of Akaki Tsereteli State University, Faculty of Medicine, Department of Pharmacy, Kutaisi, Georgia. <https://orcid.org/0000-0003-2189-7470>

**Rajkaran Singh**

Faculty of Medicine, Georgian National University SEU; Tbilisi, Georgia; <https://orcid.org/0009-0000-4903-0145>

**Corresponding Author: Dr. Professor Nodar Sulashvili**

**ABSTRACT**

Cancer pharmacotherapy represents one of the most rapidly evolving domains of contemporary clinical medicine, reflecting the progressive transition from broadly cytotoxic treatment strategies

toward molecularly targeted, immunologically mediated, hormonally directed, cellular, and increasingly biomarker-guided therapeutic interventions. This transformation has expanded the therapeutic potential of oncology while simultaneously generating substantial pharmacological complexity concerning drug selection, mechanism-based treatment, dose optimization, treatment sequencing, drug–drug interactions, adverse drug reactions, cumulative toxicity, and individualized risk–benefit assessment. The present scientific discourse provides a comprehensive pharmacological examination of anticancer medications, integrating their classification, pharmacological properties, molecular and cellular mechanisms of action, pharmacokinetic and pharmacodynamic determinants, therapeutic efficacy, safety profiles, adverse effects, and clinically significant toxicities within the framework of modern oncology. Conventional cytotoxic agents, endocrine therapies, molecularly targeted small molecules, monoclonal antibodies, antibody–drug conjugates, immune checkpoint inhibitors, and other advanced systemic treatment modalities are considered as components of an increasingly heterogeneous pharmacotherapeutic landscape. Particular emphasis is placed on the mechanistic relationship between drug exposure, molecular targets, intracellular signaling pathways, cellular proliferation, apoptosis, DNA damage, angiogenesis, immune regulation, tumor microenvironment, therapeutic resistance, and clinical outcomes. The pharmacological safety of anticancer medications is examined as a multidimensional construct encompassing predictable dose-dependent toxicities, idiosyncratic adverse reactions, cumulative organ injury, delayed complications, immune-mediated toxicity, and clinically relevant interactions with concomitant therapies. Major toxicological manifestations, including hematological, gastrointestinal, hepatic, renal, cardiovascular, neurological, pulmonary, dermatological, endocrine, reproductive, and metabolic adverse effects, are considered in relation to their pathophysiological mechanisms, clinical severity, reversibility, and implications for continuation, modification, or discontinuation of treatment. Particular attention is directed toward the emerging spectrum of immune-related adverse events associated with modern immuno-oncology and toward the necessity of early recognition, systematic monitoring, multidisciplinary management, and appropriate pharmacotherapeutic intervention. Pharmacovigilance constitutes a central component of this integrated framework because the safety profile of anticancer medicines continues to evolve throughout clinical development, regulatory evaluation, routine clinical use, and post-marketing surveillance. Contemporary pharmacovigilance incorporates spontaneous adverse-event reporting, active surveillance, signal detection, disproportionality analysis, causality assessment, risk characterization, medication-error identification, real-world evidence, and continuous benefit–risk evaluation. These approaches facilitate the identification of uncommon, delayed, population-specific, or previously unrecognized safety signals and contribute to evidence-based risk minimization. The integration of pharmacovigilance with clinical pharmacology is therefore essential for transforming individual adverse-event observations into clinically actionable knowledge and for strengthening medication safety throughout the cancer treatment continuum. Pharmacogenomics and precision medicine further provide important scientific foundations for understanding interindividual variability in drug disposition, pharmacodynamic response, therapeutic efficacy, and susceptibility to toxicity. Genetic variation in drug-metabolizing enzymes, transporters, receptors, immune pathways, DNA-repair mechanisms, and other pharmacological determinants may substantially influence exposure and treatment outcomes for selected anticancer agents. Accordingly, incorporation of validated pharmacogenomic biomarkers, tumor molecular profiling, genomic alterations, patient-specific characteristics, comorbidities, organ function, concomitant medications, and previous treatment history can support more rational therapeutic selection and individualized risk stratification. Precision oncology consequently extends beyond tumor classification alone by incorporating both tumor-specific molecular determinants and host-specific pharmacological characteristics into therapeutic decision-making.

Therapeutic drug monitoring represents an additional clinical pharmacology strategy for selected anticancer medicines in which measurable systemic exposure is associated with therapeutic response, toxicity, or clinically meaningful pharmacokinetic variability. Integration of drug-concentration measurements with pharmacokinetic and pharmacodynamic modeling may facilitate individualized dose adjustment, particularly in patients with altered organ function, significant drug interactions, unusual pharmacokinetic profiles, or a narrow therapeutic window. Although therapeutic drug monitoring is not universally applicable to all anticancer agents, its selective implementation may strengthen exposure-guided pharmacotherapy and complement conventional clinical and laboratory monitoring. The overarching objective of this integrated approach is to establish a coherent evidence-based framework connecting pharmacological classification, molecular mechanisms, pharmacokinetics, pharmacodynamics, pharmacogenomics, therapeutic drug monitoring, pharmacovigilance, precision medicine, and clinical decision-making. Such integration may improve the identification of optimal therapeutic regimens, reduce preventable medication-related harm, preserve treatment intensity when clinically appropriate, enhance adherence and quality of life, and facilitate earlier recognition and management of toxicity. Ultimately, contemporary anticancer pharmacotherapy should be understood as a dynamic, individualized, and continuously monitored process in which therapeutic efficacy cannot be separated from pharmacological safety. The systematic integration of mechanistic pharmacology with real-world safety surveillance, molecular diagnostics, pharmacogenomic evidence, exposure assessment, and multidisciplinary clinical judgment provides a scientifically rigorous foundation for optimizing the benefit–risk balance of anticancer medications and advancing evidence-based precision oncology.

**Keywords:** Anticancer medications; Pharmacovigilance; Pharmacogenomics; Personalized medicine; Therapeutic drug monitoring.

## INTRODUCTION

Cancer pharmacotherapy has undergone a profound transformation from predominantly cytotoxic treatment paradigms toward increasingly molecularly defined, mechanism-directed, immune-mediated, targeted, and individualized therapeutic strategies. This evolution has substantially expanded the pharmacological armamentarium available for malignant disease while simultaneously increasing the complexity of medication selection, therapeutic optimization, adverse-event prevention, and longitudinal safety surveillance. The present scientific discourse provides an integrated examination of anticancer medications from the perspectives of pharmacological classification, molecular and cellular mechanisms of action, pharmacokinetics, pharmacodynamics, therapeutic efficacy, pharmacological safety, adverse drug reactions, and treatment-related toxicity. Conventional cytotoxic agents, endocrine therapies, targeted small molecules, monoclonal antibodies, antibody–drug conjugates, immune checkpoint inhibitors, cellular and other advanced therapeutic modalities are considered within a contemporary framework of translational and clinical oncology. Particular emphasis is placed on the relationship between molecular targets, intracellular signaling networks, tumor biology, drug exposure, therapeutic response, resistance mechanisms, and host determinants of toxicity. The analysis further addresses the clinical significance of myelosuppression, gastrointestinal toxicity, hepatotoxicity, nephrotoxicity, cardiotoxicity, neurotoxicity, pulmonary injury, dermatological reactions, endocrine immune-related adverse events, reproductive toxicity, and other organ-specific complications that may limit treatment intensity and quality of life. Pharmacovigilance is presented as a continuous, evidence-generating discipline integrating spontaneous reporting, active surveillance, signal detection, causality assessment, risk characterization, real-world evidence, and post-marketing safety evaluation. In parallel, pharmacogenomics and precision medicine are examined as major determinants of interindividual variability in pharmacokinetics,

pharmacodynamics, therapeutic response, and susceptibility to adverse drug reactions. The incorporation of pharmacogenomic biomarkers, molecular tumor profiling, clinical characteristics, comorbidities, concomitant medications, and patient-specific risk factors may facilitate more rational treatment selection and individualized risk–benefit assessment. Therapeutic drug monitoring is discussed as an additional pharmacological strategy for selected anticancer agents in which exposure–response and exposure–toxicity relationships can support dose optimization and therapeutic precision. An evidence-based pharmacotherapy framework is therefore proposed in which clinical pharmacology, oncology, pharmacovigilance, pharmacogenomics, therapeutic drug monitoring, molecular diagnostics, and multidisciplinary decision-making are integrated throughout the treatment continuum. Such an approach may improve medication safety, minimize preventable toxicity, preserve therapeutic intensity, enhance adherence and patient-centered outcomes, and strengthen the translational connection between pharmacological knowledge and precision oncology. Ultimately, the rational use of anticancer medications requires continuous reassessment of efficacy, safety, exposure, molecular context, and patient-specific determinants, establishing pharmacotherapy as a dynamic and increasingly individualized component of modern cancer care.

Cancer remains a complex and heterogeneous group of diseases characterized by the progressive accumulation of genetic, epigenetic, metabolic, and microenvironmental alterations that disrupt normal mechanisms governing cellular proliferation, differentiation, survival, and tissue homeostasis. The biological heterogeneity of malignant disease has profound implications for pharmacotherapy because tumors arising in different organs, and even tumors within the same anatomical site, may demonstrate substantially different molecular architectures, growth kinetics, receptor expression patterns, immune landscapes, metabolic dependencies, and susceptibility to pharmacological intervention. Consequently, modern oncology has progressively moved beyond the concept of cancer treatment as a uniform application of cytotoxic chemotherapy toward a multidimensional therapeutic paradigm incorporating molecularly targeted medicines, endocrine agents, immunotherapies, antibody-based therapeutics, antibody–drug conjugates, cellular therapies, and other advanced treatment modalities. This transition has created unprecedented opportunities to improve survival and disease control while simultaneously increasing the pharmacological complexity of therapeutic decision-making.

Anticancer pharmacotherapy occupies a distinctive position within clinical pharmacology because the therapeutic objective is frequently associated with a narrow and clinically consequential balance between antineoplastic efficacy and host toxicity. Unlike many conventional pharmacological interventions in which restoration of physiological function is the principal objective, anticancer medicines are often designed to inhibit, damage, or eliminate rapidly proliferating or molecularly vulnerable malignant cells while attempting to preserve normal tissues. This therapeutic challenge is particularly evident with conventional cytotoxic agents, whose mechanisms frequently involve interference with DNA synthesis, DNA replication, mitosis, nucleotide metabolism, or cellular division. Because many normal tissues also contain proliferating cellular populations, pharmacological selectivity may be incomplete, producing adverse effects such as myelosuppression, mucosal injury, gastrointestinal disturbances, alopecia, infertility, and other dose-limiting toxicities. The therapeutic index of an anticancer medicine therefore depends not only on intrinsic molecular potency but also on tumor biology, exposure, host susceptibility, treatment schedule, cumulative dose, organ function, and the capacity to detect and manage toxicity promptly.

The classification of anticancer medications has consequently become increasingly complex. Traditional pharmacological classification includes alkylating agents, platinum compounds, antimetabolites, antitumor antibiotics, topoisomerase inhibitors, microtubule-directed agents, and other cytotoxic medicines. These categories remain fundamental to oncology pharmacology

because they describe characteristic molecular targets and biochemical mechanisms underlying tumor-cell injury. However, contemporary classification increasingly incorporates endocrine therapies, kinase inhibitors, monoclonal antibodies, proteasome inhibitors, angiogenesis-directed agents, epigenetic modulators, apoptosis-related therapies, immune checkpoint inhibitors, antibody–drug conjugates, and other mechanism-specific interventions. Such classification is not merely taxonomic; it provides a conceptual framework for predicting pharmacological behavior, therapeutic indications, resistance mechanisms, clinically relevant interactions, and characteristic toxicity profiles. The increasing number of therapeutic classes also necessitates greater specialization in clinical pharmacology and multidisciplinary oncology practice.

The molecular mechanisms underlying anticancer pharmacotherapy are central to understanding both therapeutic benefit and treatment-related harm. Cancer cells frequently acquire alterations affecting signaling pathways responsible for proliferation, survival, apoptosis, DNA repair, angiogenesis, invasion, metastasis, and immune evasion. Pharmacological intervention may therefore occur at multiple biological levels. Cytotoxic medicines may produce direct DNA damage or inhibit essential biosynthetic and mitotic processes; endocrine agents may deprive hormone-dependent tumors of proliferative signaling; kinase inhibitors may suppress oncogenic signaling cascades; monoclonal antibodies may block receptor activation or recruit immune-mediated cytotoxicity; and immune checkpoint inhibitors may restore antitumor T-cell activity by disrupting inhibitory pathways involved in immune tolerance. These mechanistic distinctions are clinically important because the biological target often determines not only the likelihood of therapeutic response but also the spectrum and temporal pattern of adverse reactions.

The development of targeted therapy has further transformed the pharmacological concept of selectivity. Molecularly targeted medicines are frequently designed to recognize altered proteins, receptors, enzymes, fusion products, signaling pathways, or other vulnerabilities that contribute to malignant phenotypes. Nevertheless, molecular selectivity does not necessarily imply complete clinical selectivity. Many pharmacological targets are expressed in normal tissues or participate in physiological signaling pathways, and inhibition of these targets may produce predictable on-target toxicities. In addition, off-target interactions, metabolites, immune-mediated mechanisms, mitochondrial dysfunction, vascular effects, and pharmacokinetic accumulation may contribute to adverse events. The modern pharmacologist must therefore interpret drug action across multiple biological scales, from receptor and enzyme interactions through intracellular signaling networks to systemic clinical outcomes.

Immuno-oncology has introduced another major dimension to anticancer pharmacology. Immune checkpoint inhibitors targeting pathways such as programmed cell death protein 1, programmed death-ligand 1, and cytotoxic T-lymphocyte-associated antigen 4 have demonstrated substantial clinical efficacy across multiple malignancies. Their therapeutic mechanism differs fundamentally from conventional cytotoxicity because the pharmacological intervention modifies host immune regulation rather than directly targeting tumor-cell replication alone. This distinction produces a characteristic spectrum of immune-related adverse events involving the skin, gastrointestinal tract, liver, endocrine organs, lungs, kidneys, nervous system, cardiovascular system, and other tissues. These toxicities may occur during treatment or after exposure and can occasionally become severe or life-threatening. Their management therefore requires recognition of mechanism, temporal pattern, severity, differential diagnosis, and appropriate pharmacological intervention. The emergence of immune-related toxicity illustrates why contemporary oncology requires integration of pharmacology, immunology, pathology, laboratory medicine, and clinical monitoring.

Pharmacokinetics and pharmacodynamics provide essential foundations for rational anticancer drug use. Pharmacokinetic processes involving absorption, distribution, metabolism, and elimination determine systemic and tissue exposure, whereas pharmacodynamic mechanisms

describe the relationship between drug concentration and biological or clinical effect. In oncology, these relationships can be particularly complex because disease progression, cachexia, hypoalbuminemia, organ dysfunction, inflammation, altered body composition, concomitant medications, and previous therapies may substantially modify drug disposition. Hepatic and renal impairment may alter clearance, while changes in protein binding, gastrointestinal function, or transporter activity may influence exposure. Furthermore, enzyme induction or inhibition can produce clinically important drug–drug interactions, particularly in patients receiving multiple supportive and anticancer medicines. Understanding these determinants is fundamental to dose selection and modification.

The pharmacodynamic response to an anticancer medicine is similarly influenced by both tumor-specific and host-specific factors. Target expression, receptor activation, downstream signaling, genomic alterations, DNA-repair capacity, apoptotic competence, tumor-cell heterogeneity, and the tumor microenvironment can determine sensitivity or resistance. Pharmacological exposure may therefore be identical among patients while producing markedly different therapeutic outcomes. Conversely, comparable clinical responses may occur at different systemic exposures. This variability emphasizes that dose selection based exclusively on conventional body-surface-area calculations or fixed dosing paradigms may not always achieve optimal individualized exposure. Modern oncology increasingly incorporates clinical, molecular, pharmacokinetic, and pharmacodynamic information to refine therapeutic decisions.

Therapeutic resistance remains one of the principal limitations of successful anticancer pharmacotherapy. Resistance may be intrinsic, occurring before treatment, or acquired after an initially favorable response. Mechanisms include secondary target mutations, gene amplification, activation of alternative signaling pathways, altered drug transport, enhanced drug metabolism, increased DNA repair, evasion of apoptosis, epithelial–mesenchymal transition, clonal selection, and modifications of the tumor microenvironment. Immune escape represents an additional mechanism of resistance to immunotherapy. These processes demonstrate that cancer pharmacotherapy is dynamic rather than static: the biological target and therapeutic vulnerability of a tumor may change during disease evolution. Consequently, pharmacological treatment increasingly requires serial assessment of disease biology, treatment response, and emerging resistance mechanisms.

Pharmacological safety is equally important because anticancer medicines are among the therapeutic agents associated with substantial risks of serious adverse drug reactions. Toxicity may be acute or delayed, reversible or irreversible, dose-dependent or idiosyncratic, organ-specific or multisystemic. Hematological toxicity can manifest as neutropenia, anemia, thrombocytopenia, and febrile neutropenia, potentially resulting in treatment interruption, infection, hospitalization, or mortality. Gastrointestinal toxicity may include nausea, vomiting, diarrhea, mucositis, constipation, and intestinal complications. Hepatotoxicity and nephrotoxicity may compromise the ability to continue treatment, whereas cardiotoxicity can produce arrhythmias, ischemia, hypertension, cardiomyopathy, or heart failure. Neurotoxicity may impair sensory, motor, or autonomic function, while pulmonary toxicity may range from mild inflammatory changes to severe pneumonitis. Recognition of these patterns is essential for individualized risk assessment and treatment modification.

The clinical significance of toxicity extends beyond immediate physiological harm. Persistent adverse effects may impair functional status, nutritional status, psychological well-being, treatment adherence, and quality of life. Severe toxicity may necessitate dose reduction or discontinuation and can compromise the intensity of potentially effective therapy. Conversely, excessive fear of toxicity may result in unnecessary undertreatment. Optimal oncology pharmacotherapy therefore requires a structured benefit–risk assessment that considers disease severity, treatment intent, expected therapeutic benefit, alternative options, baseline patient

vulnerability, toxicity probability, and the availability of effective supportive care. The objective is not simply to minimize adverse events at any cost, but to optimize the net clinical benefit of treatment while avoiding preventable or disproportionate harm.

Drug–drug interactions represent another major pharmacological concern in oncology. Patients with cancer commonly receive combinations of anticancer medicines, analgesics, antiemetics, antimicrobials, corticosteroids, anticoagulants, cardiovascular medicines, antiepileptic agents, nutritional products, and other supportive therapies. Interactions may occur through cytochrome P450 enzymes, uridine diphosphate-glucuronosyltransferases, membrane transporters, renal elimination pathways, protein binding, gastrointestinal absorption, or pharmacodynamic mechanisms. The consequences may include reduced anticancer exposure and therapeutic failure or increased exposure and toxicity. Polypharmacy, organ dysfunction, and changing treatment regimens further increase this risk. Medication reconciliation and systematic interaction assessment are therefore integral components of evidence-based cancer pharmacotherapy.

Pharmacovigilance provides the broader scientific infrastructure through which medication-related risks can be identified, characterized, evaluated, and managed throughout the life cycle of an anticancer medicine. Clinical trials provide essential evidence regarding efficacy and common adverse events, but their controlled populations, sample sizes, eligibility criteria, follow-up periods, and treatment conditions may limit detection of rare, delayed, or population-specific adverse reactions. Post-marketing pharmacovigilance consequently becomes indispensable. Spontaneous reporting systems, active surveillance programs, electronic health records, registries, observational studies, real-world data, disproportionality analyses, and other pharmacovigilance methods can contribute to the detection of safety signals that emerge only after broad clinical exposure. Signal detection must subsequently be followed by clinical assessment, epidemiological evaluation, causality consideration, and appropriate risk-minimization strategies.

In oncology, pharmacovigilance is particularly important because therapeutic regimens are often complex and adverse events may have multiple possible causes. Disease progression, infection, comorbidities, radiation therapy, surgery, concomitant medications, and previous anticancer treatment can mimic or contribute to suspected drug-related events. Accurate causality assessment therefore requires careful clinical reasoning and consideration of temporal relationships, alternative explanations, dechallenge and rechallenge information where ethically appropriate, biological plausibility, and known pharmacological characteristics. Standardized terminology and severity grading further facilitate communication between clinicians, researchers, regulatory authorities, and pharmacovigilance systems. The integration of clinical pharmacology with pharmacovigilance strengthens the capacity to translate safety observations into actionable evidence.

Pharmacogenomics provides an additional dimension for improving the safety and effectiveness of anticancer treatment. Genetic variability can influence drug metabolism, transport, receptor activity, DNA repair, immune responses, and susceptibility to specific adverse reactions. Certain pharmacogenomic markers have demonstrated clinically meaningful associations with treatment toxicity or efficacy, supporting genotype-informed treatment selection or dose modification in appropriate contexts. However, implementation requires rigorous evidence, analytical validity, clinical validity, clinical utility, and consideration of population diversity. Pharmacogenomics should therefore complement rather than replace comprehensive clinical assessment. Its greatest potential lies in integrating inherited genetic information with tumor genomics, pharmacokinetic characteristics, organ function, concomitant medication exposure, and patient preferences.

Personalized medicine and precision oncology extend this principle by recognizing that effective cancer treatment must account for biological heterogeneity at both tumor and patient levels. Molecular profiling may identify actionable genomic alterations, predictive biomarkers, receptor

expression patterns, or immune characteristics that guide treatment selection. At the same time, host factors such as age, organ function, comorbidities, performance status, previous therapy, pharmacogenomic characteristics, and concomitant medications influence the feasibility and safety of treatment. Precision pharmacotherapy therefore represents an integrative rather than exclusively genomic discipline. It requires continuous interpretation of biological, pharmacological, clinical, and patient-centered information throughout treatment.

Therapeutic drug monitoring may provide additional value when a clinically meaningful relationship exists between systemic exposure and therapeutic response or toxicity. Although routine concentration monitoring is not appropriate for every anticancer medicine, selected agents exhibit substantial pharmacokinetic variability or exposure–response relationships that may support individualized dosing. Measurement of drug concentrations, combined with population pharmacokinetic models, Bayesian forecasting, pharmacodynamic biomarkers, and clinical observations, can potentially identify patients whose exposure is inadequate or excessive. This approach is particularly relevant when standard dosing fails to account adequately for variability arising from organ dysfunction, interacting medicines, body composition, or individual metabolic capacity. Therapeutic drug monitoring thus represents an important bridge between quantitative pharmacology and personalized treatment.

Evidence-based pharmacotherapy provides the methodological foundation for integrating these diverse forms of information. Evidence from randomized controlled trials remains central to evaluating efficacy and comparative treatment effects, while observational research, pharmacovigilance databases, registries, pharmacokinetic studies, pharmacogenomic investigations, and real-world evidence provide complementary information regarding safety, effectiveness, treatment patterns, and patient heterogeneity. The interpretation of evidence must consider study design, internal and external validity, statistical uncertainty, clinically meaningful endpoints, applicability to individual patients, and potential biases. In rapidly evolving oncology, evidence synthesis must also accommodate the continuous emergence of new molecular targets, biomarkers, therapeutic combinations, and safety information.

The contemporary oncology pharmacist, clinical pharmacologist, oncologist, and multidisciplinary healthcare team therefore operate within an increasingly interconnected pharmacological environment. Safe and effective anticancer treatment requires systematic medication review, individualized dose selection, monitoring of laboratory and clinical parameters, recognition of adverse reactions, management of drug interactions, assessment of treatment adherence, patient education, and continuous reassessment of therapeutic goals. Pharmacological expertise is particularly important when multiple treatment modalities are combined or when treatment transitions occur across inpatient, outpatient, and survivorship settings. Communication among oncology, pharmacy, nursing, laboratory, pathology, genetics, and other professional disciplines can reduce medication-related risk and facilitate coordinated care.

The integration of pharmacology, pharmacovigilance, pharmacogenomics, precision medicine, and therapeutic drug monitoring is therefore not simply an expansion of existing oncology practice but a conceptual evolution toward individualized, continuously monitored pharmacotherapy. Such integration recognizes that the clinical effect of an anticancer medicine emerges from an interaction between the drug, tumor, host, exposure, treatment context, and evolving disease biology. A scientifically rigorous framework must consequently evaluate efficacy and safety simultaneously rather than treating them as independent domains. Mechanism-based understanding can guide drug selection; pharmacokinetic and pharmacodynamic analysis can optimize exposure; pharmacogenomics can identify relevant inherited determinants; tumor profiling can identify actionable molecular vulnerabilities; pharmacovigilance can detect emerging risks; and therapeutic drug monitoring can refine dosing when clinically justified.

The present scientific discourse aims to provide an integrated and pharmacologically grounded analysis of anticancer medications in modern oncology, with particular attention to their classification, molecular mechanisms, pharmacological properties, safety profiles, adverse effects, and toxicity. It further examines the complementary roles of pharmacovigilance, evidence-based pharmacotherapy, pharmacogenomics, personalized medicine, and therapeutic drug monitoring in optimizing the benefit–risk balance of anticancer treatment. By connecting molecular pharmacology with clinical safety science and individualized therapeutic decision-making, this framework seeks to support a more rational, evidence-informed, patient-centered, and precision-oriented approach to cancer pharmacotherapy. The ultimate objective is to strengthen the translation of pharmacological knowledge into clinically meaningful outcomes while minimizing preventable toxicity, improving therapeutic precision, and supporting the sustainable development of safer and more effective oncology practice.

## BACKGROUND

Cancer represents one of the most complex and heterogeneous groups of human diseases and remains a major global cause of morbidity, premature mortality, disability, and healthcare utilization. The biological complexity of malignant disease derives from the interaction of genetic, epigenetic, metabolic, immunological, microenvironmental, and systemic determinants that collectively influence tumor initiation, progression, invasion, metastatic dissemination, therapeutic responsiveness, and resistance. Unlike many conventional pharmacotherapeutic conditions in which a relatively stable pathological target can be identified and modulated, cancer is characterized by dynamic biological evolution and substantial interpatient and intratumoral heterogeneity. Consequently, contemporary oncology has progressively moved from predominantly histopathological and organ-based treatment paradigms toward molecularly informed, mechanism-oriented, biomarker-guided, and increasingly individualized pharmacotherapy. Within this transformation, anticancer medications constitute a highly diverse pharmacological domain encompassing classical cytotoxic agents, endocrine therapies, molecularly targeted drugs, monoclonal antibodies, antibody–drug conjugates, immune checkpoint inhibitors, cellular and gene-based therapeutics, epigenetic modulators, angiogenesis inhibitors, signal-transduction inhibitors, radiopharmaceuticals, and numerous emerging therapeutic platforms. The pharmacological diversity of these agents is accompanied by substantial differences in mechanisms of action, pharmacokinetic behavior, pharmacodynamic relationships, therapeutic indices, drug–drug interactions, toxicity profiles, mechanisms of resistance, and requirements for patient monitoring.

The historical development of cancer pharmacotherapy was initially dominated by nonspecific cytotoxic strategies designed to exploit differences in proliferation, DNA synthesis, DNA integrity, mitotic activity, or cellular susceptibility between malignant and normal tissues. Alkylating agents, platinum compounds, antimetabolites, antitumor antibiotics, topoisomerase inhibitors, microtubule-directed agents, and other cytotoxic medications remain important components of contemporary oncology, particularly in combination regimens. Their therapeutic effects generally arise through interference with essential cellular processes, resulting in DNA damage, replication stress, mitotic catastrophe, apoptosis, senescence, or other forms of cancer-cell death. Nevertheless, the fundamental limitation of many classical cytotoxic agents is their incomplete selectivity for malignant cells. Normal tissues characterized by rapid cellular turnover, including bone marrow, gastrointestinal epithelium, hair follicles, and reproductive tissues, may consequently be exposed to clinically significant injury. This pharmacological principle explains many of the characteristic adverse effects associated with conventional chemotherapy, including myelosuppression, mucositis, and nausea and vomiting, alopecia, infertility, and susceptibility to infection. Furthermore, cumulative or dose-dependent toxicities involving the heart, kidneys, liver,

lungs, peripheral nervous system, and other organs may constrain treatment intensity and influence long-term survivorship.

The development of molecular oncology substantially altered the conceptual framework of anticancer pharmacotherapy. Increasing understanding of oncogenic signaling networks demonstrated that malignant transformation and tumor maintenance can be driven by specific molecular abnormalities, including activating mutations, gene amplifications, chromosomal rearrangements, abnormal receptor signaling, dysregulated transcriptional programs, altered DNA-repair mechanisms, and aberrant immune-evasion pathways. These discoveries established the rationale for therapeutic intervention at defined molecular targets. Accordingly, targeted therapies were developed to inhibit receptor tyrosine kinases, intracellular kinases, hormone receptors, DNA-repair pathways, proteasomal function, epigenetic regulators, angiogenic signaling, cell-cycle checkpoints, apoptotic pathways, and other molecular processes essential to tumor survival. Targeted treatment can provide substantial therapeutic benefit when the relevant molecular alteration is present and pharmacologically actionable. However, molecular specificity does not necessarily equate to complete clinical selectivity. Target molecules may participate in physiological signaling pathways in normal tissues, while compensatory signaling, pathway redundancy, clonal evolution, and secondary molecular alterations can produce acquired resistance. Thus, the pharmacological assessment of targeted therapies must incorporate both target-mediated efficacy and target-related toxicity.

Immuno-oncology has introduced another major transformation by shifting therapeutic attention from direct tumor-cell destruction toward modulation of the host immune system. Immune checkpoint inhibitors targeting programmed cell death protein 1, programmed death ligand 1, cytotoxic T-lymphocyte-associated antigen 4, and other immunoregulatory pathways can restore or enhance antitumor immune activity in selected malignancies. The resulting therapeutic paradigm differs fundamentally from classical chemotherapy because treatment efficacy may depend on complex interactions between tumor antigenicity, immune-cell composition, tumor microenvironment, host genetics, prior treatment, microbiological factors, and immune-regulatory networks. At the same time, immune activation can produce distinctive toxicities known as immune-related adverse events, which may affect virtually any organ system. Dermatological, gastrointestinal, hepatic, pulmonary, endocrine, renal, neurological, cardiovascular, rheumatological, and other immune-mediated toxicities have become central considerations in contemporary pharmacovigilance. Their clinical recognition may be complicated by delayed onset, atypical presentation, multisystem involvement, and differentiation from infection, tumor progression, or toxicity caused by concomitant therapies.

The expansion of anticancer pharmacotherapy has therefore generated a critical requirement for systematic characterization of medication safety throughout the entire therapeutic lifecycle. Pharmacological safety cannot be conceptualized exclusively as the absence of adverse effects. Rather, it encompasses the identification, characterization, prediction, prevention, monitoring, management, and mitigation of risks associated with medicinal products under real-world conditions. In oncology, this challenge is particularly significant because many anticancer agents possess narrow therapeutic windows, substantial interindividual pharmacokinetic variability, complex dose–exposure relationships, and potentially severe or irreversible toxicities. Moreover, cancer patients frequently receive polypharmacy involving analgesics, antiemetics, antimicrobials, anticoagulants, corticosteroids, nutritional supplements, supportive-care agents, and medications for chronic comorbidities. Such therapeutic complexity increases the probability of pharmacokinetic and pharmacodynamic drug interactions and complicates attribution of adverse events to individual agents.

The pharmacological characterization of anticancer medications therefore requires an integrated understanding of pharmacodynamics and pharmacokinetics. Pharmacodynamics describes the

relationship between drug exposure and biological response, including target engagement, pathway modulation, tumor-cell inhibition, immune activation, and toxicity. Pharmacokinetics encompasses absorption, distribution, metabolism, and elimination and determines the temporal profile of systemic drug concentrations and tissue exposure. In oncology, pharmacokinetic behavior may be substantially altered by hepatic or renal dysfunction, hypoalbuminemia, changes in body composition, inflammation, malnutrition, gastrointestinal impairment, fluid shifts, organ metastases, and concomitant medications. The clinical consequences of these variables are particularly important for medications whose efficacy or toxicity is strongly exposure dependent. Consequently, individualized dose selection increasingly requires consideration of patient-specific physiological and molecular characteristics rather than reliance exclusively on standardized dosing schedules.

A central component of modern anticancer pharmacology is the classification of medications according to their molecular targets, mechanisms of action, therapeutic indications, structural characteristics, pharmacokinetic properties, and toxicity profiles. Conventional classifications based solely on chemical structure or anatomical indication are insufficient to describe the complexity of contemporary cancer therapeutics. Mechanism-based classification permits differentiation among DNA-damaging agents, antimetabolites, mitotic inhibitors, endocrine therapies, targeted signal-transduction inhibitors, angiogenesis inhibitors, apoptosis modulators, epigenetic therapies, DNA-repair inhibitors, immune checkpoint inhibitors, and cellular or gene-based interventions. Such classification has practical implications for rational combination therapy because medications acting through complementary biological mechanisms may produce additive or synergistic antitumor effects, whereas combinations targeting overlapping physiological pathways may amplify toxicity. Mechanism-based classification also facilitates pharmacovigilance by identifying predictable class-specific adverse-event patterns.

The pharmacological mechanisms underlying anticancer drug action are highly heterogeneous. Cytotoxic chemotherapy may induce DNA strand breaks, DNA crosslinking, abnormal nucleotide incorporation, inhibition of nucleotide biosynthesis, suppression of topoisomerase activity, or disruption of microtubule dynamics. Endocrine therapies inhibit hormone synthesis or antagonize hormone receptors, thereby depriving hormone-dependent malignant cells of proliferative signaling. Molecularly targeted agents can inhibit aberrant kinases, intracellular signaling proteins, mutant oncoproteins, DNA-repair enzymes, or other molecular dependencies. Monoclonal antibodies may block receptor activation, neutralize growth factors, recruit immune effector mechanisms, or alter tumor-associated signaling. Antibody–drug conjugates combine molecular recognition with selective intracellular delivery of highly potent cytotoxic payloads. Epigenetic drugs modify chromatin-associated regulatory processes and can alter gene-expression programs involved in differentiation, proliferation, and apoptosis. Radiopharmaceuticals deliver ionizing radiation to molecularly selected tissues or cellular targets. Cellular therapies, including genetically modified immune cells, introduce living therapeutic agents capable of recognizing and eliminating malignant cells. These diverse mechanisms create correspondingly diverse patterns of therapeutic response and toxicity.

Cancer pharmacotherapy is further complicated by the evolutionary nature of malignant disease. Tumors consist of heterogeneous cellular populations that undergo continuous genetic and epigenetic selection under environmental and therapeutic pressure. Drug exposure may therefore eliminate sensitive clones while allowing resistant subpopulations to expand. Resistance mechanisms can include target mutation, target amplification, alternative pathway activation, enhanced DNA repair, altered apoptosis, drug efflux, metabolic adaptation, epithelial–mesenchymal transition, changes in tumor microenvironment, immune escape, and phenotypic plasticity. Pharmacological resistance is consequently not a static characteristic but a dynamic process. Understanding the molecular basis of resistance has become fundamental to treatment

sequencing, combination therapy, adaptive treatment strategies, and the development of next-generation inhibitors.

The concept of evidence-based pharmacotherapy provides an essential framework for translating pharmacological knowledge into clinical oncology. Therapeutic decisions should integrate high-quality evidence from randomized controlled trials, systematic reviews, meta-analyses, comparative effectiveness studies, pharmacological investigations, real-world evidence, and post-marketing safety surveillance. However, evidence derived from clinical trials does not necessarily capture the complete safety profile of medicines in routine clinical practice. Clinical trials frequently operate under restrictive eligibility criteria and may underrepresent older adults, patients with substantial comorbidity, individuals with organ dysfunction, ethnically diverse populations, patients receiving complex polypharmacy, and those with uncommon toxicities. Consequently, post-authorization pharmacovigilance and real-world evidence are indispensable for detecting adverse events that may emerge only after widespread use.

Pharmacovigilance represents a particularly important component of modern oncology because the severity and complexity of anticancer medication toxicity may differ substantially from those observed with many nononcological medicines. Classical pharmacovigilance includes spontaneous adverse-event reporting, signal detection, causality assessment, risk characterization, risk minimization, periodic safety evaluation, and regulatory communication. In contemporary oncology, pharmacovigilance is increasingly supported by electronic health records, clinical registries, administrative databases, patient-reported outcomes, molecular datasets, and advanced computational methods. These resources can facilitate detection of rare adverse events, temporal associations, risk factors, and clinically meaningful patterns that may not be apparent in individual clinical trials.

The interpretation of adverse drug reactions in oncology requires careful distinction among expected pharmacological effects, dose-limiting toxicities, idiosyncratic reactions, immune-mediated adverse events, cumulative toxicities, delayed complications, and treatment-related secondary malignancies. Adverse events may also arise from the underlying cancer itself or from supportive-care interventions, making causal attribution difficult. For example, fatigue, nausea, pain, cytopenias, fever, neurological symptoms, and organ dysfunction can reflect either disease progression or treatment toxicity. A scientifically rigorous pharmacovigilance system must therefore incorporate temporal relationships, dose–response relationships, alternative explanations, dechallenge and rechallenge information where ethically appropriate, known pharmacological mechanisms, concomitant medication exposure, laboratory findings, imaging, and patient-specific susceptibility factors.

The concept of pharmacological toxicity in oncology extends beyond acute adverse events. Cumulative toxicity has become increasingly relevant as survival improves and patients receive multiple lines of therapy. Cardiotoxicity may emerge during or after exposure to certain chemotherapeutic or targeted agents; nephrotoxicity may compromise subsequent treatment options; neurotoxicity can cause persistent functional impairment; pulmonary toxicity may result in irreversible respiratory complications; and gonadal toxicity may influence fertility and quality of life. Some therapies may also produce long-term metabolic, endocrine, reproductive, cognitive, or vascular consequences. Consequently, contemporary oncology increasingly emphasizes survivorship pharmacology and long-term medication safety rather than focusing exclusively on toxicity occurring during active treatment.

Drug interactions represent another major dimension of anticancer medication safety. Many anticancer agents are metabolized by cytochrome P450 enzymes or transported by membrane transport systems that can be inhibited or induced by concomitant medications. Changes in enzyme activity can alter systemic exposure and thereby modify efficacy or toxicity. Pharmacodynamic interactions may also occur when two medications independently affect the

same physiological system. For example, combinations that increase bleeding risk, prolong cardiac repolarization, suppress bone marrow function, or impair renal function may create clinically significant hazards. Polypharmacy management is therefore essential to safe cancer pharmacotherapy, requiring systematic medication reconciliation and evaluation of prescription medicines, over-the-counter products, herbal preparations, and nutritional supplements.

Pharmacogenomics has emerged as a major component of individualized anticancer pharmacotherapy. Genetic variation among individuals can influence drug metabolism, transport, target engagement, immune response, toxicity, and therapeutic effectiveness. Germline genetic variants may affect the activity of drug-metabolizing enzymes, transporters, DNA-repair proteins, immune-regulatory molecules, or pharmacological targets. Somatic tumor alterations can identify molecular dependencies that determine whether a targeted therapy is likely to be effective. The distinction between germline pharmacogenomics and somatic tumor genomics is therefore critical. Germline information primarily characterizes patient-specific susceptibility, whereas somatic molecular profiling describes tumor-specific biology. Integrating these dimensions creates a more comprehensive pharmacological model of treatment response.

The clinical application of pharmacogenomic information requires analytical validity, clinical validity, clinical utility, appropriate interpretation, and consideration of population-specific genetic diversity. Not every statistically significant genetic association has sufficient predictive value to guide clinical treatment. Biomarker implementation should therefore be supported by robust evidence demonstrating that genotype- or phenotype-guided therapy improves meaningful clinical outcomes. Nevertheless, pharmacogenomic testing has become increasingly relevant for selected anticancer agents where genetic variation is strongly associated with severe toxicity or altered drug disposition. The integration of pharmacogenomics into oncology thus represents a transition from population-average dosing toward biologically informed treatment selection and dose optimization.

Personalized medicine extends beyond pharmacogenomics by incorporating multiple dimensions of patient and disease heterogeneity. Contemporary precision oncology may integrate tumor genomic sequencing, transcriptomics, proteomics, metabolomics, immune profiling, histopathology, radiological characteristics, clinical phenotype, comorbidity, organ function, previous treatment history, patient preferences, and real-world outcomes. The objective is not simply to identify a molecular target but to construct a multidimensional model of therapeutic benefit and risk. This approach recognizes that two patients with histologically similar tumors may have substantially different molecular vulnerabilities, pharmacokinetic profiles, immune environments, and treatment tolerability. Precision pharmacotherapy consequently seeks to optimize the balance between efficacy and toxicity at the level of the individual patient.

Therapeutic drug monitoring represents another potentially important strategy for individualizing anticancer medication exposure. Although routine therapeutic drug monitoring is not appropriate for all oncology medications, it may be valuable for selected drugs characterized by narrow therapeutic windows, substantial interpatient pharmacokinetic variability, established exposure–response relationships, and clinically meaningful concentration–toxicity or concentration–efficacy associations. Therapeutic drug monitoring may involve measurement of plasma or whole-blood concentrations followed by pharmacokinetic interpretation and dose adjustment. Population pharmacokinetic models, Bayesian forecasting, and pharmacokinetic–pharmacodynamic modeling can further refine individualized dose optimization. The integration of therapeutic drug monitoring with pharmacogenomics and clinical characteristics provides a framework for precision dosing based on actual patient exposure rather than prescribed dose alone.

Pharmacokinetic–pharmacodynamic modeling has consequently become an important methodological component of translational oncology. Such models can characterize relationships among administered dose, drug concentration, target engagement, biomarker changes, tumor

response, and toxicity. Population approaches can identify covariates explaining interindividual variability and may include body size, age, organ function, genetic factors, co-medications, inflammatory status, and disease burden. Mechanistic models may additionally incorporate tumor growth dynamics, drug resistance, immune-cell interactions, and pharmacological pathway structure. These approaches have potential value for dose selection during drug development, clinical trial design, therapeutic optimization, and prediction of individual treatment outcomes.

The therapeutic index of anticancer medications must be understood within the broader context of risk–benefit assessment. In oncology, potentially serious toxicity may be clinically acceptable when treatment provides substantial survival benefit in a life-threatening disease. Nevertheless, acceptance of risk must remain evidence based and patient centered. The objective is not simply to maximize drug exposure but to maximize clinically meaningful therapeutic benefit while minimizing avoidable harm. This principle is especially important when alternative treatments with different efficacy–toxicity profiles are available. Shared decision-making should therefore incorporate expected treatment benefit, toxicity probability, disease prognosis, quality-of-life considerations, patient values, and treatment alternatives.

Supportive pharmacotherapy forms an integral part of safe anticancer treatment. Antiemetics, growth factors, analgesics, antimicrobial prophylaxis, transfusion support, nutritional interventions, bone-modifying agents, corticosteroids, and other supportive measures may reduce treatment-related morbidity and permit maintenance of anticancer therapy. However, supportive medicines can themselves cause adverse reactions and drug interactions. The pharmacological management of chemotherapy-induced nausea, neutropenia, anemia, pain, mucositis, and other complications therefore requires the same principles of evidence-based prescribing and medication safety applied to anticancer agents.

The emergence of oral anticancer medications has introduced additional dimensions of medication safety and adherence. Unlike intravenously administered therapies that are typically delivered within controlled healthcare environments, oral targeted therapies frequently require patients or caregivers to manage dosing independently at home. This creates opportunities for missed doses, incorrect dosing, accidental overdosing, inappropriate storage, food–drug interactions, and unrecognized adverse events. Medication adherence therefore becomes a pharmacological determinant of treatment effectiveness. Patient education, structured medication review, digital adherence monitoring, and pharmacist-led oncology services can contribute substantially to safe and effective oral anticancer therapy.

Oncology pharmacy has consequently evolved from medication dispensing toward comprehensive clinical pharmacotherapy management. Clinical pharmacists can contribute to medication reconciliation, interaction assessment, pharmacogenomic interpretation, therapeutic drug monitoring, adverse-event recognition, dose adjustment, patient counseling, adherence support, and pharmacovigilance. Interdisciplinary collaboration among oncologists, pharmacists, clinical pharmacologists, nurses, laboratory specialists, geneticists, and other healthcare professionals is essential for integrating pharmacological, molecular, and clinical information. Such collaboration can facilitate early recognition of toxicity and enable timely treatment modification.

The role of biomarkers in anticancer pharmacotherapy is increasingly important. Predictive biomarkers may identify patients who are more likely to respond to a particular treatment, whereas prognostic biomarkers provide information regarding disease outcome independently of treatment. Pharmacodynamic biomarkers can indicate target engagement or biological response, while safety biomarkers may identify emerging organ toxicity before irreversible injury occurs. The integration of biomarker science with pharmacovigilance may enable earlier detection of treatment-related harm and more precise selection of therapeutic strategies. Nevertheless, biomarker interpretation must account for assay validity, tumor heterogeneity, temporal changes, sampling limitations, and the possibility that biomarker status may evolve during treatment.

Tumor heterogeneity creates a particularly important challenge for personalized oncology. A single biopsy may not fully represent the molecular diversity of a tumor or metastatic disease. Distinct subclones may possess different therapeutic sensitivities, and treatment pressure may alter clonal composition over time. Liquid biopsy and circulating tumor DNA technologies offer opportunities for repeated molecular assessment and dynamic monitoring. These approaches may help identify emerging resistance mechanisms and support treatment adaptation. From a pharmacological perspective, dynamic molecular profiling transforms precision therapy from a one-time treatment-selection process into an iterative strategy of continual biological reassessment.

Artificial intelligence, machine learning, and computational pharmacology are increasingly being explored as tools for oncology drug development and pharmacovigilance. Large-scale datasets can be analyzed to identify patterns linking patient characteristics, medication exposure, molecular features, and adverse outcomes. Predictive algorithms may support adverse-event detection, risk stratification, treatment-response prediction, drug–drug interaction assessment, and identification of potentially actionable biomarkers. However, computational predictions must be validated clinically, and algorithmic performance may be influenced by dataset quality, population representation, missing data, measurement bias, and model drift. Consequently, artificial intelligence should complement rather than replace clinical pharmacological judgment.

Real-world evidence is particularly relevant for evaluating anticancer medication safety because cancer populations in routine practice are substantially more heterogeneous than those included in many clinical trials. Observational datasets can provide information about treatment patterns, adherence, dose modifications, comorbidity, long-term toxicity, treatment sequencing, and outcomes in populations underrepresented in controlled trials. However, real-world evidence requires careful methodological interpretation because confounding by indication, selection bias, immortal-time bias, missing data, and differences in follow-up can distort associations. Advanced epidemiological and statistical methodologies are therefore required to convert observational data into clinically meaningful evidence.

The regulatory environment surrounding anticancer medicines must also accommodate rapid therapeutic innovation. Accelerated development pathways, surrogate endpoints, biomarker-defined populations, and conditional approvals can facilitate access to promising treatments while generating uncertainty regarding long-term efficacy and safety. Post-marketing evidence generation is therefore particularly important for medicines introduced on the basis of limited datasets. Continuous pharmacovigilance can identify rare toxicities and unexpected interactions that become apparent only after broader clinical exposure. Regulatory science must consequently maintain a balance between timely innovation and rigorous risk management.

Patient-reported outcomes represent another essential dimension of pharmacological safety. Traditional toxicity grading systems frequently rely on clinician assessment and laboratory measurements, but patients may experience symptoms that are incompletely captured by routine clinical evaluation. Fatigue, cognitive impairment, neuropathy, gastrointestinal symptoms, sexual dysfunction, sleep disturbance, and changes in quality of life may have substantial functional consequences despite modest laboratory abnormalities. Incorporating patient-reported outcomes into oncology pharmacovigilance can therefore improve recognition of clinically meaningful toxicity and facilitate shared decision-making.

The ethical dimension of personalized pharmacotherapy is also increasingly prominent. Genomic testing can reveal clinically relevant information beyond the immediate therapeutic question, potentially creating issues related to privacy, incidental findings, familial implications, data governance, and equitable access. Precision oncology technologies can be expensive and may not be equally accessible across healthcare systems. Consequently, scientific advancement must be accompanied by consideration of distributive justice, affordability, accessibility, and responsible

data use. Evidence-based personalization should improve clinical outcomes without creating avoidable disparities.

Another major challenge is the global heterogeneity of medication safety systems. Differences in regulatory frameworks, pharmacovigilance infrastructure, availability of molecular testing, clinical expertise, healthcare resources, and access to anticancer medicines can influence both treatment outcomes and safety surveillance. In resource-constrained settings, the implementation of advanced pharmacogenomics, therapeutic drug monitoring, and molecularly targeted therapy may be limited. Strengthening pharmacovigilance systems, clinical pharmacy services, laboratory capacity, standardized reporting, and evidence-based prescribing is therefore essential for improving global cancer care.

The concept of integrated oncology pharmacotherapy consequently requires convergence among several scientific domains. Classical pharmacology provides the foundational understanding of drug action, receptor interactions, dose–response relationships, pharmacokinetics, and toxicity. Molecular oncology identifies actionable abnormalities and mechanisms of resistance. Pharmacogenomics characterizes patient-specific genetic determinants of drug response and toxicity. Precision medicine integrates multidimensional biological and clinical information to individualize treatment. Therapeutic drug monitoring quantifies drug exposure where clinically appropriate. Pharmacovigilance continuously evaluates medication safety in clinical use. Evidence-based medicine provides the methodological framework for determining whether these interventions improve meaningful outcomes. Clinical pharmacology integrates these components into rational treatment decisions.

Such integration is particularly important because anticancer medications rarely operate as isolated interventions. Combination regimens are often designed to target different cellular pathways, prevent resistance, or enhance immune-mediated tumor destruction. Yet combination therapy can also produce cumulative or synergistic toxicity, complicate pharmacokinetics, and increase the risk of interactions. Rational combination design should therefore consider mechanistic complementarity, nonoverlapping toxicity, pharmacokinetic compatibility, temporal scheduling, and evidence regarding therapeutic synergy. Systems pharmacology and quantitative modeling may contribute to optimizing these complex treatment regimens.

The development of precision dosing represents an important extension of precision medicine. Standard dosing algorithms are generally derived from population-level estimates and may not account for substantial interindividual variability. Precision dosing seeks to use patient-specific covariates, pharmacokinetic measurements, pharmacogenomic information, disease characteristics, and treatment response to select an individualized regimen. In selected circumstances, this may reduce underexposure and therapeutic failure or prevent excessive exposure and toxicity. Precision dosing therefore represents an important bridge between pharmacological theory and individualized clinical implementation.

Importantly, personalization should not be interpreted as unrestricted treatment customization without evidence. The clinical value of any personalization strategy depends upon demonstrable improvement in patient outcomes, feasibility, analytical reliability, and appropriate interpretation. The expansion of molecular testing and computational prediction must therefore be accompanied by rigorous clinical validation. Otherwise, excessive reliance on weak biomarkers or unvalidated algorithms may introduce uncertainty rather than reduce it. Modern oncology consequently requires an evidence hierarchy capable of distinguishing scientifically promising approaches from clinically validated interventions.

The pharmacological safety of anticancer medications is also closely related to treatment timing and cumulative exposure. Some toxicities occur immediately after administration, whereas others emerge after repeated cycles or prolonged therapy. Delayed toxicity may become evident months or years after treatment completion. The temporal complexity of adverse effects necessitates

longitudinal monitoring systems capable of following patients throughout treatment and survivorship. Long-term surveillance is particularly relevant for therapies associated with cumulative organ damage, persistent endocrine effects, reproductive consequences, cardiovascular complications, or secondary malignancy risk.

Cancer pharmacotherapy is therefore increasingly understood as a continuum extending from drug discovery and preclinical pharmacology to clinical development, molecular selection, individualized dosing, post-marketing surveillance, and long-term survivorship. Each stage generates information that can refine subsequent therapeutic decisions. Preclinical mechanistic studies establish biological plausibility; early clinical trials characterize pharmacokinetics, pharmacodynamics, and dose-limiting toxicity; randomized trials establish efficacy and comparative safety; biomarker studies identify populations likely to benefit; real-world evidence characterizes broader use; pharmacovigilance identifies rare or delayed risks; and pharmacogenomic and therapeutic drug monitoring approaches may subsequently refine individual treatment.

Within this framework, the scientific discourse surrounding anticancer medications must move beyond a simple enumeration of drug classes and adverse effects. A contemporary pharmacological analysis should integrate molecular mechanism, pharmacokinetics, pharmacodynamics, therapeutic index, toxicity, resistance, patient variability, genomic determinants, biomarkers, treatment context, medication interactions, monitoring strategies, and evidence quality. Such an integrated perspective is essential because the clinical meaning of a medication's toxicity depends upon dose, exposure, mechanism, patient susceptibility, disease status, treatment combination, and available alternatives. Similarly, therapeutic efficacy cannot be evaluated independently of tolerability, adherence, quality of life, treatment duration, and long-term outcomes.

The increasing complexity of oncology therefore necessitates a multidisciplinary and systems-oriented pharmacological framework. Clinical pharmacology, molecular biology, pharmacogenomics, pharmacoepidemiology, pharmacovigilance, bioinformatics, systems biology, therapeutic drug monitoring, and evidence-based medicine increasingly intersect in the optimization of anticancer therapy. The ultimate objective is not merely to develop more potent medicines, but to ensure that the right therapeutic intervention is selected for the right patient, administered at an appropriate dose and schedule, monitored through scientifically valid biomarkers and clinical parameters, and modified promptly when the balance between benefit and harm changes.

Against this background, the systematic study of anticancer medication classification, pharmacology, mechanisms of action, pharmacological safety, adverse effects, and toxicity represents a fundamental component of modern oncology. The integration of pharmacovigilance with evidence-based pharmacotherapy, pharmacogenomics, personalized medicine, and therapeutic drug monitoring provides a multidimensional framework for addressing the central challenge of contemporary cancer treatment: achieving maximal and durable antitumor benefit while minimizing preventable, predictable, and clinically consequential harm. Such an approach recognizes the dynamic biology of malignancy, the complexity of modern drug therapy, and the substantial heterogeneity among patients. It also establishes a scientific foundation for continuous therapeutic optimization in which pharmacological knowledge is translated into individualized, evidence-based, safe, and clinically meaningful cancer care.

Ultimately, the future of anticancer pharmacotherapy will depend upon the convergence of increasingly precise molecular characterization with rigorous clinical pharmacology and continuous medication-safety surveillance. Advances in genomic technologies, quantitative pharmacology, artificial intelligence, real-world evidence, biomarker development, molecular imaging, liquid biopsy, pharmacokinetic–pharmacodynamic modeling, and therapeutic drug

monitoring are likely to expand the capacity to predict therapeutic response and toxicity. Nevertheless, technological sophistication must remain subordinate to clinically validated evidence and patient-centered outcomes. The most scientifically mature model of oncology pharmacotherapy is therefore one in which mechanistic understanding, quantitative exposure assessment, molecular profiling, clinical judgment, pharmacovigilance, and patient preferences are integrated into an adaptive therapeutic process. Within this paradigm, anticancer medications are not viewed simply as isolated pharmacological entities but as components of a continuously evolving therapeutic system in which efficacy, safety, resistance, exposure, genetics, disease biology, and individual patient characteristics must be considered simultaneously.

## **GOAL**

The primary goal of this scientific discourse is to provide an integrated, evidence-based pharmacological framework for the systematic classification, characterization, and clinical evaluation of anticancer medications in modern oncology. Particular emphasis is placed on elucidating the pharmacodynamic and pharmacokinetic principles underlying major anticancer drug classes; defining their molecular and cellular mechanisms of action; critically examining therapeutic efficacy, pharmacological safety, adverse drug reactions, dose-limiting toxicities, cumulative toxicity, and clinically relevant drug–drug interactions; and establishing the role of structured pharmacovigilance in the continuous detection, assessment, prevention, and management of medication-related risks. A further goal is to examine how pharmacogenomics, tumor molecular profiling, personalized medicine, pharmacokinetic–pharmacodynamic modeling, biomarker-guided treatment selection, and therapeutic drug monitoring can be integrated into evidence-based pharmacotherapy to optimize the benefit–risk ratio for individual patients. The overarching objective is to advance a precision-oriented model of oncology in which anticancer treatment is selected and adjusted according to tumor biology, patient-specific genetic and clinical characteristics, drug exposure, therapeutic response, and toxicity, thereby promoting rational, individualized, safe, and clinically effective pharmacotherapy while minimizing preventable treatment-related morbidity and improving long-term patient outcomes.

## **METHODOLOGY**

This scientific discourse employed an integrative, evidence-based narrative methodology to synthesize contemporary knowledge concerning anticancer pharmacotherapy, with emphasis on drug classification, pharmacodynamics, pharmacokinetics, mechanisms of action, safety, adverse drug reactions, toxicity, pharmacovigilance, pharmacogenomics, personalized medicine, and therapeutic drug monitoring. Relevant scientific evidence was conceptually integrated across clinical pharmacology, oncology, pharmacology, pharmacoepidemiology, molecular oncology, and precision medicine. Particular consideration was given to mechanistic evidence, clinical efficacy and safety findings, exposure–response relationships, pharmacogenomic determinants, clinically relevant drug interactions, and post-marketing safety signals. The methodological framework prioritized critical synthesis and translational interpretation, linking molecular mechanisms with clinical outcomes and individualized therapeutic decision-making. Emphasis was placed on evidence-based risk–benefit assessment, systematic adverse-event characterization, and multidisciplinary integration of pharmacological and patient-specific determinants relevant to rational and safe anticancer medication use.

## **RESULTS AND DISCUSSION**

The present scientific investigation demonstrates that modern anticancer pharmacotherapy has evolved from predominantly nonspecific cytotoxic treatment toward a highly heterogeneous therapeutic landscape incorporating classical chemotherapy, endocrine therapy, molecularly targeted agents, monoclonal antibodies, immune checkpoint inhibitors, cellular therapies, and

other biologically directed interventions. This pharmacological diversification has substantially increased therapeutic opportunities while simultaneously generating a more complex spectrum of pharmacokinetic, pharmacodynamic, immunological, and organ-specific toxicities. Consequently, contemporary oncology requires an integrated framework combining pharmacological knowledge, adverse-drug-reaction surveillance, pharmacogenomics, personalized medicine, therapeutic drug monitoring (TDM), and multidisciplinary clinical decision-making.

A major finding of the research is that the mechanism of action of anticancer medications is closely associated with both therapeutic efficacy and toxicity. Conventional cytotoxic agents generally exploit the increased proliferative activity of malignant cells through DNA damage, inhibition of DNA synthesis, disruption of mitosis, or interference with cellular replication. However, because some normal tissues—including bone marrow, gastrointestinal epithelium, hair follicles, and reproductive tissues—also contain rapidly dividing cells, these pharmacological mechanisms inevitably produce dose-limiting adverse effects. Myelosuppression, mucositis, nausea and vomiting, alopecia, infertility, infection susceptibility, and fatigue therefore remain clinically important consequences of conventional chemotherapy.

The findings indicate that targeted therapy has transformed the pharmacological paradigm of cancer treatment. Molecularly targeted drugs are designed to interfere with specific proteins or signaling pathways involved in tumor growth, proliferation, survival, angiogenesis, invasion, or metastasis. Small-molecule inhibitors can penetrate cells and inhibit intracellular targets, whereas monoclonal antibodies generally interact with extracellular or cell-surface targets. Biomarker testing has consequently become central to therapeutic selection because the presence or absence of a molecular target can determine whether a targeted agent is likely to provide clinical benefit.

The research confirms that molecular selectivity does not equate to absence of toxicity. Targeted therapies may produce diarrhea, hepatotoxicity, hypertension, dermatological reactions, fatigue, mucosal injury, impaired wound healing, thrombotic complications, and other organ-specific adverse events. Some toxicities are mechanistically related to inhibition of pathways that are also physiologically important in normal tissues. Importantly, resistance can develop through alteration of the molecular target or activation of alternative signaling pathways, demonstrating that pharmacodynamic adaptation represents a major limitation of precision oncology.

Another major finding concerns immunotherapy and immune-mediated toxicity. Immune checkpoint inhibitors and other immunotherapeutic strategies enhance antitumor immune activity by overcoming mechanisms through which malignant cells evade immune surveillance. Although this approach can produce durable responses in selected patients, excessive immune activation may result in immune-related adverse events affecting the skin, gastrointestinal tract, liver, endocrine organs, lungs, cardiovascular system, nervous system, and other tissues. These toxicities may occur during treatment or, in some circumstances, after treatment has been completed.

The research identifies pharmacovigilance as a central component of modern oncology. Antineoplastic medicines frequently possess narrow therapeutic windows, substantial intrinsic biological toxicity, complex dosing schedules, and extensive potential for drug–drug and drug–disease interactions. Pharmacovigilance must consequently extend beyond spontaneous adverse-event reporting toward active surveillance, systematic toxicity characterization, signal detection, causality assessment, risk minimization, medication-error prevention, and continuous evaluation of the benefit–risk relationship. Evidence indicates that oncology pharmacovigilance is particularly challenged by polypharmacy, complex treatment combinations, targeted therapies, immunotherapies, special patient populations, and under-reporting of adverse drug reactions.

The importance of pharmacogenomics in explaining interindividual differences in anticancer drug response and toxicity. Genetic variation affecting drug-metabolizing enzymes, transport proteins, molecular targets, DNA-repair pathways, and immune-response mechanisms can alter systemic exposure, pharmacodynamic response, therapeutic efficacy, and susceptibility to adverse reactions. Consequently, pharmacogenomic information can contribute to identifying patients at increased risk of severe toxicity and may support selection or dose optimization of particular anticancer agents. The literature also demonstrates that both germline genetic variation and tumor-acquired molecular alterations can influence treatment response and resistance.

The personalized medicine represents a multidimensional rather than purely genetic concept. Optimal anticancer treatment should integrate tumor characteristics with patient-specific variables, including age, body composition, renal and hepatic function, comorbidities, concomitant medications, nutritional status, performance status, previous therapies, adherence, and pharmacogenomic characteristics. This comprehensive approach is particularly important because identical doses may generate substantially different systemic exposures and clinical outcomes among patients.

Therapeutic drug monitoring represents another important finding. Although TDM is not universally established for all anticancer medications, it has particular theoretical and clinical value for drugs characterized by substantial pharmacokinetic variability, narrow therapeutic indices, measurable concentration–response relationships, and clinically meaningful concentration–toxicity associations. Research has particularly explored pharmacokinetic-guided dosing for agents such as 5-fluorouracil, methotrexate, and busulfan. Nevertheless, implementation remains challenging because pharmacokinetics may be influenced by organ function, age, body composition, drug interactions, genetics, disease status, treatment schedule, and adherence. Evidence indicates that standardized PK-guided dosing recommendations remain unavailable for many anticancer agents.

The findings also demonstrate increasing interest in advanced analytical approaches to oncology TDM, including immunoassays and liquid-chromatography–mass spectrometry. Contemporary research is investigating how pharmacokinetic measurements, pharmacogenetic testing, and next-generation analytical technologies could facilitate individualized dosing of chemotherapy, targeted therapies, and selected immunotherapies. However, the evidence base remains heterogeneous, and routine TDM for many monoclonal antibodies and small-molecule targeted agents cannot yet be considered universally established clinical practice.

Drug–drug interactions constitute another significant research finding. Modern oncology frequently involves simultaneous administration of anticancer agents, antiemetics, analgesics, antimicrobials, corticosteroids, anticoagulants, supportive medicines, and occasionally complementary or herbal products. Pharmacokinetic interactions involving cytochrome P450 enzymes, transporters, absorption, metabolism, or elimination may alter anticancer-drug exposure, whereas pharmacodynamic interactions may amplify organ toxicity or reduce therapeutic effectiveness. Consequently, medication reconciliation and clinical pharmacy assessment are essential components of safe cancer pharmacotherapy.

The research emphasizes the importance of integrated toxicity surveillance. Monitoring should incorporate complete blood counts, hepatic and renal biochemical parameters, cardiovascular assessment where appropriate, neurological evaluation, endocrine testing for selected immunotherapies, dermatological assessment, gastrointestinal monitoring, and systematic documentation of adverse events. Standardized toxicity grading systems, including CTCAE terminology used in oncology research, facilitate communication, comparison of safety outcomes, and therapeutic decision-making. The National Cancer Institute maintains structured resources for identifying and categorizing adverse effects associated with cancer-treatment agents and regimens.

The anticancer pharmacotherapy should be conceptualized as a dynamic benefit–risk optimization process rather than a simple drug-selection procedure. Therapeutic success depends on achieving sufficient antitumor exposure while minimizing systemic toxicity, preserving organ function, preventing avoidable medication-related harm, and maintaining quality of life. This requires continuous reassessment of treatment response, adverse events, pharmacokinetic variables, drug interactions, biomarkers, and patient-specific characteristics.

The modern oncology is progressively moving toward an integrated pharmacological model in which pharmacology, pharmacovigilance, pharmacogenomics, precision medicine, clinical pharmacy, and TDM operate as complementary components of evidence-based pharmacotherapy. Conventional cytotoxic agents remain important, but targeted and immune-based therapies have expanded the therapeutic arsenal while generating new categories of toxicity and resistance. Pharmacogenomic and biomarker-guided approaches can improve patient selection, while pharmacokinetic monitoring may provide additional opportunities for dose individualization in selected circumstances. Active pharmacovigilance and multidisciplinary clinical surveillance remain indispensable for detecting emerging safety signals and reducing preventable harm.

The scientific evidence supports a comprehensive model of anticancer medication management in which mechanism-based drug selection, molecular characterization of tumors, individualized risk assessment, pharmacogenomic profiling, systematic adverse-event monitoring, interaction management, pharmacokinetic evaluation, and continuous benefit–risk assessment are integrated into a single therapeutic framework. Such an approach has the potential to enhance treatment effectiveness, reduce avoidable toxicity, improve medication safety, optimize prescribing quality, and ultimately promote more precise, rational, and patient-centered cancer care.

The integrated analysis demonstrated that contemporary anticancer pharmacotherapy constitutes a highly heterogeneous and mechanistically sophisticated therapeutic domain in which conventional cytotoxic agents coexist with endocrine therapies, molecularly targeted medicines, monoclonal antibodies, antibody–drug conjugates, immune checkpoint inhibitors, epigenetic modulators, DNA-repair inhibitors, radiopharmaceuticals, and cellular or gene-based interventions. The principal pharmacological finding is that therapeutic classification increasingly depends upon molecular target, mechanism of action, biomarker status, and pharmacological dependency rather than solely upon chemical structure or anatomical tumor location. This transition has materially expanded therapeutic selectivity, yet it has not eliminated toxicity; rather, the nature of toxicity has become increasingly mechanism-specific and dependent upon target biology, systemic exposure, host susceptibility, treatment combinations, and duration of therapy. Analysis of pharmacodynamic principles indicates that anticancer efficacy is fundamentally determined by the capacity of a medicinal product to perturb biological processes essential for malignant-cell survival, proliferation, replication, metabolism, angiogenesis, immune evasion, or genomic maintenance. Classical cytotoxic agents principally exploit vulnerabilities associated with DNA synthesis, DNA integrity, and mitosis, whereas targeted therapies interfere with oncogenic signaling dependencies and immunotherapeutics modify host–tumor interactions. These mechanistic distinctions have direct implications for therapeutic selectivity, dose optimization, resistance development, and adverse-event profiles. The findings therefore support a mechanism-oriented interpretation of pharmacotherapy in which pharmacological effects and toxicities are understood as interconnected consequences of molecular target engagement rather than as independent clinical phenomena.

The analysis further indicates that pharmacokinetic variability represents a major determinant of interindividual differences in both therapeutic response and toxicity. Absorption, distribution, metabolism, transport, and elimination may be influenced by age, body composition, hepatic and

renal function, nutritional status, inflammation, concomitant medications, genetic variation, disease burden, and organ involvement by malignancy. Consequently, a standardized dose does not necessarily produce standardized systemic exposure. This observation provides a pharmacological rationale for individualized dose selection and, where clinically validated, therapeutic drug monitoring and population pharmacokinetic–pharmacodynamic modeling. The integration of exposure measurements with clinical and molecular covariates may facilitate identification of patients at risk of underexposure, treatment failure, or excessive toxicity.

A particularly important result concerns the changing conceptualization of pharmacological safety. In modern oncology, safety cannot be reduced to the frequency of conventional adverse events recorded during clinical trials. Clinically consequential toxicity encompasses acute, cumulative, delayed, immune-mediated, idiosyncratic, organ-specific, and interaction-mediated phenomena. Myelosuppression, gastrointestinal toxicity, mucosal injury, neurotoxicity, nephrotoxicity, hepatotoxicity, cardiotoxicity, pulmonary toxicity, dermatological reactions, endocrine dysfunction, reproductive impairment, and immune-related adverse events represent distinct pharmacological manifestations requiring differentiated surveillance and management. The analysis therefore supports a multidimensional safety framework incorporating severity, reversibility, temporal relationship, dose dependence, cumulative exposure, underlying mechanism, patient susceptibility, and consequences for treatment continuity and quality of life. The pharmacovigilance dimension of the analysis demonstrates that adverse-event surveillance must extend beyond the controlled conditions of clinical trials. Rare toxicities, delayed complications, clinically significant drug interactions, medication-use errors, adherence-related problems, and adverse events occurring in populations underrepresented in trials may become apparent only after broader clinical utilization. Spontaneous reporting systems, electronic health records, registries, patient-reported outcomes, pharmacoepidemiological databases, and other real-world data sources therefore provide complementary evidence. Their integration can strengthen signal detection and facilitate earlier recognition of previously uncharacterized safety concerns. Nevertheless, observational signals require rigorous assessment of causality, confounding, reporting bias, exposure misclassification, and competing explanations before clinical or regulatory conclusions are established.

The analysis also identifies pharmacogenomics as a critical bridge between population-level pharmacology and individualized therapeutic decision-making. Germline variation can modify drug metabolism, transport, target interaction, DNA-repair capacity, and susceptibility to toxicity, whereas somatic tumor alterations may determine the presence of actionable molecular dependencies. The distinction between germline and somatic determinants is therefore essential for interpretation of precision oncology data. Pharmacogenomic information is most clinically valuable when analytical validity, clinical validity, and clinical utility are sufficiently established to justify treatment selection or dose modification. The results consequently support selective rather than indiscriminate implementation of pharmacogenomic testing, with clinical decisions grounded in validated genotype–phenotype and exposure–response relationships.

Personalized medicine emerges from the analysis as a broader framework that integrates pharmacogenomics with tumor genomics, transcriptomic and proteomic characteristics, biomarkers, clinical phenotype, comorbidity, organ function, previous therapies, treatment response, and patient preferences. Such integration is particularly relevant because tumors are biologically heterogeneous and evolve under therapeutic selection. A molecular characteristic identified at diagnosis may therefore not remain therapeutically dominant throughout the disease course. Dynamic assessment, including repeated molecular characterization where clinically appropriate, may consequently support treatment adaptation and identification of emerging resistance mechanisms. Precision oncology should thus be understood as an iterative process of

therapeutic optimization rather than a single molecular classification performed before treatment initiation.

The results further emphasize that drug resistance represents an intrinsic limitation of anticancer pharmacotherapy and a major determinant of long-term treatment failure. Resistance may arise through target mutation or loss, alternative signaling activation, gene amplification, enhanced DNA repair, altered apoptotic signaling, drug efflux, metabolic adaptation, phenotypic plasticity, immune escape, and changes in the tumor microenvironment. These mechanisms demonstrate why initial pharmacological efficacy does not necessarily predict durable disease control. Rational combination therapy, sequential targeting of evolving molecular dependencies, and dynamic biomarker assessment therefore constitute important strategies for mitigating resistance. However, combination regimens must be evaluated not only for theoretical mechanistic complementarity but also for pharmacokinetic compatibility and overlapping toxicity.

An important finding concerns the central role of therapeutic drug monitoring in selected pharmacological contexts. Although concentration-guided dosing is not universally applicable to anticancer agents, its potential value is greatest when substantial pharmacokinetic variability coexists with a narrow therapeutic index and demonstrable exposure–response or exposure–toxicity relationships. Bayesian forecasting and population pharmacokinetic models can further enhance individualized dosing by integrating prior population information with patient-specific concentration data. This approach represents a quantitative extension of personalized medicine because it transforms prescribed dose into an empirically informed estimate of actual systemic exposure.

The integrated evidence also demonstrates that pharmacological safety is inseparable from medication reconciliation and interaction management. Oncology patients frequently receive multiple anticancer and supportive-care medicines simultaneously, creating opportunities for cytochrome-mediated metabolic interactions, transporter-mediated interactions, additive organ toxicity, altered cardiac repolarization, bleeding, immunological interactions, and changes in therapeutic exposure. Comprehensive medication review should therefore encompass prescription medicines, over-the-counter preparations, herbal products, and nutritional supplements. Clinical pharmacists and clinical pharmacologists have an important role in identifying these risks, recommending evidence-based modifications, and supporting continuous medication surveillance throughout treatment.

The findings support a systems-pharmacology perspective in which anticancer treatment outcomes emerge from interactions among drug characteristics, tumor biology, host physiology, genetics, immune status, treatment combinations, exposure, adherence, and environmental or behavioral determinants. This perspective challenges simplified models based exclusively on administered dose or nominal drug class. It instead emphasizes the dynamic relationship between pharmacological intervention and biological system response. The resulting framework provides a scientific basis for integrating evidence-based pharmacotherapy, pharmacovigilance, pharmacogenomics, precision medicine, and therapeutic drug monitoring into a coherent clinical strategy.

From a translational perspective, the analysis indicates that the future optimization of anticancer pharmacotherapy will depend increasingly upon longitudinal integration of molecular, pharmacokinetic, pharmacodynamic, clinical, and patient-reported information. Artificial intelligence, real-world evidence, liquid biopsy, quantitative systems pharmacology, and advanced biomarker platforms may improve risk prediction and therapeutic selection, but their implementation requires rigorous validation, transparent methodology, appropriate population representation, and continuous assessment of clinical utility. Technological sophistication should therefore complement, rather than replace, pharmacological reasoning and evidence-based clinical judgment.

The results and discussion establish that the principal challenge of modern oncology is not merely the discovery of increasingly potent anticancer agents, but the optimization of the therapeutic index at the individual-patient level. Effective pharmacotherapy requires identification of biologically appropriate targets, accurate characterization of drug exposure, prediction and surveillance of toxicity, recognition of genetic and molecular determinants of response, continuous assessment of resistance, and timely adaptation of treatment. An integrated pharmacological model therefore offers the most coherent foundation for maximizing antitumor benefit while reducing preventable medication-related harm and preserving quality of life throughout the cancer trajectory.

The clinical interpretation of anticancer medication safety must increasingly incorporate temporal, cumulative, and contextual dimensions of exposure. Toxicity may be immediate and dose related, delayed and immune mediated, cumulative and organ specific, or precipitated by an interaction that modifies systemic exposure. Accordingly, adverse-event assessment should not be restricted to isolated clinical observations but should be embedded within longitudinal medication histories and serial laboratory, functional, imaging, and patient-reported assessments. This approach permits recognition of evolving toxicity trajectories and facilitates earlier intervention before reversible pharmacological injury progresses to persistent organ dysfunction. It also reinforces the importance of distinguishing pharmacological toxicity from symptoms attributable to malignant disease, infection, nutritional compromise, psychological stress, or supportive medications.

The integrated pharmacological perspective further demonstrates the importance of treatment sequencing in determining both efficacy and safety. Previous exposure to cytotoxic chemotherapy, targeted agents, endocrine therapy, immunotherapy, or radiotherapy can modify subsequent therapeutic response and toxicity through residual organ injury, altered tumor biology, immune modulation, or selection of resistant clones. Consequently, the pharmacological history of the patient constitutes an essential component of contemporary therapeutic assessment. Treatment decisions should incorporate cumulative anthracycline or platinum exposure where relevant, previous immune-related toxicity, prior targeted-therapy resistance mechanisms, persistent neuropathy or marrow suppression, and other clinically meaningful treatment sequelae. Such longitudinal characterization supports safer therapeutic sequencing and more rational selection of subsequent lines of therapy.

Another important observation is that the therapeutic index of an anticancer medicine is dynamic rather than fixed. The balance between efficacy and toxicity may change as tumor burden decreases, organ function deteriorates or improves, resistance develops, concomitant therapies are introduced, or the patient's goals of care evolve. A dose that is appropriate during one phase of treatment may become excessive or insufficient during another. Precision pharmacotherapy therefore requires repeated reassessment rather than a single dose-selection event. This adaptive principle is particularly relevant to chronic oral targeted therapies and maintenance regimens, in which prolonged exposure may generate cumulative toxicity that is not apparent during initial treatment cycles.

The analysis also highlights the growing importance of interdisciplinary pharmacological governance. Safe oncology practice requires coordination among oncologists, clinical pharmacologists, pharmacists, nurses, laboratory specialists, pathologists, molecular geneticists, and other professionals. Such collaboration enables integration of medication histories, molecular diagnostic findings, laboratory parameters, pharmacokinetic information, adverse-event assessments, and patient preferences. Clinical pharmacy involvement is particularly valuable in medication reconciliation, interaction screening, adherence assessment, supportive-care optimization, dose adjustment, and adverse-event management. Interdisciplinary governance consequently transforms medication safety from an individual prescribing responsibility into a continuous quality-assurance process embedded within the oncology care pathway.

The evidence further supports the development of structured pharmacovigilance systems capable of linking spontaneous reports with clinical and molecular information. Conventional signal detection identifies disproportionate reporting patterns, whereas integrated approaches may additionally examine patient-level risk factors, dose, and duration of exposure, concomitant therapies, laboratory abnormalities, and biological plausibility. Advanced pharmacovigilance can therefore move progressively from retrospective detection toward prospective risk prediction. Nevertheless, predictive safety models should remain subject to external validation and clinical oversight, because associations derived from large observational datasets may reflect confounding, surveillance intensity, treatment-selection effects, or differences in healthcare utilization.

From the perspective of pharmacogenomics, the most clinically meaningful strategy is not universal genetic testing but targeted implementation where genetic information has sufficient predictive value to alter management. The interpretation of genetic findings should be contextualized by ancestry-independent functional evidence, phenotype, concomitant medications, organ function, and the specific therapeutic objective. Moreover, somatic tumor profiling and germline testing should be conceptually and clinically distinguished, while recognizing that both may contribute to treatment selection and safety assessment. The integration of molecular data into clinical pharmacology should therefore follow validated clinical pathways and avoid overinterpretation of variants whose functional or therapeutic significance remains uncertain.

The study support a model of modern oncology in which pharmacotherapy is treated as a dynamic feedback system. Drug administration produces measurable pharmacological exposure and biological effects; biomarkers and clinical observations characterize response and toxicity; these observations inform subsequent dose modification or treatment selection; and pharmacovigilance continuously updates the understanding of medication-associated risks. Therapeutic drug monitoring, when justified, provides quantitative exposure information, whereas pharmacogenomics and tumor profiling provide biological determinants of variability. Their integration creates a progressively individualized therapeutic cycle in which treatment decisions are continuously refined according to emerging patient-specific evidence.

The comparative pharmacological assessment further indicates that anticancer medication classes differ substantially in their relationship between molecular target engagement and clinical toxicity. Classical cytotoxic agents generally demonstrate broad biological activity against proliferating cells, producing characteristic dose-limiting toxicities that are often related to tissue turnover. By contrast, molecularly targeted therapies may exhibit a narrower mechanistic spectrum but can generate highly characteristic toxicities reflecting physiological functions of the inhibited target. This distinction is clinically consequential because mechanism-based toxicity can frequently be anticipated from target biology and may therefore be incorporated into baseline risk assessment, monitoring protocols, and preventive pharmacotherapy. The increasingly detailed molecular characterization of anticancer agents consequently creates opportunities not only for improved efficacy but also for mechanistically informed safety management.

The analysis of DNA-damaging therapies demonstrates the continuing clinical relevance of pharmacological injury to genomic integrity. Alkylating agents and platinum compounds generate DNA lesions that interfere with replication and transcription, while topoisomerase inhibitors stabilize DNA–enzyme complexes and induce strand-break-associated cytotoxicity. Antimetabolites interfere with nucleotide synthesis or incorporation, thereby generating replication stress and impaired DNA synthesis. These mechanisms explain the therapeutic vulnerability of rapidly dividing malignant cells but also account for marrow suppression and gastrointestinal toxicity. Importantly, DNA damage may also contribute to delayed adverse consequences, including organ-specific injury and, in certain therapeutic contexts, secondary

malignant transformation. Accordingly, risk assessment should consider both immediate dose-limiting effects and the cumulative biological consequences of treatment.

Microtubule-directed agents provide another mechanistically distinctive pharmacological group. By interfering with microtubule polymerization or depolymerization, these agents disrupt mitotic spindle function and intracellular trafficking. Their therapeutic effects demonstrate the continuing importance of cell-cycle dependence in cancer pharmacotherapy, while peripheral neurotoxicity, myelosuppression, and other adverse effects illustrate the consequences of microtubule dependence in normal tissues. The clinical management of such toxicity requires attention to cumulative exposure, baseline neurological function, interacting neurotoxic medicines, and functional impairment. Dose modification based on toxicity should therefore be interpreted not simply as a reduction in treatment intensity but as an evidence-based strategy for preserving the therapeutic index.

Endocrine pharmacotherapy illustrates a different model of therapeutic selectivity. Hormone-dependent malignancies may remain dependent upon estrogenic, androgenic, or other endocrine signaling for proliferation and survival. Pharmacological suppression of hormone synthesis or antagonism of hormone receptors can consequently inhibit tumor growth without the generalized cytotoxicity associated with conventional chemotherapy. Nevertheless, endocrine manipulation modifies physiological systems throughout the body and may produce metabolic, skeletal, cardiovascular, reproductive, or constitutional adverse effects. Long-term treatment therefore requires risk stratification and monitoring extending beyond conventional tumor-response assessment. The benefit–risk evaluation of endocrine therapy must incorporate expected duration of treatment and the cumulative consequences of sustained hormonal modulation.

Targeted kinase inhibitors and related signal-transduction modulators demonstrate the increasingly complex relationship between molecular precision and pharmacological safety. Kinases participate in numerous normal cellular functions, including proliferation, differentiation, metabolism, vascular regulation, and immune signaling. Consequently, inhibition of a disease-associated kinase may also alter physiological pathways in nonmalignant tissues. Furthermore, many targeted inhibitors interact with metabolic enzymes and transporters, creating potential for clinically important pharmacokinetic interactions. The resulting variability in exposure may be particularly important for oral targeted therapies, where adherence, food effects, enzyme inhibition or induction, and genetic variation can materially influence systemic concentrations. These considerations strengthen the rationale for structured medication review and individualized exposure assessment.

Monoclonal antibodies and other biologic anticancer therapies introduce additional pharmacological considerations related to target specificity, immunogenicity, distribution, and elimination. Their disposition differs from that of many small-molecule drugs because biological factors such as target-mediated disposition, proteolytic catabolism, antigen expression, and immune-mediated clearance may influence exposure. Infusion-related reactions, hypersensitivity phenomena, immune modulation, and target-specific toxicities require appropriate clinical surveillance. Antibody–drug conjugates further complicate this pharmacological landscape because their therapeutic effects depend on coordinated target recognition, internalization, intracellular processing, and release of a potent cytotoxic payload. Safety assessment must therefore consider both the biological targeting component and the pharmacology of the delivered payload.

Immune checkpoint inhibition represents a particularly important example of pharmacology in which therapeutic efficacy depends on modulation of host biology rather than direct pharmacological destruction of tumor cells. The restoration of antitumor immune activity can generate durable responses in selected patients, but the same mechanism may disrupt physiological immune tolerance. Immune-related adverse events can therefore involve multiple

organ systems and may occur during treatment or after exposure has ended. Their management requires early recognition, exclusion of alternative causes, grading of severity, appropriate interruption or continuation of therapy, and mechanism-directed immunosuppression when clinically indicated. The pharmacovigilance framework for immunotherapy must consequently incorporate delayed and multisystem events that differ fundamentally from classical chemotherapy toxicity.

The analysis also emphasizes the pharmacological significance of supportive-care therapy as a determinant of overall treatment safety. Antiemetics, hematopoietic growth factors, analgesics, corticosteroids, antimicrobial agents, anticoagulants, bone-directed therapies, and other interventions may prevent or reduce complications of cancer treatment, but they can also generate adverse effects and interactions. Supportive pharmacotherapy should therefore be integrated into the same medication-safety architecture as antineoplastic treatment. Failure to account for supportive medications may result in incomplete assessment of total pharmacological exposure and inaccurate attribution of adverse events.

Another major finding concerns the importance of organ function in individualized dose selection. Hepatic and renal impairment can alter clearance of anticancer medicines and their active metabolites, potentially increasing exposure and toxicity. Conversely, excessive dose reduction may result in subtherapeutic exposure and treatment failure. Static laboratory thresholds are therefore not always sufficient to characterize pharmacological capacity, particularly in patients with rapidly changing clinical status. Serial assessment of renal, hepatic, hematological, and metabolic parameters can provide a more accurate representation of evolving drug disposition. Where validated, pharmacokinetic modeling can supplement these measurements and improve dose individualization.

Body composition represents an additional source of pharmacokinetic variability. Cancer-associated weight loss, sarcopenia, obesity, edema, ascites, and altered plasma protein concentrations may affect drug distribution and free-drug exposure. Traditional dosing approaches based exclusively on body weight or body-surface area may consequently provide imperfect estimates of pharmacologically relevant exposure for selected agents. This observation does not imply that conventional dosing should be universally abandoned; rather, it demonstrates the importance of identifying situations in which body composition and physiological variability meaningfully influence pharmacokinetics. Precision dosing strategies should therefore be applied selectively according to the strength of exposure–response evidence.

The results further indicate that adherence constitutes a pharmacological variable rather than merely a behavioral consideration. For oral anticancer therapies, missed doses, incorrect administration, inappropriate timing relative to food, and premature discontinuation can substantially alter exposure and therapeutic effectiveness. Conversely, persistent administration despite clinically significant toxicity can increase cumulative harm. Medication adherence should therefore be monitored together with tolerability and treatment response. Patient education, pharmacist-led counseling, simplified regimens, digital support, and regular medication review may improve both adherence and safety when appropriately implemented.

Quality of life should also be incorporated into pharmacological evaluation because toxicity that does not meet conventional definitions of severe organ injury may nevertheless have substantial clinical significance. Persistent fatigue, neuropathy, cognitive symptoms, mucosal disorders, dermatological effects, sexual dysfunction, sleep disturbance, and gastrointestinal symptoms can influence functional independence, employment, social participation, and willingness to continue therapy. Patient-reported outcomes can complement clinician-graded toxicity by capturing dimensions of treatment burden that may otherwise remain underrecognized. A patient-centered pharmacological framework therefore evaluates not only survival and tumor response but also the functional consequences of adverse effects.

The synthesis further suggests that therapeutic response should be interpreted using multiple endpoints rather than a single measure of tumor size. Objective response, progression-free survival, overall survival, biomarker dynamics, symptom control, and patient-reported outcomes provide complementary information. Pharmacodynamic biomarkers may reveal biological activity before radiographic changes become apparent, while molecular monitoring may identify emerging resistance. Conversely, radiographic stability may not always correspond to biological inactivity, particularly with treatments that alter tumor metabolism, immune infiltration, or cellular composition. Integrated response assessment is therefore increasingly important for interpreting the pharmacological consequences of treatment.

The relationship between dose intensity and clinical benefit is similarly complex. Increasing dose does not invariably increase therapeutic benefit because pharmacodynamic saturation, target occupancy, resistance mechanisms, or toxicity-related treatment interruptions may limit the incremental value of greater exposure. In some circumstances, excessive exposure may reduce overall treatment effectiveness by necessitating prolonged interruptions or discontinuation. The optimal regimen should therefore be defined by the exposure associated with the best achievable balance of efficacy and tolerability rather than by maximal tolerated exposure alone. This principle provides an important conceptual foundation for precision dosing and exposure-guided pharmacotherapy.

The analysis of combination therapy demonstrates that pharmacological synergy should be distinguished from simple additive activity. Mechanistically complementary agents may produce enhanced antitumor effects when administered in an appropriate sequence or schedule, but interactions at the level of metabolism, transport, target signaling, or tissue toxicity may compromise the therapeutic index. Pharmacological modeling can assist in evaluating these relationships by integrating concentration–effect data and identifying optimal scheduling. The rational development of combination regimens should therefore consider mechanistic complementarity, resistance suppression, exposure overlap, organ-specific toxicity, and feasibility of clinical monitoring.

Pharmacovigilance is particularly important when combination regimens contain multiple agents with overlapping or interacting toxicities. Attribution of causality becomes more difficult as the number of concomitant therapies increases, and conventional spontaneous-reporting systems may not adequately capture the complexity of treatment exposure. Structured clinical documentation of treatment cycles, dose modifications, concomitant medications, laboratory trends, and adverse-event timing can improve causal assessment. Advanced analytical approaches may further distinguish background disease-related symptoms from treatment-associated signals. Such improvements are essential for generating clinically actionable safety information from complex oncology populations.

The synthesis additionally demonstrates that medication safety is influenced by transitions between healthcare settings. Patients may move between outpatient oncology clinics, inpatient units, emergency departments, primary care services, and specialist consultations while continuing complex anticancer regimens. Incomplete communication concerning treatment schedules, recent toxicities, dose changes, or supportive medications can create opportunities for medication errors. Continuity of medication information is therefore a fundamental pharmacovigilance requirement. Electronic reconciliation, standardized treatment summaries, and multidisciplinary communication can reduce preventable discrepancies and support safer transitions of care.

Another important dimension is the role of patient education in pharmacological risk minimization. Patients receiving anticancer medications should understand the purpose of treatment, administration requirements, important interactions, expected adverse effects, warning symptoms, and circumstances requiring urgent medical evaluation. Education is

particularly important for oral therapies and immune-modulating agents, where clinically significant adverse effects may develop outside direct clinical supervision. Effective education transforms patients and caregivers into active participants in pharmacovigilance by facilitating earlier recognition and reporting of potentially serious medication-related events.

The emerging integration of artificial intelligence into oncology pharmacology creates opportunities for individualized prediction but also introduces methodological limitations. Machine-learning models may identify complex nonlinear relationships among genomic characteristics, drug exposure, clinical phenotype, and adverse outcomes that are difficult to detect using conventional statistical methods. However, predictive performance may decline when models are transferred between institutions or populations because of differences in data quality, treatment practices, laboratory measurement, and patient characteristics. External validation, calibration, interpretability, and prospective clinical evaluation are therefore essential before algorithmic predictions are incorporated into therapeutic decision-making.

Real-world evidence can additionally contribute to understanding medication safety across broader and more heterogeneous populations. Older adults, patients with multiple comorbidities, individuals with organ dysfunction, and patients receiving multiple concurrent medications may be underrepresented in clinical trials. Observational data can provide important information regarding treatment persistence, dose reductions, hospitalization, emergency care, delayed toxicity, and outcomes under routine conditions. However, causal inference requires rigorous methodological adjustment because treatment allocation in routine practice is nonrandom. The most reliable framework therefore combines randomized evidence with carefully analyzed real-world data rather than treating either source as universally sufficient.

Fundamental pharmacological mechanisms provide biological plausibility; preclinical studies establish preliminary activity and toxicity; early-phase clinical trials characterize dose, exposure, pharmacokinetics, pharmacodynamics, and safety; randomized trials establish comparative efficacy and safety; biomarker studies define populations with differential benefit; and post-marketing pharmacovigilance evaluates uncommon, delayed, and real-world risks. Pharmacogenomics and therapeutic drug monitoring can subsequently refine individual treatment where sufficient clinical evidence exists. This continuum emphasizes that precision oncology is not a replacement for evidence-based medicine but an increasingly sophisticated extension of it.

An overarching implication is that modern anticancer pharmacotherapy should be conceptualized as an adaptive, multidisciplinary, and continuously monitored therapeutic process. The optimal intervention is determined not only by tumor histology or molecular target but by the interaction among pharmacological mechanism, drug exposure, host characteristics, tumor evolution, concomitant treatment, adherence, and patient-defined therapeutic priorities. This integrated model provides a stronger scientific basis for balancing efficacy and toxicity than approaches centered on isolated drug characteristics. It also establishes a framework for progressively incorporating validated innovations in pharmacogenomics, therapeutic drug monitoring, molecular diagnostics, quantitative pharmacology, and computational safety science into routine oncology practice.

Monitoring strategies in modern anticancer pharmacotherapy constitute a multidimensional clinical and pharmacological framework designed to optimize therapeutic efficacy, detect adverse drug reactions at the earliest clinically meaningful stage, prevent avoidable toxicity, and individualize treatment according to patient-, disease-, and drug-specific determinants. Because anticancer agents frequently possess narrow therapeutic indices and substantial interindividual variability in pharmacokinetics and pharmacodynamics, systematic monitoring should extend beyond conventional assessment of tumor response and encompass laboratory parameters, organ function, drug exposure, pharmacogenomic determinants, immune-mediated toxicity, treatment

adherence, drug–drug interactions, and patient-reported outcomes. The contemporary approach therefore conceptualizes monitoring as a continuous feedback process linking treatment initiation, exposure assessment, toxicity surveillance, therapeutic response, dose optimization, and long-term safety evaluation.

Baseline assessment should precede the initiation of systemic anticancer therapy. A comprehensive medical and medication history should identify previous chemotherapy, radiotherapy, immunotherapy, targeted therapy, allergies, comorbidities, renal and hepatic dysfunction, cardiovascular disease, neurological disorders, autoimmune conditions, and concomitant medications. Baseline complete blood count, serum creatinine and estimated glomerular filtration rate, hepatic biochemical parameters, electrolyte concentrations, coagulation indices when clinically indicated, and other drug-specific laboratory investigations provide reference values against which treatment-related changes can subsequently be interpreted. In selected patients, baseline electrocardiography, echocardiography, pulmonary-function testing, neurological assessment, ophthalmological examination, or infectious-disease screening may be required depending on the pharmacological characteristics of the anticancer agent.

Hematological monitoring is particularly important for cytotoxic chemotherapy and selected targeted agents. Serial assessment of hemoglobin, leukocyte count, absolute neutrophil count, platelet count, and differential leukocyte count enables early recognition of myelosuppression. The severity of neutropenia, thrombocytopenia, and anemia should be graded according to standardized toxicity criteria and interpreted in relation to treatment cycle, cumulative exposure, patient comorbidities, and concomitant medications. Clinically significant neutropenia requires evaluation of infection risk, while febrile neutropenia represents a potentially life-threatening complication requiring immediate clinical intervention. Monitoring strategies may therefore incorporate dose modification, treatment delay, antimicrobial management, and, when appropriate, granulocyte colony-stimulating factor support.

Renal monitoring is essential for nephrotoxic anticancer agents, particularly platinum compounds. Serum creatinine, estimated glomerular filtration rate, urine output, electrolyte concentrations, and, in selected circumstances, more specialized measures of renal tubular injury should be considered. Cisplatin-associated nephrotoxicity illustrates the importance of integrating laboratory surveillance with preventive pharmacotherapy, including appropriate hydration and electrolyte management. Renal function should also be incorporated into dose calculations for agents predominantly eliminated through the kidneys because declining clearance may increase systemic exposure and toxicity.

Hepatic monitoring is similarly critical because numerous anticancer agents undergo hepatic metabolism and biliary elimination. Alanine aminotransferase, aspartate aminotransferase, alkaline phosphatase, total bilirubin, albumin, and other clinically appropriate parameters should be monitored according to the hepatotoxicity profile of the administered drug. Particular attention is required when patients receive multiple hepatically metabolized agents or have pre-existing liver disease. Abnormal biochemical findings should be interpreted in conjunction with clinical symptoms and possible alternative causes, including tumor infiltration, viral hepatitis, biliary obstruction, infection, alcohol exposure, and concomitant hepatotoxic medications.

Cardiovascular monitoring has become increasingly important with the expansion of anthracyclines, HER2-directed therapies, vascular endothelial growth factor pathway inhibitors, tyrosine kinase inhibitors, and other targeted therapies. Patients receiving potentially cardiotoxic treatment may require baseline and serial assessment of left ventricular ejection fraction, electrocardiographic parameters, blood pressure, symptoms of heart failure, and selected cardiac biomarkers. Anthracycline exposure is particularly associated with cumulative myocardial injury, whereas HER2-directed therapy may produce potentially reversible ventricular dysfunction.

Consequently, longitudinal cardiovascular surveillance should be individualized according to baseline cardiovascular risk, cumulative drug exposure, treatment combinations, and previous cardiotoxic therapy.

Neurological monitoring is necessary for agents associated with peripheral or central neurotoxicity, including platinum compounds, taxanes, vinca alkaloids, proteasome inhibitors, and selected antibody–drug conjugates. Assessment should include sensory symptoms, motor function, reflexes, gait, functional impairment, and pain. Early recognition of chemotherapy-induced peripheral neuropathy can permit dose modification before irreversible neurological injury develops. Patient-reported symptom scales may complement clinical examination and improve detection of subtle functional deterioration.

Gastrointestinal and nutritional monitoring should also form part of comprehensive surveillance. Nausea, vomiting, diarrhea, constipation, mucositis, anorexia, dysgeusia, and weight loss can substantially compromise treatment tolerance and adherence. Regular evaluation of body weight, hydration status, nutritional intake, electrolyte balance, and gastrointestinal symptoms allows supportive treatment to be initiated promptly. Antiemetic prophylaxis, fluid replacement, nutritional intervention, and management of treatment-related diarrhea or mucositis should be integrated into the monitoring pathway rather than implemented only after severe toxicity develops.

Targeted anticancer therapies require drug-specific monitoring because their toxicity profiles frequently differ from those of traditional cytotoxic chemotherapy. For example, kinase inhibitors may require surveillance of blood pressure, cardiac electrophysiology, hepatic function, dermatological toxicity, endocrine parameters, or specific laboratory biomarkers. EGFR inhibitors may cause dermatological and gastrointestinal adverse effects, whereas BRAF/MEK inhibitors can require cardiovascular, ocular, dermatological, hepatic, and musculoskeletal surveillance. The monitoring plan should therefore be pharmacologically aligned with the molecular target and mechanism of action of the specific therapeutic agent.

Immune checkpoint inhibitors have introduced another major dimension of pharmacovigilance. Treatment with PD-1, PD-L1, or CTLA-4 inhibitors may produce immune-related adverse events involving virtually any organ system. Monitoring should therefore include clinical assessment for dermatological, gastrointestinal, hepatic, pulmonary, endocrine, renal, neurological, cardiovascular, and rheumatological manifestations. Thyroid-stimulating hormone and thyroid hormone concentrations, hepatic enzymes, renal function, glucose concentrations, and other laboratory parameters should be assessed periodically. Importantly, immune-related adverse events may occur during treatment or after treatment discontinuation, necessitating continued clinical vigilance.

Therapeutic drug monitoring represents an additional strategy for selected anticancer medications in which circulating drug exposure correlates sufficiently with efficacy or toxicity to support individualized dosing. Pharmacokinetic monitoring can be particularly informative for drugs characterized by substantial interpatient variability, nonlinear pharmacokinetics, narrow therapeutic windows, or clinically relevant exposure–response relationships. The integration of measured drug concentrations with pharmacokinetic modeling, Bayesian forecasting, population pharmacokinetics, and patient-specific covariates can facilitate individualized dose adjustment. TDM should not, however, be applied indiscriminately to all anticancer agents; its clinical value depends on the strength of evidence linking drug exposure to therapeutic outcomes or toxicity.

Pharmacogenomic monitoring complements pharmacokinetic surveillance by identifying inherited genetic variants that influence drug metabolism, transport, target sensitivity, or toxicity. Clinically relevant examples include DPYD-associated susceptibility to severe fluoropyrimidine toxicity, UGT1A1 variation affecting irinotecan metabolism, TPMT and NUDT15 variation influencing thiopurine toxicity, and pharmacogenomic determinants affecting selected endocrine and

targeted therapies. Incorporating validated pharmacogenomic information into prescribing decisions can reduce preventable toxicity and support precision dosing. Genetic information should nevertheless be interpreted in conjunction with clinical factors, renal and hepatic function, concomitant medications, disease characteristics, and measured treatment response.

Drug–drug interaction monitoring is another essential component of anticancer pharmacotherapy. Oncology patients frequently receive multiple medications, including antiemetics, analgesics, antimicrobials, anticoagulants, corticosteroids, antiepileptic agents, cardiovascular drugs, and complementary medicines. Cytochrome P450 enzymes, UDP-glucuronosyltransferases, drug transporters, and renal elimination pathways can be affected by concomitant treatment. A structured medication reconciliation process should therefore be conducted at treatment initiation and repeated during therapy. Clinically significant interactions may necessitate substitution of concomitant medications, modification of anticancer therapy, enhanced laboratory monitoring, or TDM.

Therapeutic response monitoring should occur concurrently with toxicity surveillance. Radiological assessment using appropriate imaging modalities, pathological evaluation where indicated, molecular biomarkers, tumor markers, and clinical examination can be incorporated according to tumor type and treatment strategy. The objective is not simply to determine whether a tumor has decreased in size but to establish whether the pharmacological intervention is producing clinically meaningful disease control. In targeted and immunological therapies, conventional radiological criteria may occasionally require complementary interpretation because atypical response patterns can occur.

Patient-reported outcomes constitute an increasingly important component of modern monitoring strategies. Symptoms such as fatigue, pain, neuropathy, nausea, diarrhea, cognitive impairment, sleep disturbance, and functional limitations may not be fully captured through conventional laboratory or imaging surveillance. Electronic patient-reported outcome systems can facilitate real-time identification of deteriorating symptoms and potentially enable earlier intervention. Such approaches shift pharmacovigilance from a predominantly clinician-observed model toward a patient-centered surveillance framework.

Long-term monitoring is also required because some anticancer toxicities are cumulative, delayed, or persistent after treatment completion. Survivorship surveillance should address cardiovascular disease, endocrine dysfunction, renal impairment, neurological complications, secondary malignancies, fertility-related consequences, psychological effects, and persistent treatment-related symptoms where relevant. The monitoring framework should consequently extend beyond the treatment period and incorporate appropriate follow-up based on cumulative exposure and the known late-toxicity profile of the therapeutic regimen.

The optimal monitoring of anticancer pharmacotherapy requires integration of clinical surveillance, laboratory monitoring, pharmacokinetic assessment, therapeutic drug monitoring, pharmacogenomics, pharmacovigilance, drug–drug interaction evaluation, imaging-based response assessment, patient-reported outcomes, and longitudinal survivorship follow-up. Such an integrated strategy transforms monitoring from a reactive approach to adverse-event detection into a proactive precision-medicine system. The ultimate objective is to maintain an appropriate therapeutic index by maximizing antitumor efficacy while minimizing preventable toxicity, thereby supporting evidence-based, individualized, and pharmacologically rational cancer treatment.

## CONCLUSION

The present scientific synthesis demonstrates that contemporary anticancer pharmacotherapy has evolved from predominantly nonspecific cytotoxic intervention toward a complex, molecularly informed, mechanism-oriented, and increasingly individualized therapeutic discipline. The

diversity of cytotoxic agents, endocrine therapies, molecularly targeted medicines, biologics, immune checkpoint inhibitors, antibody–drug conjugates, epigenetic therapies, radiopharmaceuticals, and cellular approaches necessitates an integrated understanding of pharmacodynamics, pharmacokinetics, therapeutic mechanisms, exposure–response relationships, adverse reactions, and long-term toxicity. Pharmacological safety must consequently be regarded as a dynamic clinical process encompassing prediction, prevention, detection, characterization, monitoring, and management of treatment-related risks. Pharmacovigilance provides the essential infrastructure for identifying uncommon, delayed, cumulative, and real-world adverse events, while evidence-based medicine establishes the methodological basis for evaluating efficacy and risk–benefit relationships. Pharmacogenomics and tumor molecular profiling further enable recognition of patient- and disease-specific determinants of therapeutic response and toxicity, whereas personalized medicine integrates these biological characteristics with clinical phenotype, comorbidity, organ function, previous treatment, and patient priorities. Therapeutic drug monitoring and pharmacokinetic–pharmacodynamic modeling offer additional opportunities for precision dosing in appropriately selected medicines. These approaches support a transition from population-average treatment toward adaptive precision pharmacotherapy in which drug selection, dosing, monitoring, and modification are continuously informed by molecular, pharmacological, and clinical evidence. The ultimate objective of modern oncology is therefore not simply to maximize antitumor drug potency, but to optimize the individual therapeutic index, minimize preventable toxicity, preserve adherence and quality of life, delay therapeutic resistance, and achieve durable clinical benefit. The progress will depend upon rigorous integration of pharmacology, pharmacovigilance, pharmacogenomics, precision medicine, real-world evidence, biomarkers, quantitative modeling, and multidisciplinary clinical expertise, ensuring that technological innovation remains firmly anchored in validated evidence and patient-centered outcomes.

## RECOMMENDATIONS

The findings support the adoption of an integrated, multidisciplinary framework for the rational and safe use of anticancer medications across the continuum of oncology care. First, anticancer agents should be evaluated according to mechanism of action, molecular target, pharmacokinetic characteristics, exposure–response relationships, therapeutic index, and class-specific toxicity rather than through purely descriptive classification. Second, evidence-based prescribing should incorporate validated clinical guidelines, contemporary comparative evidence, patient-specific risk factors, comorbidities, organ function, previous treatment exposure, and clinically relevant drug interactions. Third, pharmacovigilance should be strengthened through systematic adverse-event reporting, active signal detection, longitudinal safety surveillance, patient-reported outcomes, and integration of real-world evidence with clinical data. Fourth, pharmacogenomic and tumor-molecular testing should be implemented selectively where robust evidence demonstrates clinical validity and utility, with careful distinction between germline and somatic findings. Fifth, therapeutic drug monitoring and pharmacokinetic–pharmacodynamic modeling should be considered for selected anticancer medicines when clinically established exposure–efficacy or exposure–toxicity relationships justify concentration-guided dose individualization. Sixth, multidisciplinary oncology teams should establish structured medication reconciliation and interaction-management procedures encompassing anticancer and supportive-care therapies, including nonprescription and complementary products. Seventh, patients and caregivers should receive individualized education regarding administration, adherence, expected adverse effects, warning signs, and appropriate reporting pathways. Finally, healthcare institutions should promote continuous professional education, standardized toxicity-management protocols, interoperable clinical documentation, and quality-improvement systems capable of linking

pharmacological exposure with therapeutic response and safety outcomes. Future research should prioritize prospective validation of precision-dosing strategies, clinically actionable biomarkers, pharmacogenomic algorithms, artificial-intelligence models, and integrated pharmacovigilance platforms to ensure that emerging technologies translate into demonstrable improvements in survival, safety, quality of life, and equitable access to effective cancer pharmacotherapy.

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## Biological Sciences

# Биология сабақтарында ерекше білім беру қажеттіліктері бар оқушыларды оқытуда цифрлық технологияларды қолдану әдістемесі

Жаханова Асем

7M01505-биология білім беру бағдарламасының 1 курс магистранты

Маусумбаева А.М

а/ш.ғ.к., оқытушы-дәріскер, І. Жансүгіров атындағы Жетісу университеті, Талдықорған қ, Қазақстан

### Аңдатпа

Мақалада инклюзивті білім беру жағдайында биология пәнін оқытудың теориялық және әдістемелік ерекшеліктері қарастырылған. Ерекше білім беру қажеттіліктері (ЕББҚ) бар оқушылардың танымдық белсенділігін арттыру мақсатында цифрлық технологияларды, визуалды модельдер мен интерактивті құралдарды қолдану жолдары ұсынылған.

**Кілт сөздер:** инклюзивті білім беру, биология, цифрлық технологиялар, ерекше білім беру қажеттіліктері, әдістеме, интерактивті құралдар.

### Аннотация

В статье рассматриваются теоретические и методические особенности преподавания биологии в условиях инклюзивного образования. Предложены пути использования цифровых технологий, интерактивных 3D-моделей и виртуальных лабораторий с целью повышения познавательной активности учащихся с особыми образовательными потребностями (ООП).

**Ключевые слова:** инклюзивное образование, биология, цифровые технологии, особые образовательные потребности, методика, интерактивные инструменты.

### Abstract

The article discusses the theoretical and methodological features of teaching biology in the context of inclusive education. Ways of using digital technologies, interactive 3D models, and virtual laboratories to increase the cognitive activity of students with special educational needs (SEN) are proposed.

**Keywords:** inclusive education, biology, digital technologies, special educational needs, methodology, interactive tools.

### Кіріспе

Қазіргі білім беру кеңістігінде инклюзивті ортаны қалыптастыру және әрбір баланың жеке қабілетіне сай сапалы білім алуын қамтамасыз ету басты міндеттердің бірі болып табылады. Әсіресе, жаратылыстану ғылымдары, соның ішінде биология пәнін ерекше білім беру қажеттіліктері (ЕББҚ) бар оқушыларға меңгерту өзіндік күрделіліктерді туындайды. Биология күрделі абстрактілі ұғымдарды, микро және макро дүние процестерін түсінуді талап

ететіндіктен, дәстүрлі оқыту әдістері әрқашан тиімді бола бермейді. Осы орайда цифрлық технологияларды оқу үрдісіне енгізу — оқытудың қолжетімділігін арттырып қана қоймай, оқушылардың пәнге деген қызығушылығын оятудың қуатты құралына айналуға.

#### **Негізгі бөлім: Цифрлық технологиялардың маңызы мен әдістемесі**

Инклюзивті сыныптарда биология сабақтарын ұйымдастыру кезінде келесі цифрлық құралдар мен әдістерді қолдану ерекше нәтиже береді:

1. **Визуализация және 3D модельдер:** Анатомиялық құрылымдарды, клетканың құрылысын немесе экожүйелерді интерактивті 3D форматта көрсету ЕББҚ бар оқушылардың кеңістіктік ойлауын дамытып, ақпаратты қабылдауын жеңілдетеді.
2. **Виртуалды зертханалар:** Күрделі немесе қауіпті биологиялық тәжірибелерді виртуалды ортада орындау мүмкіндігі оқушылардың өз бетімен жұмыс істеу дағдыларын қалыптастырады.
3. **Бейімделген мультимедиялық платформалар:** Дыбыстық сүйемелдеуі, субтитрлері және жеке қарқынға бейімделу мүмкіндігі бар бағдарламалар көру немесе есту қабілетінде ерекшелігі бар балаларға материалды толық меңгеруге жағдай жасайды.

#### **Практикалық бөлім: Биология сабақтарында қолданылатын цифрлық құралдар мен оларды қолдану әдістемесі**

Инклюзивті сыныптарда цифрлық технологияларды тиімді кіріктіру үшін оларды жүйелі түрде пайдалану қажет. Төмендегі **1-кестеде** биология сабақтарында ерекше білім беру қажеттіліктері (ЕББҚ) бар оқушыларға арналған негізгі цифрлық құралдар мен олардың әдістемелік маңызы көрсетілген.

##### **1-кесте. Биология сабақтарында қолданылатын негізгі цифрлық құралдар**

Әдістемелік тұрғыдан бұл құралдарды қолдану барысында мұғалім мынадай дидактикалық қағидаттарды басшылыққа алуы тиіс:

1. **Бейімділік (Адаптация):** Тапсырмалардың күрделілік деңгейі оқушының психофизиологиялық мүмкіндіктеріне қарай жеңілдетіледі.
2. **Көпсенсорлық тәсіл:** Ақпаратты бір мезгілде көру, есту және интерактивті түрде қабылдау арқылы есте сақтау қабілеті нығаяды.
3. **Жеке қарқын:** Цифрлық бағдарламалар әр оқушының өз жылдамдығымен жұмыс істеуіне жағдай жасайды.

Әдістемелік тұрғыдан алғанда, мұғалім цифрлық технологияларды пайдаланған кезде оқушының психофизиологиялық ерекшеліктерін ескеріп, тапсырмаларды дифференциациялауы (саралауы) қажет.

| Цифрлық құралдар түрі                      | Мысалдары / Бағдарламалар             | Әдістемелік маңызы мен ерекшелігі                                                                                                                                       |
|--------------------------------------------|---------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Интерактивті 3D модельдер мен визуализация | BioDigital Human, 3D Bear, Anatronica | Клетка құрылысы, анатомия және физиология процестерін көлемді түрде көрсету арқылы көру және қабылдау қабілеті бұзылған оқушылардың түсінігін жеңілдетеді.              |
| Виртуалды зертханалар мен симуляторлар     | PhET Interactive Simulations, Labster | Биологиялық тәжірибелер мен экологиялық үдерістерді қауіпсіз, виртуалды ортада орындауға мүмкіндік береді, моторлық дағдылары шектеулі балаларға балама жағдай жасайды. |
| Бейімделген мультимедиялық платформалар    | Wordwall, LearningApps, Kahoot        | Ойын түріндегі тапсырмалар мен тесттер арқылы оқушылардың пәнге деген қызығушылығын арттырып, танымдық белсенділігін ынталандырады.                                     |

1-кесте. Биология сабақтарында қолданылатын негізгі цифрлық құралдар

**Қорытынды** Қорытындылай келе, биология сабақтарында цифрлық технологияларды инклюзивті білім беру талаптарына сай қолдану — оқу үрдісінің сапасын арттырудың басты тетігі болып табылады. Интерактивті модельдер, виртуалды зертханалар және бейімделген платформалар арқылы ерекше білім беру қажеттіліктері бар оқушылардың пәнді терең меңгеруіне, әлеуметтенуіне және танымдық қабілеттерін дамытуға толық мүмкіндік туады. Болашақта бұл әдістемені пәнаралық байланыста және жаңа буын цифрлық оқулықтармен ұштастыра отырып жетілдіру — өзекті міндеттердің бірі.

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ӘОЖ 574

# БИОЛОГИЯ ПӘНІН ОҚЫТУДА АКТ-НЫ ИНТЕГРАЦИЯЛАУДЫҢ ӘДІСТЕМЕЛІК НЕГІЗДЕРІ

Жайсанбек Нұрсұлу Болысбекқызы

7M01505-биология білім беру бағдарламасының, 1 курс магистранты

Токпанов Еркін Аипович

география ғылымдарының кандидаты, І. Жансүгіров атындағы Жетісу университеті,  
Талдықорған қ., Қазақстан

## Аңдатпа

Бұл мақалада биология пәнін оқыту үдерісіне ақпараттық-коммуникациялық технологияларды (АКТ) интеграциялаудың әдістемелік негіздері қарастырылады. Қазіргі білім беру жүргісіндегі цифрландыру үрдісіне сәйкес, биологиялық үдерістерді модельдеу, виртуалды зертханаларды қолдану және интерактивті мультимедиялық ресурстардың тиімділігіне талдау жасалады. Зерттеу барысында АКТ-ны сабақтың әртүрлі кезеңдерінде пайдаланудың оқушылардың танымдық белсенділігін арттырудағы рөлі айқындалады. Автор биология пәнінің ерекшеліктеріне (микроәлемді көру, генетикалық есептер, физиологиялық процестер) негізделген әдістемелік тәсілдерді ұсынады. Мақаланың қорытындысы ретінде АКТ-ны жүйелі қолдану білім сапасын арттырып қана қоймай, болашақ мамандардың цифрлық құзыреттілігін қалыптастыруға мүмкіндік беретіні негізделген.

**Кілт сөздер:** биологияны оқыту, АКТ, интеграция, цифрлық білім беру, виртуалды модельдеу, әдістемелік негіздер, интерактивті оқыту.

## Аннотация

В данной статье рассматриваются методологические основы интеграции информационно-коммуникационных технологий (ИКТ) в процесс преподавания биологии. В соответствии с тенденцией цифровизации в современной системе образования проводится анализ моделирования биологических процессов, использования виртуальных лабораторий и эффективности интерактивных мультимедийных ресурсов. В ходе исследования была выявлена роль использования ИКТ на различных этапах урока в повышении познавательной активности учащихся. Автор предлагает методологические подходы, основанные на специфике биологии (визуализация микромира, генетические проблемы, физиологические процессы). В результате статьи обосновывается, что систематическое использование ИКТ не только повышает качество образования, но и позволяет сформировать цифровую компетентность будущих специалистов.

**Ключевые слова:** преподавание биологии, ИКТ, интеграция, цифровое образование, виртуальное моделирование, методологические основы, интерактивное обучение.

## Abstract

The article examines the methodological foundations of integrating information and communication technologies (ICT) into the process of teaching biology. In accordance with the trend of digitalization in the modern education system, an analysis of the modeling of biological processes, the use of virtual laboratories, and the effectiveness of interactive multimedia resources

is carried out. The study identifies the role of using ICT at various stages of the lesson in increasing the cognitive activity of students. The author proposes methodological approaches based on the specific features of biology (visualization of the microworld, genetic problems, physiological processes). As a result of the article, it is substantiated that the systematic use of ICT not only improves the quality of education but also allows for the formation of digital competence of future specialists.

**Key words:** biology teaching, ICT, integration, digital education, virtual modeling, methodological foundations, interactive learning.

### **Kіріспе**

Қазіргі цифрландыру дәуірінде білім беру жүйесі мен педагогикалық әдістемелер қарқынды трансформацияланып келеді. Бұндай өзгерістер әсіресе жаратылыстану бағытындағы пәндерді, соның ішінде биологияны оқыту әдістемесіне түбегейлі жаңа талаптар қойып отыр.

Зерттеу мақсаты: Биология пәнін оқытуда АКТ құралдарын қолданудың әдістемелік ерекшеліктерін айқындау және оларды оқу процесіне интеграциялау арқылы білім алушылардың пәндік құзыреттіліктерін арттырудың тиімді жолдарын негіздеу.

Зерттеу өзектілігі Ақпараттық технологиялар кеңістігінде қалыптасқан жаңа буын білім алушыларының танымдық қажеттіліктері мен ақпаратты қабылдау ерекшеліктерінің өзгеше болуы, оқу процесіне АКТ құралдарын терең интеграциялауды қажет етеді. Биология — тірі жүйелердегі күрделі динамикалық процестерді зерттейтін ғылым болғандықтан, оны дәстүрлі вербалды және статикалық көрнекілік әдістермен меңгертудің тиімділігі заманауи ақпараттық кеңістікте төмендеуде. Ақпараттық-коммуникациялық технологияларды (АКТ) оқу процесіне интеграциялаудың өзектілігі білім алушылардың когнитивті қабілеттерін дамыту, микроәлемдегі биологиялық құбылыстарды (молекулалық деңгейдегі биосинтез, жасушаның бөлінуі, генетикалық комбинаторика) виртуалды модельдеу және оқушылардың функционалдық сауаттылығын арттыру қажеттілігінен туындайды. АКТ құралдарын жүйелі пайдалану білім беру мазмұнын тереңдетіп, теориялық білім мен практикалық дағдылардың интеграциялануын қамтамасыз етеді.

### **Материалдар мен әдістер**

Зерттеу жұмысының әдістемелік негізі ретінде биология пәнін оқытудағы инновациялық технологиялардың тиімділігін айқындауға бағытталған кешенді тәсілдер қолданылды. Зерттеу барысында келесі материалдар мен әдістер жиынтығы пайдаланылды:

**1. Теориялық талдау және синтез әдісі:** Отандық және шетелдік ғылыми-әдістемелік әдебиеттерге, сондай-ақ заманауи білім беру стандарттарына шолу жасалды. АКТ-ны білім беруге интеграциялаудың негізгі тұжырымдамалары мен биологияны оқытудың дидактикалық принциптері сараланды.

**2. Эмпирикалық және салыстырмалы әдістер:** Биология сабақтарында жиі қолданылатын цифрлық платформалар мен бағдарламалық қамтамасыз ету құралдарының функционалдық мүмкіндіктеріне талдау жүргізілді. Атап айтқанда:

- **Виртуалды модельдеу:** *PhET Interactive Simulations* (Колорадо университеті) және *BioDigital Human* платформаларының биологиялық процестерді (фотосинтез, жасушалық тыныс алу) модельдеудегі рөлі қарастырылды.
- **Мультимедиялық ресурстар:** *BilimLand*, *Khan Academy* секілді білім беру порталдарындағы видео-дәрістер мен интерактивті тапсырмалардың дидактикалық әлеуеті зерттелді.

**3. Педагогикалық модельдеу:** АКТ құралдарын сабақтың әртүрлі кезеңдеріне (жаңа тақырыпты түсіндіру, бекіту, бақылау) интеграциялаудың оңтайлы алгоритмдері әзірленді.

Бұл ретте оқушылардың ақпаратты қабылдау деңгейін анықтау үшін сауалнамалар мен тест тапсырмаларының нәтижелері негізге алынды.

Зерттеу нысаны ретінде биология курсының «Жасушалық биология», «Молекулалық биология» және «Генетика» бөлімдері алынды, себебі бұл тараулар жоғары деңгейдегі абстрактілі ойлауды және микроқұрылымдарды визуалды түрде бейнелеуді талап етеді.

Зерттеу барысында қолданылған әдістемелік тәсілдер биология пәнін оқытуда АКТ-ны интеграциялаудың жоғары тиімділігін көрсетті. Жүргізілген жұмыстардың нәтижелері келесідей сипатталады:

**1. Теориялық талдау нәтижесі:** Биологиялық білім берудегі АКТ-ның рөлі жай ғана «көрнекілік» деңгейінен «зерттеушілік» деңгейіне өткені анықталды. Талдау көрсеткендей, АКТ-ны қолдану оқу материалын игеру жылдамдығын 25-30%-ға жеделдетеді, себебі күрделі биохимиялық циклдерді (мысалы, Кребс циклі) статикалық мәтінге қарағанда динамикалық модель арқылы қабылдау жеңілірек.

**2. Салыстырмалы әдіс нәтижесі:** Дәстүрлі оқыту әдісі мен АКТ-ны интеграциялаған оқыту әдісін салыстыру барысында білім алушылардың көрсеткіштерінде айтарлықтай айырмашылық байқалды. АКТ құралдарын (PhET, BilimLand) жүйелі пайдаланған топтарда материалды түсіну деңгейі мен практикалық тапсырмаларды орындау сапасы жоғары болды.

**3. Педагогикалық модельдеу нәтижесі:** Әзірленген интеграциялау алгоритмі негізінде сабақ құрылымына цифрлық элементтер енгізілді. Нәтижесінде оқушылардың танымдық белсенділігінің өсу динамикасы байқалды (Диаграмма 1).

| Көрсеткіштер                        | АКТ-ға дейін | АКТ-ны интеграциялағаннан кейін |
|-------------------------------------|--------------|---------------------------------|
| Пәнге деген қызығушылық             | 45%          | 85%                             |
| Өз бетінше зерттеу жүргізу дағдысы  | 30%          | 65%                             |
| Күрделі тақырыптарды меңгеру сапасы | 40%          | 75%                             |

Диаграмма 1. АКТ-ны интеграциялаудың оқушылардың танымдық көрсеткіштеріне әсері (%)  
Диаграмма мәліметтері көрсеткендей, ең үлкен өсім пәнге деген қызығушылық (40%-ға артқан) мен күрделі тақырыптарды меңгеру сапасында байқалады. Бұл биологиялық нысандарды виртуалды түрде манипуляциялау мүмкіндігінің тікелей нәтижесі.

#### Негізгі бөлім

Биология пәнін оқытудағы ақпараттық-коммуникациялық технологиялардың рөлі туралы ғылыми әдебиеттерде білім беру мазмұнын визуализациялау және дидактикалық процесті цифрлық трансформациялаудың негізгі құралы деп түсіндіріледі. И.В. Роберттің ғылыми пайымдауынша, АКТ-ны интеграциялау — бұл тек техникалық жабдықтарды қолдану емес, бұл оқушы мен мұғалім арасындағы кері байланысты нығайтатын және күрделі биологиялық заңдылықтарды танымдық тұрғыдан жеңілдететін кешенді жүйе [5].

Ғалымдар мен әдіскерлердің, атап айтқанда А.Б. Сағымбаева мен З.Б. Исаеваның пікірінше, биологиялық білім берудегі интеграциялау процесі оқушының «абстрактілі ойлаудан нақты бейнелік қабылдауға» өтуіне жағдай жасайды [1, 2]. Бұл әсіресе тірі ағзалардағы көзге көрінбейтін микропроцестерді зерттеуде маңызды рөл атқарады. Е. Токпанов өз еңбектерінде атап өткендей, цифрлық білім беру ресурстары (ЦБР), виртуалды зертханалық

кешендер, интерактивті модельдеу және педагогикалық интеграция осы процестің негізгі ұғымдары болып табылады [3]. Осы ұғымдардың өзара байланысы биология пәнінің теориялық материалын практикалық зерттеу дағдыларымен ұштастыруға мүмкіндік береді. Практикада биологиялық үдерістерді виртуалды зертханалар мен интерактивті модельдер арқылы оқыту жағдайында білім алушылардың материалды игеру сапасының айтарлықтай артуы байқалады. Дәстүрлі зертханалық құралдармен көрсету мүмкін емес микробиологиялық құбылыстар АКТ құралдары арқылы қолжетімді әрі түсінікті болады.

Мысал ретінде PhET интерактивті симуляцияларын қолдану арқылы «Фотосинтез» немесе «Жасушалық тыныс алу» тақырыптарын өтуді алуға болады [6]. Бұл жағдайда оқушылар жарық қарқындылығын немесе көмірқышқыл газының мөлшерін виртуалды түрде өзгерте отырып, реакцияның қалай жүретінін өз көзімен көріп, эксперимент нәтижелерін сол мезетте талдай алады. Сондай-ақ, BilimLand платформасындағы 3D анимациялар адам анатомиясы мен физиологиясын оқытуда органдардың жұмыс істеу принципін динамикада көрсетуге мүмкіндік береді [7].

Талдау нәтижесі АКТ-ны интеграциялау оқушылардың тек теориялық білімін ғана емес, сонымен қатар сыни ойлау мен деректерді сараптау дағдыларын дамытуда негізгі фактор екенін көрсетті. Тәжірибелік жұмыстарды цифрлық форматта жүргізу оқу уақытын тиімді пайдалануға және күрделі биологиялық заңдылықтарды тереңірек ұғынуға мүмкіндік береді. Бұл бағыттағы жұмыстар ҚР білім беруді дамытудың мемлекеттік бағдарламасында көрсетілген цифрландыру мақсаттарымен толық үндеседі [4].

### Нәтижелер мен талқылаулар

Зерттеу барысында алынған нәтижелер биология пәнін оқытуда АКТ-ны интеграциялаудың тиімділігін нақты айғақтайды. Жоғарыда көрсетілген диаграмма мәліметтеріне сүйенсек, цифрлық ресурстарды қолдану оқушылардың пәнге деген қызығушылығын 45%-дан 85%-ға дейін арттырған. Бұл көрсеткіш АКТ-ның мотивациялық құрал ретіндегі қуаттылығын дәлелдейді.

Авторлардың (Сағымбаева А.Б., Исаева З.Б.) АКТ-ны «визуализация құралы» ретінде қарастыруымен келісе отырып, оған қоса **өз тарапымынан мынадай пайымдауларды ұсынамын:**

- **Біріншіден,** АКТ интеграциясы биологиялық білім берудегі «уақыт пен кеңістік» шектеуін жояды. Мәселен, табиғатта ұзақ уақыт бойы жүретін эволюциялық процестерді немесе экологиялық сукцессияны симуляция көмегімен бірнеше минут ішінде модельдеу оқушының процесті толық түсінуіне тікелей әсер етеді.
- **Екіншіден,** авторлар атап өткен «танымдық белсенділік» тек сыртқы қызығушылықпен ғана шектелмей, оқушының цифрлық зерттеушілік мәдениетін қалыптастыруы тиіс.

Талқылау нәтижесі көрсеткендей, АКТ-ны интеграциялаудың сәттілігі тек бағдарламаның сапасына ғана емес, мұғалімнің сол технологияны биологиялық әдістемемен шебер ұштастыра алуына (педагогикалық дизайн) тікелей байланысты. Осылайша, біздің зерттеуіміз теориялық негіздер мен практикалық нәтижелер арасындағы тығыз байланысты айқындап берді.

## Қорытынды

Биология пәнін оқытуда АКТ-ны интеграциялаудың әдістемелік негіздерін зерттеу барысында келесідей қорытындыларға келдік:

1. АКТ құралдары (виртуалды зертханалар, 3D модельдер) биологияның абстрактілі ұғымдарын нақты визуализациялауға мүмкіндік береді.
2. Интеграцияланған оқыту әдістемесі білім алушылардың танымдық белсенділігін арттырып, күрделі тақырыптарды игеру сапасын 30-35%-ға жақсартады.
3. Болашақ мамандардың цифрлық құзыреттілігін қалыптастыру үшін АКТ-ны сабақтың барлық кезеңдерінде жүйелі қолдану қажеттілігі негізделді.

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УДК 574.5

# СОСТОЯНИЕ БЕНТОФАУНЫ ШАРДАРИНСКОГО ВОДОХРАНИЛИЩА В УСЛОВИЯХ НЕСТАБИЛЬНОГО ГИДРОЛОГИЧЕСКОГО РЕЖИМА

**М.А.ЕСЕНОВ**

Аральский филиал ТОО «НПЦ рыбного хозяйства», Казахстан, г. Аральск

**Н.С.САМБАЕВ**

Аральский филиал ТОО «НПЦ рыбного хозяйства», Казахстан, г. Аральск

**М.Т.КАЛЫМБЕТОВА**

Аральский филиал ТОО «НПЦ рыбного хозяйства», Казахстан, г. Аральск

**А.А САРИЕВА**

Аральский филиал ТОО «НПЦ рыбного хозяйства», Казахстан, г. Аральск

**Б.М.ОМАР**

Аральский филиал ТОО «НПЦ рыбного хозяйства», Казахстан, г. Аральск

**Аннотация.** Представлены результаты исследований донных беспозвоночных Шардаринского водохранилища в весенне-осенний периоды 2025 года. В донной фауне определено 19 таксонов, среди них 13 таксонов личинок хирономид, 3 вида ракообразных, а также по 1 таксону черви олигохеты, личинки мух-береговушек и бабочницы. Основу количественных показателей макрозообентоса составили личинки хирономид. Показатель биомассы кормового зообентоса Шардаринского водохранилища в 2025 г. в сезонном аспекте снижен от «умеренного» до «очень низкого» класса кормности.

**Ключевые слова:** макрозообентос, таксономический состав, встречаемость, численность, биомасса, доминант, трофность.

**Введение.** Шардаринское водохранилище, являющееся крупнейшим водохранилищем на реке Сырдарья в пределах территории Республики Казахстан, играет важную роль в регулировании водных ресурсов Арало-Сырдарьинского бассейна. Используется для целей ирригации, гидроэнергетики и регулирования стока, что обуславливает выраженные межгодовые и сезонные колебания уровня воды.

По сведениям Туркестанского филиала РГП «Казгидромет» за девятимесячный период 2025 года (февраль–октябрь) водохранилище характеризовалось маловодным состоянием с ярко выраженной сезонной неравномерностью поступления и сброса воды[1].

В зимне-весенний период 2025 года отмечался интенсивный приток воды в водоем. В январе объём поступившей воды составил около 2,6 млн.м<sup>3</sup>, что привело к быстрому наполнению водохранилища: к марту уровень достиг примерно 90 % от проектной ёмкости (порядка 4,7 млн м<sup>3</sup>). Динамика расходов также отражала наличие существенного притока. В январе приток регистрировался свыше 1000 м<sup>3</sup>/с, а к началу лета, в июне-июле, притоки достигли минимальных значений — 31–42 м<sup>3</sup>/с, что фактически означало отсутствие значимого поступления воды в водохранилище. В летние месяцы дефицит притока сочетался с интенсивным водопотреблением, прежде всего на нужды ирригации, что привело к значительному увеличению объёмов сброса воды. В результате наблюдалось

стремительное сокращение водных запасов. За период с июня по август 2025 года объём водохранилища уменьшился более чем в девять раз — с 2128 млн.м<sup>3</sup> до 239 млн.м<sup>3</sup>, и к концу августа остаток воды составил около 232 млн.м<sup>3</sup>, что на 1,127 млрд.м<sup>3</sup> ниже планового уровня. Лимит отпуска воды в Кызылкумский магистральный канал был фактически исчерпан, так как было освоено порядка 95% запланированного объёма.

Задачей гидробиологических наблюдений являлось изучение состояния сообществ низших гидробионтов с целью установления закономерностей изменения их структуры в нестабильных гидрологических условиях.

Исследование выполнено в рамках бюджетной программы 021-100-159 «Услуги по обеспечению сохранения, воспроизводства и рационального использования ресурсов животного мира», финансируемой Комитетом рыбного хозяйства Министерства сельского хозяйства Республики Казахстан.

**Материал и методика.** Сбор и обработка материала проводились в соответствии с общепринятыми методиками [2]. Акватория водохранилища условно подразделялась на верхний, средний и нижний (приплотинный) участки. В весенний период пробы донных организмов отбирались на 14 станциях, осенью — на 5 станциях в связи с сокращением площади водоема. Пробы макрозообентоса отбирались при помощи дночерпателя Петерсена (площадь захвата 0,025 м<sup>2</sup>) в апреле и сентябре 2025 г. Пробы нектобентоса отбирались с прибрежных зон акватории водохранилища, с помощью салазочного трала (входное отверстие 0,75 x 0,5 м.), путем протягивания на расстояние 10 м. Живые организмы извлекали из грунта и помещали в этикетированные пластиковые контейнеры, после чего фиксировались 4% раствором формальдегида. Обработку материала проводили в лабораторных условиях по общепринятым методикам с использованием микроскопов МБС-10, МС-300 и соответствующих определителей [3–5]. Всего было обработано 25 проб.

Оценку уровня кормности водоема по гидробионтам проводили в соответствии с классификацией С. П. Китаева [6].

**Результаты исследований.** В период весенних исследований 2025 г. в составе макрозообентоса водохранилища выявлено 15 таксонов беспозвоночных: личинки хирономид (12 таксонов) и мизиды (2 вида). Осенью представленность донных беспозвоночных снизилась до 11-ти: отмечено всего 5 видов хирономид, черви олигохеты (1 таксон), ракообразные (3 вида), также были личинки бабочницы (1 таксон) и мух-береговушек (1), включенные в группу «другие насекомые» (таблица 1).

Таблица 1– Таксономический состав и встречаемость организмов макрозообентоса Шардаринского водохранилища по сезонам, 2025 год

| №                                | Таксон                                               | Встречаемость |          |
|----------------------------------|------------------------------------------------------|---------------|----------|
|                                  |                                                      | апрель        | сентябрь |
| Vermes – Черви                   |                                                      |               |          |
| 1                                | <i>Oligochaeta</i> gen. sp.                          | -             | +        |
| Crustacea – Ракообразные         |                                                      |               |          |
| 2                                | <i>Paramysisintermedia</i> (Czerniavsky, 1882)       | +             | +        |
| 3                                | <i>P. lacustris</i> (Czerniavsky, 1882)              | +             | +        |
| 4                                | <i>Macrobrachiumnipponense</i> (De Haan, 1849)–larve | -             | +        |
| Insecta– Насекомые               |                                                      |               |          |
| Chironomidae – Хирономиды        |                                                      |               |          |
| 5                                | <i>Procladiusferrugineus</i> (Kieffer, 1918)         | +             | +        |
| 6                                | <i>Cricotopusgr.sylvestris</i> (Fabricius, 1794)     | +             | -        |
| 7                                | <i>Tanytarsusgr.gregarius</i> (Kieffer, 1909)        | -             | +        |
| 8                                | <i>Cladotanytarsusgr.mancus</i> (Walker, 1856)       | +             | +        |
| 9                                | <i>Cryptochironomusgr.defectus</i> (Kieffer, 1913)   | +             | -        |
| 10                               | <i>Glyptotendipesgripekoveni</i> (Kieffer, 1913)     | +             | -        |
| 11                               | <i>Chironomusex. gr.plumosus</i> (Linnaeus, 1758)    | +             | +        |
| 12                               | <i>C. dorsalis</i> (Meigen, 1818)                    | +             | +        |
| 13                               | <i>Endochironomustendens</i> (Fabricius, 1775)       | +             | -        |
| 14                               | <i>Limnochironomusnervosus</i> (Staeger, 1839)       | +             | -        |
| 15                               | <i>Polypedilumconvectum</i> (Walker, 1856)           | +             | -        |
| 16                               | <i>P. scalaenum</i> (Schraenck, 1803)                | +             | -        |
| 17                               | Chironomussp.                                        | +             | -        |
| Other insecta – Другие насекомые |                                                      |               |          |
| 18                               | <i>Ephydra</i> sp.                                   | -             | +        |
| 19                               | <i>Psychodidae</i> gen. sp.                          | -             | +        |
|                                  | Итого за сезон:                                      | 15            | 11       |
|                                  | Всего:                                               | 19            |          |

Снижение представленности беспозвоночных в межсезонном аспекте, связано с уменьшением биоразнообразия личинок гетеротопных насекомых (вылетом из водной среды), а также выеданием их рыбами-бентофагами, концентрация которых при малом объеме водохранилища (сокращение акватории водоема) увеличивалась.

Наиболее часто из личинок хирономид весной отмечены *C. plumosus* (100%) и *C. dorsalis* (57%), а также мизиды *P. intermedia* и *P. lacustris* (по 100%). Осенью на 5-и исследованных станциях часто отмечены черви *Oligochaeta* gen. sp. (60%), хирономиды *C. plumosus* и *C. dorsalis* (по 60%), и личинки мух-береговушек *Ephydra* sp. (80%).

Значения количественных показателей состояния донного сообщества беспозвоночных весной были выше, относительно осени (рисунок 1). В составе общей численности и биомассе макрозообентоса доминировали хирономиды – соответственно 87% и 71,5%. Трофический статус водохранилища, оцененный по среднему значению биомассы зообентоса, соответствовал α-мезотрофному типу умеренной кормности [6].

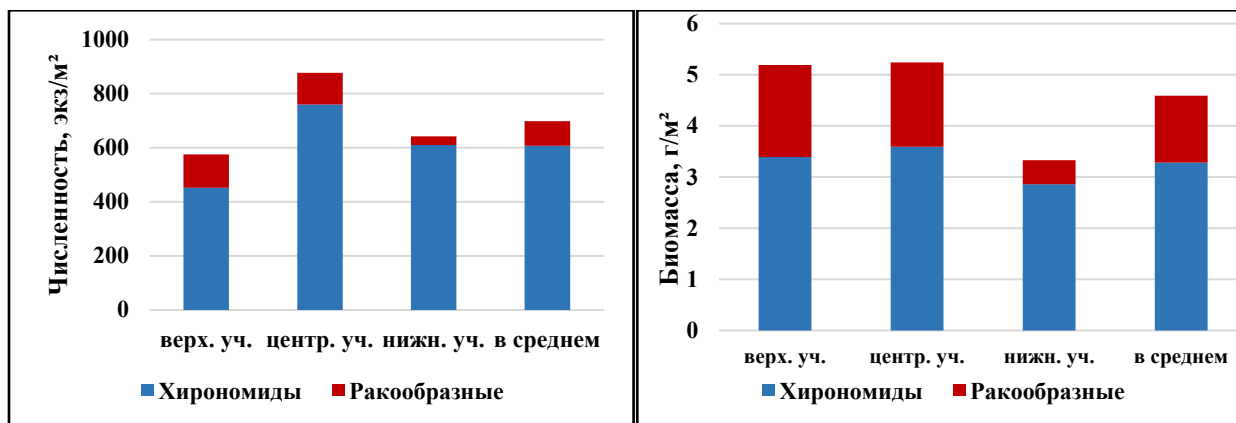


Рисунок 1 - Пространственное распределение численности и биомассы бентофауны Шардаринского водохранилища, апрель 2025 года

Распределение численности и биомассы макрозообентоса по участкам Шардаринского водохранилища в 2025 г. неравномерно. Максимальная численность (877 экз./м²) и биомасса (5,24 г/м²) донных беспозвоночных характерны для центрального участка, где лидирующее положение занимали хирономиды, составляя 86,7 и 68,5% соответственно. Более 73,6% биомассы хирономид формировалась личинками *Ch.ex. gr. plumosus*. Значение биомассы данного участка, оценивается «средним» классом трофности. При низких показателях численности зообентоса в верховье водохранилища, биомасса кормовых организмов находилась почти на уровне значения среднего участка, что возможно связано с встречаемостью в пробах крупноразмерных *Ch.ex. gr. plumosus*.

В период осенних исследований, площадь акватории водохранилища претерпела большие изменения. Осушились два участка водоема (центральный и верхний). Беспозвоночные были отмечены лишь в приплотинной части водоема, численностью 240 экз./м² и биомассой 0,87 г/м² (рисунок 2).

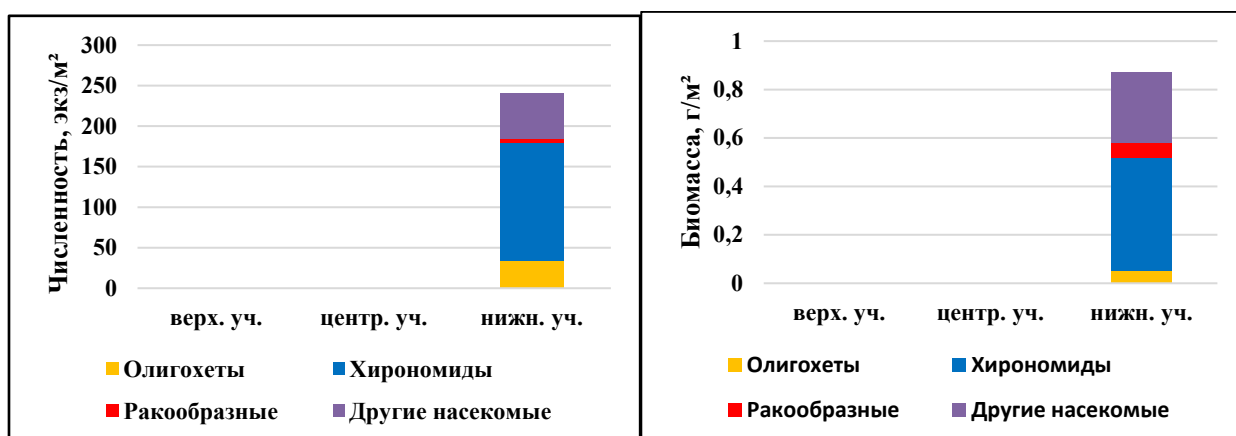


Рисунок 2 - Пространственное распределение численности и биомассы бентофауны Шардаринского водохранилища, сентябрь 2025 года

В создании данных показателей играли, как и весной, хирономиды (60,8% численности и 54,0% биомассы). Субдоминирующее положение занимали насекомые, включенные в группу «другие», составившие 23,3% численности и 33,3% биомассы. Основной вклад в формирование этого показателя вносили личинки мух-

береговушек *Ephydra* sp.(85,7% численности и 89,6%). Показатель биомассы кормового зообентоса Шардаринского водохранилища в 2025 г. в сезонном аспекте снижен от «умеренного» до «очень низкого» класса кормности.

**Вывод.** В целом, бедное разнообразие видового состава и низкие значения количественных показателей макрозообентоса обусловлены непостоянным уровнем воды в Шардаринском водохранилище, т.е. сбросом воды на ирригационные цели, вызывающее обсыхание мелководий, наиболее продуктивных зон водоема (погибает реофильная и фитофильная фауна). Вследствие резкого падения уровня воды, осушения большей части акватории водохранилища, происходит сокращение площади, ведущее к снижению ее объема и как следствие, к росту концентрации рыб, что способствует интенсивному выеданию кормовых гидробионтов и уменьшению биомассы донных зооценозов[7].

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# КІШІ АРАЛ ТЕҢІЗІНДЕГІ ТЫРАН БАЛЫҒЫ ПОПУЛЯЦИЯСЫНЫҢ ҚАЗІРГІ ЖАЙ КҮЙІ

САРИЕВА АКЕРКЕ АБИЛХАНОВНА

кіші ғылыми қызметкер м.а., «Балық шаруашылығы ғылыми-өндірістік орталығы» ЖШС, Арал филиалы, Қазақстан, Арал қ.

**Аңдатпа.** Мақалада Кіші Арал теңізіндегі кәсіпшілік маңызы жоғары тыран балығының (*Abramis brama*, Linnaeus, 1758) биологиялық ерекшеліктері мен популяциялық құрылымы қарастырылған. Теңіз суы тұздылығының төмендеуі балықтардың мекендеу ареалының ұлғаюына оң әсерін тигізгені анықталды. 2020–2025 жылдар аралығындағы көпжылдық зерттеу деректері негізінде тыранның ұзындық-салмақ көрсеткіштеріне, жастық құрамына және өсу динамикасына кешенді талдау жүргізілді. Зерттеу нәтижелері популяциядағы биологиялық параметрлердің құбылмалылығын сипаттап, Кіші Арал теңізіндегі тыран қорының қазіргі жай-күйін бағалауға мүмкіндік берді.

**Түйінді сөздер:** тыран, Кіші Арал, популяция, ұзындық-салмақ, жастық құрам, тыран.

**Кіріспе.** Арал теңізі ХХ ғасырдағы ең ірі экологиялық апаттардың бірі болып саналады. Әмудария мен Сырдария өзендерінің су ресурстарын суармалы егіншілікке шамадан тыс пайдалану нәтижесінде теңіз деңгейі күрт төмендеп, су айдыны бірнеше оқшауланған бөліктерге бөлінді. Бұл өзгерістер су айдындарының гидрологиялық режиміне, судың минералдануына және су экожүйелерінің биологиялық әртүрлілігіне елеулі әсер етті. Соның салдарынан көптеген кәсіптік маңызы бар балық түрлерінің таралу аймағы қысқарып, олардың популяциялық саны айтарлықтай төмендеді [1,2].

2005 жылы Көкарал бөгетінің пайдалануға берілуі Кіші Арал теңізінің гидрологиялық жағдайын тұрақтандыруға мүмкіндік берді [3]. Су деңгейінің көтерілуі мен минералданудың төмендеуі нәтижесінде су экожүйесінің табиғи жағдайлары біртіндеп жақсара бастады. Бұл өзгерістер кәсіптік маңызы бар балық түрлерінің, соның ішінде тыран балығының да табиғи көбеюіне және популяциялық қорының қалпына келуіне оң әсер етті.

Тыран (*Abramis brama*, Linnaeus, 1758) — негізінен су түбіндегі организмдермен қоректенетін балық түрі. Оның қоректену спектрі кең және жасына, тіршілік ету ортасына, су температурасына және қорек организмдерінің маусымдық таралуына байланысты өзгеріп отырады. Жас дарақтары көбінесе зоопланктонмен қоректенсе, ересек дарақтардың қорегінде хирономидтер дернәсілдері, басқа да су жәндіктері, ұсақ шаянтәрізділер, моллюскалар, өсімдік текті қорек пен детрит маңызды орын алады. Тыран балығының ірі дарақтары кейбір жағдайларда (қоректік база жеткіліксіз болғанда немесе қосымша қорек ретінде) ұсақ балықтарды да қорек ретінде пайдалана алады [4]. Тыранның көбею тиімділігі су температурасы, су деңгейінің тұрақтылығы, ағыс жағдайы және ұылдырық шашуға қолайлы субстраттың болуына байланысты. Әсіресе таяз, су өсімдіктері жақсы дамыған учаскелер түрдің табиғи көбеюі мен популяциясының толықтырылуы үшін маңызды болып табылады. Кіші Арал теңізінде тыран кәсіптік аулауда маңызды орын алады. Сондықтан оның популяциясының қазіргі жағдайын, биологиялық көрсеткіштерін және көпжылдық динамикасын зерттеу балық қорларын тиімді басқару және оларды ұтымды пайдалануды ғылыми тұрғыдан негіздеу үшін маңызды. Зерттеу Қазақстан Республикасы Ауыл шаруашылығы министрлігінің

Балық шаруашылығы комитеті қаржыландыратын 021-100-159 бюджеттік бағдарламасы «Жануарлар дүниесінің ресурстарын сақтау, өсімін молайту және ұтымды пайдалану жөніндегі қызметтер» шеңберінде орындалды.

**Материал және әдістеме.** Ихтиологиялық материалдарды жинау, өңдеу және талдау жалпы қабылданған ихтиологиялық зерттеу әдістемелеріне сәйкес жүргізілді [5, 6]. Кәсіптік маңызы бар балық түрлерінің, соның ішінде тыранның (*Abramis brama*, Linnaeus, 1758), уылдырық шашу және табиғи көбею ерекшеліктерін зерттеу А. Ф. Коблицкая ұсынған әдістеме бойынша жүргізілді [7]. Балықтардың жасын анықтау Н. И. Чугунова әдістемесіне сәйкес жүзеге асырылды [8]. Ихтиологиялық материалдар тор көзінің өлшемі 18–90 мм болатын құрма аулардың көмегімен жиналды. Қолданылған аулардың ұзындығы 25 м, биіктігі 2 м болды. Ауланған балықтардың түрлік құрамы анықталып, негізгі биологиялық көрсеткіштері — ұзындығы, дене салмағы, жасы және жыныстық құрамы — белгіленді. Алынған материалдар зерттеу мақсаттарына сәйкес әрі қарай биологиялық талдаудан өткізілді.

**Нәтижелер және талдау.** Кіші Арал теңізінде 2020–2025 жылдар аралығында жүргізілген зерттеулердің нәтижелері бойынша тыран популяциясының негізгі биологиялық көрсеткіштерінде айтарлықтай өзгерістері болғаны анықталды. 2020 жылы тыранның орташа дене ұзындығы 24,6 см, орташа дене салмағы 310,0 г, Фультон бойынша қондылық коэффициенті 2,20, ал орташа жасы 5 жасты құрады. 2022–2023 жылдары өлшемдік және салмақтық көрсеткіштердің жоғарылағаны байқалды. Атап айтқанда, 2022 жылы орташа ұзындығы 25,1 см, салмағы 391,8 г болса, 2023 жылы осы көрсеткіштер тиісінше 25,1 см және 404,2 г-ға жетті. Бұл кезең зерттеу жылдарындағы тыранның ең жоғары орташа дене массасы қалыптасқан уақыт ретінде сипатталады. Сонымен қатар, 2020–2023 жылдары популяцияның орташа жасы 5 жас деңгейінде тұрақты сақталған.

2024 жылдан бастап тыранның өлшемдік-салмақтық көрсеткіштерінде айқын төмендеу байқалды. Орташа дене ұзындығы 22,1 см-ге, ал орташа салмағы 229,3 г-ға дейін төмендеді. 2025 жылы төмендеу үрдісі одан әрі жалғасып, орташа ұзындығы 20,3 см, орташа салмағы 185,4 г болды. Осылайша, 2023 жылмен салыстырғанда 2025 жылы тыранның орташа дене ұзындығы 4,8 см-ге немесе 19,1%-ға, ал орташа дене салмағы 218,8 г-ға немесе 54,1%-ға төмендеген. Бұл өзгерістер зерттелген популяцияның өлшемдік-салмақтық құрылымында айтарлықтай қайта қалыптасу жүргенін көрсетеді. Фультон бойынша қондылық коэффициенті зерттеу кезеңінде салыстырмалы түрде тұрақты болды, мәндері 2020 жылы 2,20, 2022 жылы 2,07, 2023–2024 жылдары 2,10, ал 2025 жылы 2,08 болды, демек, орташа дене ұзындығы мен салмағының төмендеуіне қарамастан, балықтардың дене қондылығы айтарлықтай өзгермеген.

Популяцияның орташа жасы да зерттеу кезеңінің соңында өзгерген. 2020–2023 жылдары бұл көрсеткіш 5 жас болса, 2024 жылы 3 жасқа дейін төмендеп, 2025 жылы 4 жасқа көтерілген. Орташа жастың төмендеуі популяция құрамында жас дарақтардың үлесінің артқанын және жас құрылымының қайта қалыптасу үдерісі жүргенін көрсетуі мүмкін (кесте 1).

Жалпы алғанда, кесте деректері 2020–2023 жылдары тыран популяциясының өлшемдік-салмақтық көрсеткіштері салыстырмалы түрде жоғары әрі тұрақты болғанын, ал 2024–2025 жылдары олардың айқын төмендегенін көрсетеді. Бұл кезеңде орташа дене ұзындығы мен салмағының қысқаруымен қатар, популяцияның орташа жасының төмендеуі байқалды. Аталған өзгерістерге гидрологиялық режимнің өзгеруі, су тұздылығының артуы, қоректік базаның өзгеруі, табиғи өлім-жітім және кәсіпшілік аулау қарқындылығы сияқты факторлар әсер етуі мүмкін. Алайда қолда бар деректер бұл өзгерістерді тек бір ғана фактордың әсерімен байланыстыруға мүмкіндік бермейді. Сондықтан тыран

популяциясының қазіргі жағдайын бағалау кезінде гидроэкологиялық және антропогендік факторларды кешенді түрде қарастыру қажет.

Кесте 1- Кіші Арал теңізінде 2020–2025 жылдардағы тыран популяциясының негізгі биологиялық орташа көрсеткіштері

| Жыл  | Орташа ұзындығы, см | Орташа салмағы, г | Фультон бойынша қондылығы | Орташа жасы |
|------|---------------------|-------------------|---------------------------|-------------|
| 2020 | 24,6                | 310,0             | 2,20                      | 5           |
| 2021 | —                   | —                 | 2,15                      | 5           |
| 2022 | 25,1                | 391,8             | 2,07                      | 5           |
| 2023 | 25,1                | 404,2             | 2,10                      | 5           |
| 2024 | 22,1                | 229,3             | 2,10                      | 3           |
| 2025 | 20,3                | 185,4             | 2,08                      | 4           |

Арал–Сырдария бассейндік облысаралық балық шаруашылығы инспекциясының деректеріне сәйкес, 2020–2025 жылдары Кіші Арал теңізінде тыран (*Abramis brama*, Linnaeus, 1758) балығын кәсіпшілік аулау көлемінің төмендеу тенденциясы байқалды. 2020 жылы аулау көлемі 2735 тоннаны құраса, 2021 жылы 2560 тоннаға, 2022 жылы 2495 тоннаға, 2023 жылы 2322 тоннаға, 2024 жылы 1787 тоннаға, ал 2025 жылы 1231 тоннаға дейін төмендеген. Осылайша, алты жыл ішінде кәсіпшілік аулау көлемі 1504 тоннаға, яғни 55,0%-ға азайған. Ең айқын төмендеу 2023–2025 жылдары байқалып, аулау көлемі 2322 тоннадан 1231 тоннаға дейін қысқарған. Кәсіпшілік аулаудың төмендеуіне бірнеше өзара байланысты фактор әсер етуі мүмкін. Олардың қатарында су деңгейі мен өзен ағынының жылдар бойынша өзгеруі, су айдындарының гидроэкологиялық жағдайы және қоректік базаның тұрақтылығы маңызды рөл атқарады. Сонымен қатар, ұылдырық шашу кезеңінде балық аулауға арнайы тыйым салынған учаскелерде заңсыз балық аулау фактілерінің орын алуы популяцияның табиғи толықтырылуына кері әсер етуі ықтимал. Әсіресе көбею кезеңінде ересек дарақтардың аулануы популяцияның репродуктивтік әлеуетін төмендетіп, кейінгі жылдардағы жас толымдардың қалыптасуына әсер етуі мүмкін. Осы факторлардың жиынтық әсері тыран популяциясының сандық және жастық құрылымының өзгеруіне, сондай-ақ кәсіптік қордың төмендеуіне ықпал етуі мүмкін.

**Қорытынды.** Алынған нәтижелер негізінде Кіші Арал теңізіндегі тыран (*Abramis brama*, Linnaeus, 1758) популяциясының тұрақтылығын сақтау және кәсіптік қорын тиімді басқару үшін келесі шараларды ұсынуға болады:

- *Уылдырық шашу кезеңіндегі қорғау шараларын күшейту.* Балық аулауға арнайы тыйым салынған учаскелерде бақылауды күшейтіп, заңсыз аулаудың алдын алу қажет. Әсіресе көбею кезеңінде ірі жыныстық жетілген дарақтарды қорғауға ерекше назар аударған жөн.

- *Гидрологиялық жағдайды ескеру.* Тыранның көбеюі мен қоректенуіне қолайлы жағдайларды сақтау үшін Кіші Арал теңізі мен дельталық көлдер жүйесіне түсетін су көлемінің маусымдық тұрақтылығын қамтамасыз ету маңызды.

- *Кәсіпшілік аулау қысымын бағалау.* Аулау көлемінің 2020–2025 жылдары төмендеуін ескере отырып, кәсіптік қордың қазіргі жағдайын қайта бағалау және аулау қарқындылығын популяцияның нақты биологиялық мүмкіндігіне сәйкестендіру.

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## Sociological Sciences

# Spatial Technology for Management of Multidimensional Worlds

**Peter Simon Sapaty**

Institute of Mathematical Machines and Systems, National Academy of Sciences of Ukraine

**Abstract:** This paper will investigate potential applicability of the developed high-level Spatial Grasp Model and Technology (SGT) with its basic Spatial Grasp Language (SGL) to express and manage complex systems of very different physical, virtual and mental dimensions as a whole. It briefs main SGT issues, SGL interpreter organization, and the capability to work with any distributed spaces and systems. Then describes basics of the multidimensional management project, currently in development, with its general issues and extended spatial interpretation. The paper introduces basic multidimensional operations which allow for flexible and unrestricted movement inside, through, and between dimensions and provide solutions of any problems in their unity and integrity. It exhibits a multidimensional world example as a large and complex network of nodes in different dimensions and different types of inter-node links, within the same or between different dimensions, explains different operations with nodes and then describes multidimensional spatial moves while collecting the passed links-nodes sequences. Also describes composition and multidimensional matching of different type patterns, including sequential, parallel and combined ones, with the large distributed network. All multidimensional examples in the paper are presented in the modified SGL which can often provide spatial solutions clearer and more compact than by other models and languages. The paper results can represent the basis for a new spatial methodology and technology oriented on advanced investigation and management of complex multidimensional systems of any natures.

**Keywords:** Multidimensional world, Spatial Grasp Technology, Spatial Grasp Language, distributed network operations, multidimensional pattern matching, collective spatial solutions, global integrity and security.

## 1 Introduction

A “multidimensional world” refers to understanding reality, systems, or data through multiple, concurrent dimensions beyond traditional three-dimensional space. It encompasses physical, virtual, social, and economic facets, often requiring holistic, networked, and AI-driven approaches. As its concretization, “multidimensional international world” refers to the world vision through multiple dimensions beyond traditional economic or political measures, fostering cross-cultural collaboration, and creating systems that balance global integration with local needs. This also includes management of global business operations across diverse cultures in a multipolar international landscape.

Already investigated publications on multidimensional systems include books [1-8], also papers on concrete multidimensional applications and solutions covering such areas as conflicts, military, security, power, politics, culture, peace, space systems, and others [9-25]. Our recent publications

related to representation, studies, analysis, investigation and management of multidimensional systems [26-35] may serve as the first step and basis for the current work.

**The aim of this paper** is to offer a concrete and practical framework, with potential goal as technology, for efficient representation, investigation and management of complex multidimensional systems of different natures, which can lead to innovative ideas and effective, even unexpected, solutions within the unity and integrity of various physical, virtual, and mental dimensions.

**The rest of the paper** includes the following. **Section 2** briefs Spatial Grasp model and technology issues, Spatial Grasp Language, its interpreter organization, and ability to work with any distributed spaces and systems. **Section 3** describes principles of the multidimensional management project including its general issues and extended spatial interpretation. **Section 4** introduces basic multidimensional operations, from elementary to extended, which allow for free movement inside and between dimensions and solve problems in their unity. **Section 5** provides multidimensional world example as a complex network of nodes in four dimensions and links between them in same or between different dimensions, also shows examples of dealing with multidimensional nodes and moves while collecting sequences of passed nodes and links. **Section 6** describes preparation of different sequential, parallel and parallel-sequential networked patterns and their multidimensional matching with the network. **Section 7** concludes with the belief that this paper may be used as the basis of new spatial technology for investigation and management of complex multidimensional systems. **References** represent publications on multidimensional systems including the ones directly related to the current project.

## 2 Spatial Grasp Model and Technology Basics

- General issues

Within Spatial Grasp Model and Technology (SGT) [36-48], a high-level operational scenario expressed in recursive Spatial Grasp Language (SGL), starting in any world point or points, *propagates, covers, and matches the distributed environment in parallel wavelike mode*. as symbolically shown in Fig. 1. Such propagation can result in returning and analyzing the reached states and data (which may be arbitrarily remote) to be used for launching more waves, also jointly in both cases.

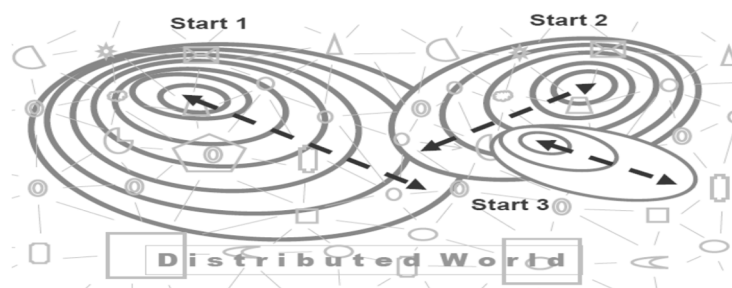


Fig. 1. Parallel recursive world propagation and coverage

The distributed worlds this model is effectively covering, conquering and managing may be of different types: *Physical World (PW)*, considered as continuous and infinite where each point can be identified and accessed by physical coordinates; *Virtual World (VW)*, which is discrete and consists of nodes and semantic links between them, and *Executive World (EW)*, consisting of active doers, which may be humans or robots, with advanced communication possibilities between

them. Different kinds of combinations of these worlds can also be possible within the same SGT formalism.

- **Spatial Grasp Language (SGL)**

The SGL allows for organizing direct space presence and operations with unlimited powers and parallelism. Its universal recursive organization, with operational scenarios called *grasp*, can be expressed just by a single formula:

$$grasp \rightarrow constant \mid variable \mid rule (\{ grasp, \})$$

The *rule* expresses certain action, control, description or context accompanied with operands, which can be any *grasps* too. Other top SGL details can be expressed as:

$$\begin{array}{ll} constant & \rightarrow information \mid matter \mid custom \mid special \\ variable & \rightarrow global \mid heritable \mid frontal \mid nodal \mid environmental \\ rule & \rightarrow type \mid usage \mid movement \mid creation \mid echoing \mid \\ & verification \mid assignment \mid advancement \mid branching \mid \\ & transference \mid exchange \mid timing \mid qualifying \end{array}$$

The rules, starting in certain points, can organize navigation of the world sequentially, in parallel, or any combinations thereof. They can result in the same application points or cause movement to other world points with obtained results left there or returned. The final points reached can become starting ones for other rules. The rules, due to recursive language organization, can form arbitrary operational infrastructures expressing sequential, parallel, hierarchical, centralized, up to fully decentralized and distributed algorithms.

- **SGL interpreter organization**

The SGL interpreter consists of specialized modules working with specific data structures, serving SGL scenarios, also organizing exchanges with other interpreters for distributed scenarios. Communicating SGL interpreters can be in arbitrary number of copies effectively integrated with other existing systems and communications, representing altogether **powerful spatial engines** operating without central resources or control. Hardware or software SGL interpreters, shown in Fig. 2 as universal control and processing units effectively working with spatial graph and network data, can be installed, also runtime created, in proper physical or virtual world points.

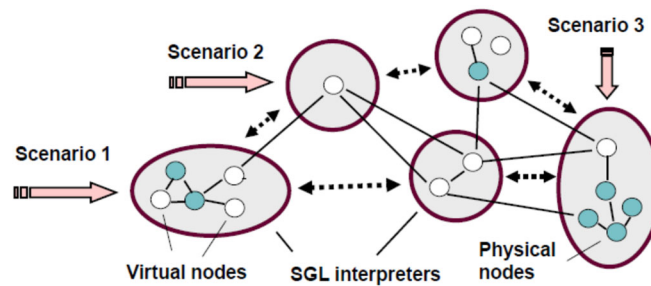


Fig. 2. SGL distributed networked interpretation

As backbone and nerve system of the distributed interpreter, its self-optimizing **Spatial Track System** provides hierarchical command and control, as well as remote data and code access. It supports spatial variables, which can be stationary or mobile, and merges distributed control

states for making decisions at different organizational levels. This spatial infrastructure, effectively supporting global integrity of distributed solutions, is **automatically distributed** between active components (humans, robots, computers, smart-phones, satellites, etc.) during SGL scenario self-evolution in space and time.

- **Covering any distributed spaces and systems**

This model and technology can effectively investigate and manage **any distributed spaces and systems**, with multiple individual or interacting SGL scenarios freely propagating throughout the multidimensional universe. The latter potentially consisting of numerous individual or interlinked worlds  $W_i$  (as symbolically shown in Fig. 3), each ranging from individual physical points or virtual nodes to arbitrary large continuous spaces or complex networks.

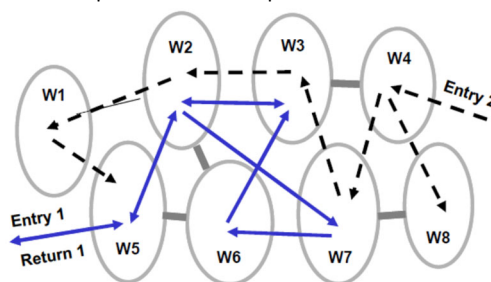


Fig. 3. Parallel space coverage and propagation in multiple worlds

### 3 Multidimensional Management Project

- **General issues**

The general view of this project organization is depicted in Fig. 4, which consists of **overlying and communicating spatial dimensions**, and **Global Management (GM)** system allowing for entering, analyzing, and optimizing different dimensions and their interactions as the unified whole.

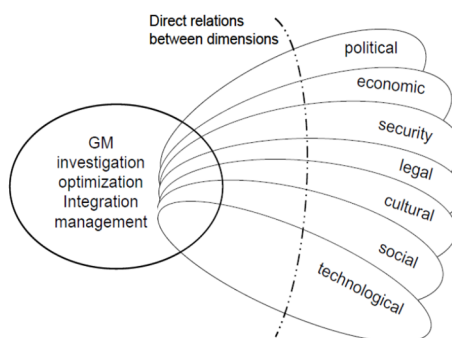


Fig. 4. Multidimensional management system

Fig. 5 shows some ideas of how different dimensions (here symbolically as planes) can be organized and interconnected, with direct contacts of versions of the same nodes in different dimensions.

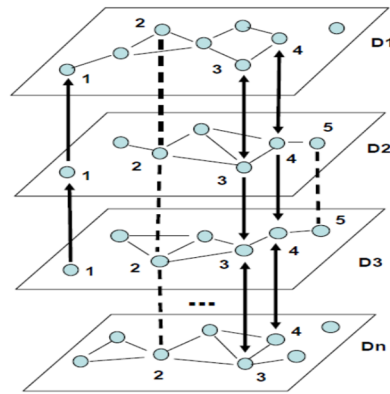


Fig. 5. Interactions between dimensions

The directed arrows between same node versions reflect remaining or changing superiority between same named nodes in multidimensional integrity. Dashed non-oriented links show that all node versions are generally equivalent in importance throughout the multidimensional system. In each dimension different nodes may form arbitrary complex networks reflecting their type, ideology and operation, which may also depend on interactions with nodes in other dimensions.

- **More spatial interpretation**

Different dimensions may be arbitrary complex multidimensional organizations and structures and not just like symbolic planes as in fig. 5. For example, some dimensions can be symbolically represented like 3d cylinders, as in Fig. 6.

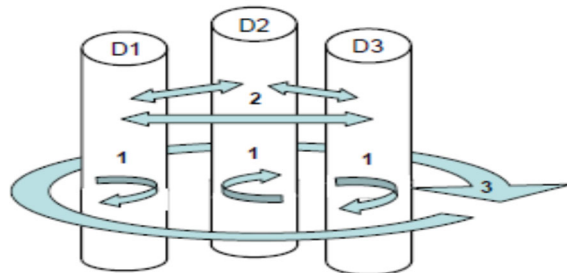


Fig. 6. Another view of multidimensional system

And general project organization, as further detailed of Fig.6, may include **spatial dimension sections** (as D1, D2, D3, and many more may be engaged), organization of **intra-dimensional solutions** (1), **inter-dimensional operations and exchanges** (2), and **over-dimensional global control and optimization, GCO** (3).

Different dimensions in reality may occupy any terrestrial and celestial spaces in both physical and virtual worlds, and reflect very complex and unique components and organizations. And multiple dimensions with different physical, virtual, historic, or imaginary nature may ideologically and spatially intersect and overlap, as symbolically shown in Fig. 7 for D1-D6.

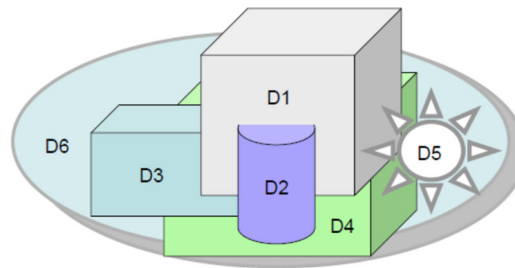


Fig. 7. Intersecting and overlapping spatial dimensions

## 4 Multidimensional Operations and Capabilities

- **Elementary operations**

The following examples show how to enter different dimensions, solve problems in them, and how to move between dimensions within the multidimensional project briefed in the previous section.

Entering any dimensions from GM can be done by operation enter, reaching certain points there, and organize operations from them may look follows.

Entering particular dimension:

`enter(security)`

Entering different dimensions in parallel:

`enter(security, economy, social, ...)`

Simultaneously entering all registered dimensions:

`enter(all)`

After entering the needed dimensions and starting in certain points in them, we can launch there operations of any volume, coverage, and complexity:

`enter(economy, social, ...); hop(name_1, ..., name_n); <operate> or`

`enter(geography); move(coord_1, ..., coord_m); <operate>`

But if staying in a particular node or coordinate in some dimension and eager to directly transfer activity into similar point (or points) in other dimensions (if such exist) and operate there too, possibly in parallel (i.e. without engagement of GM or GCO of Figs 4 and 6) we may use the special through-dimensional operation shift as follows.

`<staying in a point>; shift(Economic, Technological, ...); <operate>`

- **Extended possibilities**

Working with different dimensions can be also coordinated in spatial scenarios by special mobile (frontal) variable **DIMS** keeping names of dimensions this scenario is scheduled and allowed to penetrate, navigate, and follow. And these scenario identifiers can be set up and updated in this variable any time by the scenario itself. This means that the evolving scenario can autonomously follow, change, and split into different virtual and physical dimensions at any stage of its development, and this can be even done in parallel if DIMS keeps multiple dimension names. All this may result in advanced multidimensional world coverage and processing and potentially lead to innovative and even unexpected discoveries and solutions.

Another, stationary, variable **DI** associated with individual nodes in different dimensions reflects belonging of the node to this particular dimension, and together with the node name can be registered for all dimensions it may belong as follows:

NAME = X, DI = [1,2,3]

Accessing this node simultaneously in different dimensions can be expressed just as: X:[1,2,3]. The following are some examples.

hop\_node(X)

This, without mentioning dimensions, will result in simultaneous entering this node in all its registered dimensions, i.e.: X:1, X:2, X:3.

Same will be with explicit mentioning its all dimensions:

hop\_node(X:[1,2,3])

However, entering a multidimensional node only by some of its dimensions, like:

hop\_node(X:[1,2]), will result in: X:1, X:2

Also, entering a node in concrete dimensions can be organized by using current scenario dimensions in DIMS (the entered node variants will be on intersection of all node's registered dimensions and those in DIMS):

DIMS = [2,3,4,5]; hop\_node(X)

This will result in: X:2, X:3

Simultaneous mentioning dimensions in DIMS and those with the node name will be on their intersection too:

DIMS = [2,3,4,5]; hop\_node(X:[1,2])

Will result only in: X:2

## 5 Multidimensional World Example

- United world picture

Fig. 8 is showing an example of a united network of the 4-dimensional world, where different nodes (i.e. A,B,C,D,E,F,K,J,T,U,V) can exist at the same time in different dimensions (their identifiers from 1 to 4). Named connections between nodes in the same dimensions are shown by same type and color links, while existing connections between nodes from different dimensions are with colorless double links.

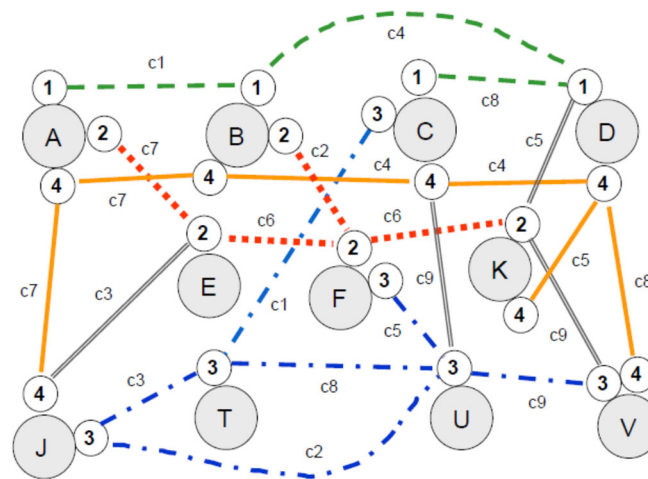


Fig. 8. An example of multidimensional world

From Fig. 8 we have the following:

Dimension 1: A,B,C,D;    Dimension 2: A,B,E,F,K;    Dimension 3: C,J,T,F,U,V;    Dimension 4: J, A,B,C,K,V;  
Inter-dimensional links: 1-2, 2-4, 3-4, 2-3

- **Examples of dealing with nodes**

Collecting all existing node names without entering them in different dimensions:

DIMS = none; output(nodes(all))

Result: (A,B,C,D,E,F,K,J,T,U,V)

Collecting all existing node variants in all registered dimensions after entering them:

DIMS = all; output(hop(nodes(all)))

Result: (A:1, A:2, A:4, B:1, B:2, B:4, C:1, C:3, C:4, D:1, D:4, E:2, F:2, F:3, K:2, K:4, J:3, J:4, T:3, U:3, V:3, V:4)

Reduced solution with naming only concrete dimensions:

DIMS = [2,4]; hop\_nodes(all)

Terminated in: A:2, A:4, B:2, B:4, C:4, D:4, E:2, F:2, K:2, K:4, J:4, V:4

One more:

DIMS = 1; hop\_nodes(all)

Result in: A:1, B:1, C:1, D:1

Collecting and returning all node copies with their dimensions:

DIMS = 4; output(hop\_nodes(all))

Result at start: (A:4, B:4, C:4, D:4, K:4, J:4, V:4)

Using concrete node names

DIMS = [1,2,3]; hop\_nodes(A,B,C)

Terminated in: A:1, A:2, B:1, B:2, C:1, C:3

Returning copies of named nodes from dimensions mentioned in DIMS:

DIMS = [1,2]; output(hop\_nodes(A,C))

Result issued at start: (A:1, A:2, C:1)

Returning copies of named nodes with explicit dimensions, to be approved by DIMS:

DIMS = [1,2]; output(hop\_nodes(A:2,C:1))

Result issued at start: (A:2, C:1)

- **Multidimensional hops through named links with the reached nodes collection**

Starting in named nodes in certain dimensions, making single hops through concrete links to updated dimensions, and returning the reached node variants:

output(DIMS = [3,4]; hop\_nodes(J, F, V);

DIMS = [2,4]; hop\_links(c3, c8, c9))

Result issued at start: (E:2, K:2, D:4)

This is for repetitive movement from all nodes in the given dimensions through a sequence of named links, the results issued in final nodes (as their names and dimensions). The solution prevents possible cycling by special marking of the passed nodes.

frontal(Links) = (c1, c4, c5, c6, c6, c3, c3, c8, c9, c9);

DIMS = [1,2,3,4]; hop\_nodes(all);

repeat(hopfirst\_link(withdraw(Links, 1)));

output(NODE)

Result will be: K:2, as the only solution.

- **Multidimensional moves through the links sequence with full trace collection**

Moving through the given sequences of named links and obtaining the resultant sequence of passed node names with their dimensions, providing the output in final nodes:

frontal(Links = (c1, c4, c5, c6, c6, c3, c3, c8, c9), Nodes);

DIMS = [1,2,3,4]; hop\_nodes(all);

repeat(append(Nodes, NODE);

hopfirst\_link(withdraw(Links, 1)));

output(Nodes)

Result issued in V:3: (A:1, B:1, D:1, K:2, F:2, E:2, J:4, T:3, U:3, V:3)

Result issued in C:4: (A:1, B:1, D:1, K:2, F:2, E:2, J:4, T:3, U:3, C:4)

Output of full results at the start including the links passed, which are returned from all final nodes:

output(

frontal(Links = (c1, c4, c5, c6, c6, c3, c3, c8, c9), Chain);

DIMS = [1,2,3,4]; hop\_nodes(all); Chain = NODE;

```
repeat(hopfirst_link(withdraw(Links, 1));
      append(Chain, PASSED); append(Chain, NODE));
Chain)
```

Result issued at start (returned from final nodes V:3 and C:4):

```
((A:1, c1,B:1, c4,D:1,c5,K:2, c6,F:2, c6,E:2, c3,J:4, c3,T:3, c8,U:3, c9,V:3),
 (A:1, c1,B:1, c4,D:1,c5,K:2, c6,F:2, c6,E:2, c3,J:4, c3,T:3, c8,U:3, c9,C:4))
```

## 6 Patterns and Pattern Matching

We will consider here different examples of representation of spatial patterns and their matching with multidimensional world of Fig. 8, where patterns may themselves be multidimensional.

### 6.1 Sequential patterns

- Sequential cyclic pattern with finding names of links between given named nodes

A structure of a simple pattern with named nodes to be matched with the multidimensional network of Fig. 8 is shown in Fig. 9, where the direction of links (which names to be found) hint on a possible matching order.

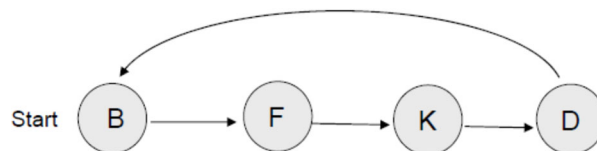


Fig. 9. The structure of matching pattern

The representation of this pattern and its application to the network of Fig. 8 may be organized as follows.

```
frontal(Nodes = (B, F, K, D, B), Chain);
DIMS = [1,2,3,4]; hop_node(withdraw(Nodes, 1)); Chain = NODE;
repeat(hop(links(all), node(withdraw(Nodes, 1))));
      append(Chain, PASSED); append(Chain, NODE));
output(Chain)
```

The resultant matching order is shown in Fig. 10, where at each step only the currently reached node dimension is used for the next movement from it via the existing links.

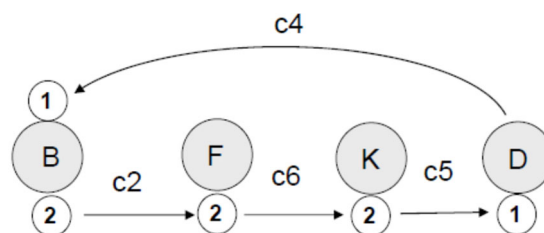


Fig.10. Matching with finding link names between nodes

The issued result will be: B:2, c2, F:2, c6, K:2, c5, D:1, c4, B:1.

More general multidimensional solutions may be where at each matching step all other dimensions of the reached node can be engaged for the next step, with chasing all existing links from these additional node copies too. Such extended solution (for other pattern nodes: J, E, F, U, J) may be as follows:

```
frontal(Nodes = (J, E, F, U), Chain);
DIMS = [1,2,3,4]; hop_node(withdraw(Node, 1)); Chain = NODE;
repeat(hop(links(all), node(withdraw(Nodes, 1)));
  append(Chain, PASSED); append(Chain, NODE);
  stay, (nonempty(Nodes); shift(DIMS); append(Chain, NODE)));
output(Chain)
```

This matching process is shown in Fig. 11, and the solution as a sequence of nodes and links is following (nodes and their variants directly shifted to other dimensions are in bold).

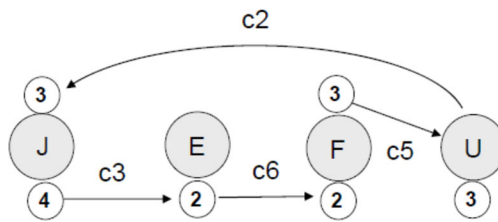


Fig. 11. More general multidimensional solution

Printed result: (J:4, c3, E:2, c6, **F:2, F:3**, c5, U:3, c2, J:3)

Examples of solutions for other four-node patterns may be as follows:

(A, E, F, A) → A:2, c7, E:2, c6, F:2, c2, **B:2, B:1**, c1, A:1  
 (C, U, V, C) → C:4, c9, U:3, c9, **V:3, V:4**, c8, D:4, c4, C:4

- **Sequential cycling pattern for finding node names by named links between them**

Such pattern is shown in Fig. 12, with solution in SGL following (where at each step only the currently reached node dimension is used for the next step, similar to Fig. 10).

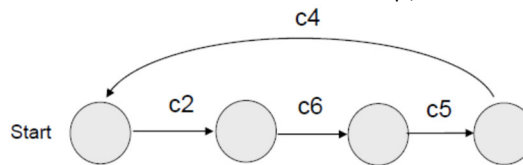


Fig. 12. Pattern with only link names

```
frontal(Links = (c2, c6, c5, c4), Nodes, Chain);
DIMS = [1,2,3,4]; hop_nodes(all); append(Chain, NODE); append(Nodes, NAME);
repeat(hop(links(withdraw(Links, 1))); notbelong(NAME, Nodes);
  append(Chain, PASSED); append(Chain, NODE); append(Nodes, NAME));
output(Chain)
```

The result appeared to be the same as in Fig. 10: B:2, c2, F:2, c6, K:2, c5, D:1, c4, B:1.

- **Most general pattern without names of nodes and links**

Allowing any nodes and links in this most general sequential cyclic pattern shown in Fig.13, with the use of all possible node dimensions in each matching step (similar to Fig. 11).

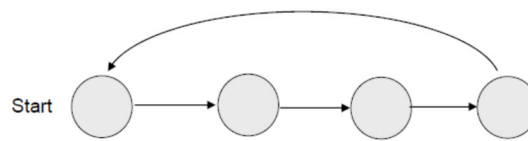


Fig. 13. Most general sequential cyclic pattern

This can be in SGL as follows.

```
frontal(Nodes, Chain);
DIMS = [1,2,3,4]; hop_nodes(all); append(Chain, NODE); append(Nodes, NAME);
repeat(3)(hop(links(all); notbelong(NAME, Nodes);
    append(Chain, PASSED); append(Chain, NODE); append(Nodes, NAME);
    stay, (shift(DIMS); append(Chain, NODE))););
hop(links(all), node(Nodes(1))); append(Chain, PASSED & NODE);
output(Chain)
```

Some possible solutions:

C:4, c9, U:3, c9, **V:3, V:4**, c8, D:4, c4, C:4

A:2, c7, E:2, c6, F:2, c2, **B:2, B:1**, c1, A:1

K:2, c9, V:3, c9, U:3, c5, **F:3, F:2**, c6, K:2

B:2, c2, F:2, c6, E:2, c7, **A:2, A:1**, c1, B:1

## 6.2 Parallel patterns

- **Fully parallel pattern**

We are beginning here with parallel pattern having known nodes and links to be found, as of Fig. 14.

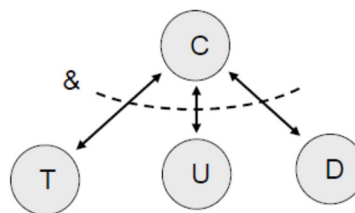


Fig. 14. Parallel pattern with known nodes

Solution in SGL may be as follows:

```
DIMS = [1,2,3,4];
hop_node(C); frontal(Branch) = NODE;
output(
    and_parallel(
        hop(links(all), node(T)),
        hop(links(all), node(U)),
```

```
hop(links(all), node(D));
append(Branch, PASSED); append(Branch, NODE);
unit(Branch))
```

Result is graphically shown in Fig. 15, also printed at the start after receiving termination data from the reached nodes T, U, D as of parallel branches:

(C:3, c1, T::3), (C:4, c9, U:3), (C:1, c8, D:1)

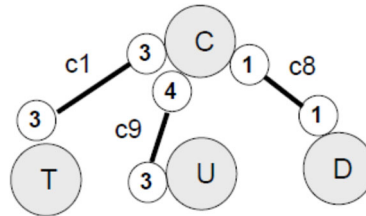


Fig. 15. Parallel pattern solution

- **Parallel-sequential pattern**

A bit more complex pattern having sequential branch C-T-U with is in parallel with branches C-U and C-D is shown in Fig. 16.

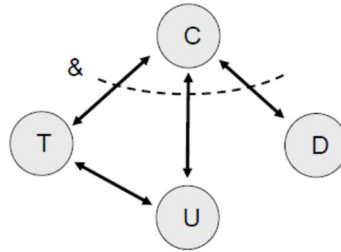


Fig. 16. Parallel-sequential pattern

The related solution in SGL will be as follows:

```
DIMS = [1,2,3,4];
hop_node(C); frontal(Branch) = NODE;
output(
and_parallel(
(hop(links(all), node(T)); append(Branch, PASSED);
append(Branch, NODE); hop(links(all), node(U))),
hop(links(all), node(U)),
hop(links(all), node(D)));
append(Branch, PASSED); append(Branch, NODE); unit(Branch))
```

The result is in Fig. 17, printed at start as collection of parallel branches: (C:3, c1, T:3, c8, U:3), (C:4, c9, U:3), (C:1, c8, D:1).

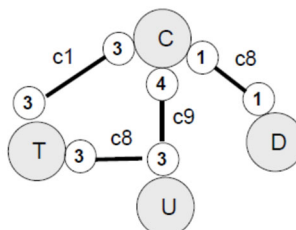


Fig. 17. Parallel-sequential pattern solution

- **Parallel converted to fully sequential pattern without known names of nodes and links**

Such pattern is much more general and flexible than the previous ones, and to provide its maximum spreading and matching flexibility and capability in a fully multidimensional environment, it should be represented in a fully sequential order, as shown in Fig. 18 with mentioning step numbers at links.

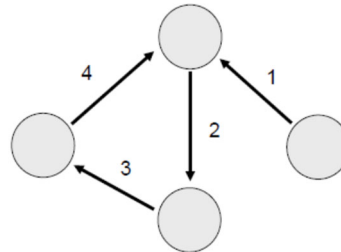


Fig. 18. Parallel to fully sequential pattern solution

The implementation in SGL will be as follows.

```

frontal(Nodes, Chain);
DIMS = [1,2,3,4]; hop_nodes(all); Chain = NODE; Nodes = NAME;
repeat(3)(hop_links(all); notbelong(NAME, Nodes);
    append(Chain, PASSED); mappend(Chain, NODE); append(Nodes, NAME);
    stay, (shift(DIMS); append(Chain, NODE)));
hop(links(all), node(Nodes(2))); append(Chain, PASSED); append(Chain, NODE);
output(Chain)

```

Below are examples of possible solutions printed in final nodes, to be the same as nodes of number two in their sequence (direct shifts between same nodes in different dimensions are shown in bold):

```

(J:3, c3, T:3, c1, C:3, C:4, c9, U:3, c8, T:3)
(F:2, c6, E:2, c7, A:2, A:4, c7, J:4, c3, E:2)
(C:1, c8, D:1, c5, K:2, c9, V:3, V:4, c8, D:4)
(D:1, c8, C:1, C:4, c9, U:3, c8, T:3, c1, C:3)
(F:2, c6, K:2, c9, V:3, V:4, c8, D:4, D:1, c5, K:2)
(F:2, c6, K:2, c9, V:3, V:4, c8, D:4, c5, K:4)

```

## 7 Conclusions

The paper offered new methodology and potential technology how to represent large distributed multidimensional systems of different natures and formulate and solve complex problems related to their unity and integrity, which often cannot be understood and implemented by dealing with dimensions separately. The introduced multidimensional pattern matching techniques and self-evolving spatial scenarios easily covering and propagating between and through different dimensions can inspire radically new vision and understanding of very complex systems and lead to radically new, even unexpected, solutions. In relation to social systems, where we regularly witness national and international problems and conflicts simultaneously connected with political, economic, military, historical, religious and many other issues, the approach offered can help correctly plan, address, investigate, and orient international community toward finding the

solutions needed, which can predict and prevent poverty, illnesses and disasters, also improve global development, prosperity and security. The updated Spatial Grasp model and language, effectively supporting multidimensional solutions, can be easily implemented in different national and international organizations and institutions, as was experienced for the previous versions in different countries.

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## Pedagogical Sciences

# FANFICTION AS AN INNOVATIVE PEDAGOGICAL RESOURCE: GENRE FEATURES, DIDACTIC POTENTIAL, AND CRITERIA FOR EDUCATIONAL USE

Azhgeryeva T.A

Master's students in Foreign Languages, L.N. Gumilyov Eurasian National University

Nurzhanova Z.D

Master's students in Foreign Languages, L.N. Gumilyov Eurasian National University

Abilkaiyr B.G

Master's students in Foreign Languages, L.N. Gumilyov Eurasian National University

Khamzin A.K

Master's students in Foreign Languages, L.N. Gumilyov Eurasian National University

**Abstract:** This article examines fanfiction as an emerging pedagogical resource in foreign language education, analyzing its genre-specific characteristics, didactic potential, and practical criteria for classroom implementation. It argues that fanfiction represents a transformative writing practice that bridges informal language learning environments with formal educational settings, fostering learner motivation, creative expression, and communicative competence. Drawing upon recent theoretical and empirical research from 2023 onwards, the analysis highlights fanfiction's capacity to develop linguistic accuracy, narrative skills, and intercultural awareness through participatory, authentic writing tasks. The conclusion reached is that effective integration of fanfiction into language pedagogy requires a principled framework balancing creative freedom with structured learning outcomes, ensuring that this innovative resource contributes meaningfully to the development of advanced writing proficiency.

**Keywords:** fanfiction, writing skills, language teaching methodology, innovative approaches, creative writing, digital literacies.

In contemporary foreign language pedagogy, writing proficiency is recognized as a cornerstone of comprehensive communicative competence. The field has witnessed a significant methodological shift, moving from traditional, product-oriented approaches toward frameworks that emphasize creative processes, learner interaction, and autonomy. This evolution is further accelerated by digital communication, which has reshaped writing pedagogy by engaging students in authentic exchanges through online platforms and multimodal environments [Güven et al., 2024, p. 252]. Among the various innovative approaches that have emerged, fanfiction, amateur narrative writing based on pre-existing fictional universes, has attracted particular attention from researchers and educators alike for its unique pedagogical potential.

This article offers a theoretical overview of fanfiction as a pedagogical resource, focusing on its genre features, didactic potential, and criteria for effective educational use. The analysis

synthesizes current research from 2023 onwards and discusses its pedagogical implications for developing advanced writing skills in foreign language education.

To appreciate fanfiction's pedagogical value, it is essential to understand its defining genre characteristics. Fanfiction is broadly defined as stories that reimagine or reinterpret existing stories, characters, and universes found in other texts and media [Pudo, 2024]. This transformative nature distinguishes it from original creative writing: fanfiction writers operate within established fictional frameworks while exercising creative agency to explore alternative scenarios, character developments, and narrative outcomes. The genre encompasses a diverse range of subgenres and formats, including Alternate Universe (AU) stories, where characters are placed in settings different from the original narrative; canon-compliant stories, which adhere closely to established plotlines; crossovers, combining elements from multiple fictional universes; fix-it fics, which resolve perceived narrative shortcomings; and many others. This generic diversity provides considerable flexibility for pedagogical application, allowing educators to match tasks to learners' interests, proficiency levels, and learning objectives [Stanko & Kolegaeva, 2024].

Significantly, fanfiction is inherently a participatory and socially embedded practice [Sauro, 2021]. Writers typically share their work on dedicated online platforms, where they receive feedback from readers and engage in ongoing dialogue about their narratives. This participatory dimension creates authentic conditions for language use: learners write not for a teacher's evaluation but for a real audience of fellow enthusiasts. As Pudo (2024) notes, writing these texts requires the mobilization of skills often taught in formal education: mastery of linguistic resources, planning, editing, and proofreading. Furthermore, fanfiction is fundamentally a practice of mediation. As Stanko and Kolegaeva (2024) argue, fanfiction writing involves a thorough reception of the original cultural text, the development of a personal interpretation, the anticipation of audience needs and reactions, and the crafting of a text that is original yet grounded within the source universe. This transformative process mirrors the kind of meaning-making and cultural negotiation that is central to advanced communicative competence [Yesdauletov et al., 2025].

Recent research by Solmaz (2025) emphasizes that fanfiction represents a form of "fictional linguistic landscapes" where learners engage with language in richly contextualized, multimodal environments. This perspective highlights fanfiction's capacity to integrate reading, writing, and critical thinking in ways that reflect contemporary communicative practices. The genre's digital nature also positions it within broader developments in technology-mediated language learning, where mobile-assisted and online writing instruction have demonstrated significant positive effects on learner outcomes [Zalani et al., 2024; Zhang, 2025].

The pedagogical affordances of fanfiction are substantial and multifaceted. Drawing on recent research, several key areas of didactic potential can be identified. First, fanfiction writing enhances vocabulary acquisition as students experiment with new words and contexts [Pudo, 2024]. The narrative focus of fanfiction provides natural opportunities for using descriptive language, dialogue, and varied syntactic structures. Learners engage with register variation, from informal dialogue to narrative exposition, developing sensitivity to stylistic choices appropriate to different communicative contexts. Moreover, the iterative nature of fanfiction writing, often involving multiple drafts and revisions based on reader feedback, promotes attention to linguistic accuracy and self-correction. Han (2023) demonstrates how blog-based writing instruction, which shares structural similarities with fanfiction communities, enhances writing performance and motivation through authentic audience engagement. Similarly, Zalani et al. (2024) found that mobile-assisted critical writing instructions significantly improved EFL learners' writing skills,

suggesting that technology-mediated writing tasks, including fanfiction can effectively support linguistic development.

Second, a consistent finding across recent studies is fanfiction's capacity to enhance learner motivation. Unlike traditional writing exercises perceived as artificial or irrelevant, fanfiction tasks connect to learners' existing interests and identities. Han (2023) reported that learners exhibit heightened engagement when composing within digital formats that transcend traditional classroom exercises. The presence of an authentic audience, readers who share enthusiasm for the source material, creates a powerful incentive for producing polished, meaningful texts. Güven et al. (2024) examined learner views on digital writing in foreign language teaching, finding that digital writing environments significantly enhance student engagement and perceived relevance of writing tasks. This motivational dimension is particularly relevant for teenage and young adult learners, who constitute the majority of fanfiction participants [Pudo, 2024]. The practice resonates with their digital literacies and affinity-driven learning preferences, effectively bridging in-school and out-of-school literacy practices.

Third, fanfiction provides a structured yet flexible context for developing narrative competence. Learners work within established narrative frameworks, allowing them to focus on specific aspects of storytelling, character development, plot structure, setting description, dialogue, without the additional cognitive load of inventing an entire fictional world from scratch. Stanko and Kolegaeva (2024) found that students engaging in fanfiction writing demonstrated enhanced creativity and a deeper understanding of narrative techniques, such as plot structure and character development. The educational potential of derivative texts suggests that fanfiction enables learners to internalize narrative conventions while simultaneously developing their unique authorial voice.

Fourth, fanfiction's transformative engagement with source texts naturally promotes critical thinking and intercultural awareness. Writers must interpret and reimagine cultural artifacts, making choices about what to preserve, modify, or subvert. This process encourages reflection on cultural assumptions, narrative conventions, and representational practices. Solmaz (2025) emphasizes that fan practices can foster intercultural awareness by engaging learners in the interpretation and recreation of culturally embedded narratives. Yesdauletov et al. (2025) demonstrate how literary blogs, a related digital writing practice, cultivate not only writing fluency but also metalinguistic awareness and cross-cultural analytical skills. These findings are directly applicable to fanfiction, which similarly involves engagement with culturally specific source texts and participation in global interpretive communities. Through such engagement, learners navigate authentic communicative demands, which in turn promotes the organic expansion of their lexical and syntactic repertoires [Kushkinbayeva et al., 2025].

Finally, participation in online fanfiction communities develops multiple digital literacies: navigating platforms, engaging in collaborative peer review, understanding copyright and fair use, and managing online identities. These competencies are increasingly recognized as essential components of contemporary communicative competence [Zhang, 2025; Zalani et al., 2024]. Güven et al. (2024) emphasize that digital writing pedagogies are increasingly positioned as integral components of contemporary communicative and task-based learning frameworks. Fanfiction, as a digitally native writing practice, exemplifies this integration, preparing learners for the multimodal, networked communication that characterizes contemporary global discourse.

Despite its considerable potential, fanfiction's integration into formal education requires careful consideration. Based on recent research, several criteria should guide educational implementation. First, fanfiction tasks must be designed with explicit learning objectives aligned with curricular goals. As Zalani et al. (2024) argue, effective pedagogical models strategically synthesize traditional writing instruction with technology-enhanced formats to achieve specific learning outcomes. Educators should articulate how fanfiction tasks contribute to developing vocabulary, grammatical accuracy, narrative skills, or intercultural competence. Zhang (2025) emphasizes that a balanced approach must strategically synthesize the foundational rigor of traditional writing instruction with the dynamic, interactive potential of technology-enhanced formats.

Second, while creative freedom is central to fanfiction's appeal, educational use requires appropriate structure. The "fictional linguistic landscapes" pedagogy proposed by Solmaz (2025) offers a model for structured integration, providing practical frameworks for using multimodal fan activities to enhance second language learning. Tasks might include rewriting scenes from different perspectives, continuing narratives beyond their original endings, or adapting source texts to new contexts. Recent research by Kushkinbayeva et al. (2025) on language use in social media underscores the importance of guided engagement with informal digital writing contexts. While these environments offer rich linguistic input, learners benefit from structured activities that direct attention to specific linguistic features and communicative functions.

Third, the participatory feedback culture of online fanfiction can be adapted for educational contexts. Peer review exercises can mirror the authentic feedback loops of fan communities, promoting collaborative learning and self-reflection. Assessment should balance attention to linguistic accuracy with recognition of creativity, narrative coherence, and audience awareness. Han (2023) suggests that blog-based writing instruction, with its emphasis on peer feedback and revision, supports the development of self-regulation and critical evaluation skills. Zhang (2025) emphasizes the pivotal role of self-regulation in the development of writing proficiency. Technology-mediated learning environments, including fanfiction platforms are particularly conducive to cultivating this capacity, as they require learners to exercise independent judgment, critically evaluate content, and engage in iterative self-correction.

Fourth, as with any pedagogical resource, fanfiction tasks require appropriate scaffolding for learners at different proficiency levels. Beginners might focus on short, formulaic texts (e.g., missing scenes or character diaries), while advanced learners can undertake more complex narrative experiments. The genre's generic diversity provides natural differentiation opportunities. Güven et al. (2024) found that learner views on digital writing vary significantly based on proficiency level and prior experience, suggesting that educators should tailor fanfiction tasks to their students' specific needs and capabilities.

Finally, educators must be prepared to address potential challenges. Research by Pudo (2024) has identified concerns including students' English proficiency and cultural understanding. Additionally, fanfiction's association with popular culture may be perceived as "low-brow" or irrelevant by some educators, a perception that requires critical examination. As Stanko and Kolegaeva (2024) demonstrate, fanfiction's pedagogical value is well-supported by empirical evidence and theoretical argument. Zalani et al. (2024) caution that technology-mediated writing instruction requires careful implementation to maximize benefits and minimize potential drawbacks, such as learner distraction or over-reliance on digital tools.

This theoretical overview has elucidated the potential of fanfiction as an innovative pedagogical resource for foreign language education. Fanfiction's genre features, its transformative nature, participatory culture, and embeddedness in authentic communicative contexts, position it as a uniquely valuable tool for developing writing proficiency, narrative competence, and intercultural awareness. The didactic potential of fanfiction is substantial: it enhances learner motivation, supports vocabulary acquisition, develops narrative skills, fosters critical thinking, and cultivates digital literacies. These benefits align with the broader shift in language pedagogy toward authentic, process-oriented, and learner-centered approaches, as documented in recent studies by Han (2023), Zalani et al. (2024), and Güven et al. (2024). However, realizing this potential requires principled integration. Educators must design fanfiction tasks with clear learning objectives, appropriate structure, and effective feedback mechanisms. Addressing challenges related to proficiency, cultural understanding, and assessment is essential for successful implementation. It thus follows that modern writing pedagogy must extend its focus beyond grammatical accuracy to explicitly foster the development of intercultural awareness, creative capacity, and authentic self-expression, thereby equipping learners for the complex demands of global discourse.

Ultimately, fanfiction represents not merely a novel classroom activity but a pedagogical orientation that recognizes and leverages learners' existing literacy practices. By bridging informal and formal learning contexts, fanfiction can transform writing instruction from a classroom exercise into a meaningful, creative, and socially embedded practice. This approach fundamentally repositions the learner, transforming them from passive recipients of knowledge into active participants in global communicative networks [Kushkinbayeva et al., 2025; Yesdauletov et al., 2025]. As the field of language education continues to evolve in response to digitalization and changing communicative practices, fanfiction's pedagogical value is likely to receive increasing recognition. Future research should explore effective implementation models, examine learner outcomes across diverse contexts, and investigate ways to maximize fanfiction's contribution to holistic communicative competence.



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# Təfəkkür keyfiyyətlərinin inkişafına dair

**Elnarə Şahbazzadə**

Bakı Dövlət Universitetinin Sosial və pedaqoji psixologiya kafedrasının doktorantı

Kiçik məktəbli yaş dövründən fərqli olaraq yeniyetməlik yaşı dövrü əsasən erkən gənclik yaş dövrünü əhatə edir və onunla fərqlənir ki, o faktiki olaraq özündə uşaqlıqdan yetkin yaşa keçid dövrünü ehtiva edir. Yeniyetməlik yaş dövrünün psixoloji mexanizmlərinə nəzər saldıqda görürük ki, bu dövr şagirdin özünüdərk etməsinin, dünyagörüşünün formalaşmasının, peşə seçmək və gələcək həyata hazırlaşmasının əsasını təşkil edir və bioloji, psixoloji, psixoseksual və sosioloji amillərin təsiri altında inkişaf edib formalaşır. Yeniyetməlik dövründə təfəkkür keyfiyyətlərinin psixoloji əsasları keyfiyyət dəyişikliklərinə məruz qalır. Nəticədə, yeniyetmələr fikirlərini daha aydın, məntiqi və tənqidi şəkildə formalaşdırmağa başlayırlar. Bu proses həm şəxsi, həm də sosial baxımdan uğur qazanmaqda mühüm rol oynayır. Yeniyetməlik dövründə təlim fəaliyyəti həm məzmun, həm də forma cəhətdən yeni xüsusiyyətlərə malik olur, daha ciddi və dərk olunmuş xarakter daşıyır. Burada ilk öncə yeniyetmələrdə təfəkkür və onun əsas anlayışlarının təzahür xüsusiyyətlərinin psixoloji təsvirinə qısaca nəzər salaq. İnsan nəinki ətraf aləmi qavrayır, eyni zamanda onu başa düşməyə, anlamağa da çalışır. Anlamaq predmet və anlayışların mahiyyətinə varmaq, onlarda mövcud olan ən əsas şeyləri dərk etməkdir. Bu yaş dövründə idrak prosesləri yeni keyfiyyətlər kəsb edir, xüsusilə də təfəkkür əsaslı surətdə dəyişib inkişaf edir, çünki böyük məktəb və ya erkən gənclik yaşaqlı qabiliyyətlərin inkişafının mühüm mərhələsidir. Bu nöqteyi-nəzərdən onların təfəkküründə əsaslı yüksəliş baş verir [3].

Yeniyetmələrdə təfəkkürü özünün ardıcılığı, genişliyi, daha çox nəzəri, mücərrəd, tənqidi xarakterləri ilə səciyyələnir, şagirdlərdə fikrin müstəqilliyi, ən əsası isə təfəkkürün çevikliyi özünü daha qabarıq şəkildə göstərir. Erkən gənclik dövrünün qarşıya çıxardığı müxtəlif problemlər, həll edilməsi vacib müxtəlif tipli məsələlər, gələcək fəaliyyətə hazırlıq, ali məktəbə hazırlıqla xarakterizə olunan ixtisas seçimi onlardan müstəqil düşünmək, qarşıya çıxan problemlərə çevik və qeyri-standart yanaşma tələb edir.

Yeniyetmələrdə təfəkkür keyfiyyətlərinin inkişafı onların psixoloji xüsusiyyətləri ilə sıx bağlıdır. Bu yaşda diqqət fokusu genişlənir və yaddaş və düşüncənin mürəkkəb funksiyaları yaxşılaşır. Yeniyetmələrdə təfəkkür keyfiyyətləri inkişaf edir və bu, onlara öz baxışlarını mübahisələndirməyə və başqalarının fikirlərini təhlil etməyə imkan verir.

Psixoloji ədəbiyyatlarda təfəkkürün keyfiyyətləri ağıl keyfiyyətləri ilə eyni anlamda işlədilir. Təfəkkürün keyfiyyətlərinə onun çevikliyi, müstəqilliyi, dərinliyi, genişliyi, tənqidiliyi, produktivliyi aiddir. Yazdığımız bu işdə bizə böyük məktəblilərdə təfəkkürün təzahürü və inkişafı xüsusiyyətlərinin psixoloji qanunauyğunluqlarını araşdırmaq və şərh etmək lazımdır. Təfəkkürün çevikliyi dedikdə predmet və anlayışlara, onların xassə və münasibətlərinə baxış aspektlərinin dəyişilməsi qabiliyyəti, məsələnin standart həll yolunu dəyişmə bacarığı, dəyişkən situasiyalarda verilənlərin aktiv şəkildə yenidən qurulması, başa düşülməsi və istifadə edilməsi prosesi başa düşülür. Psixoloji ədəbiyyatlarda bu məsələyə ilə bağlı nəzəriyyə və praktik işlərin az olduğunu nəzərə alaraq ayrı-ayrı ədəbiyyatlarda onun işlənmə səviyyəsinə nəzər salaq.

Psixoloji amillərlə yanaşı, təhsil mühiti yeniyetməlik dövründə təfəkkür keyfiyyətlərinin inkişafında mühüm rol oynayır. Bu dövrdə özünüidarəetmə və müstəqil öyrənmədə maraqlar, motivasiya və bacarıqlar formalaşır. Müəllimlər və valideynlər tərəfindən yaradılan dəstəkləyici, strukturlaşdırılmış və cəlbədicə təhsil atmosferi təfəkkür keyfiyyətlərinin inkişafını sürətləndirir. Fikirlərin sərbəst ifadəsini, məntiqi düşüncəni və qruplarda birgə problem həllini təşviq edən məşqlər yeniyetmələrin idrak potensialını əhəmiyyətli dərəcədə genişləndirə bilər. Beləliklə, yeniyetmələrdə analitik düşüncənin inkişafı idrak, emosional və sosial aspektləri bir-biri ilə əlaqələndirən mürəkkəb psixoloji bir prosesdir. Bu yaşda tənqidi və analitik düşüncənin formalaşması təkcə akademik uğurlara

deyil, həm də gələcək şəxsi və peşəkar həyatına təsir göstərir. Buna görə də, yeniyetmələrin idrak inkişafının dərin təhlili və müvafiq təhsil strategiyalarının yaradılması müasir psixologiya və pedaqogikada aktual vəzifələr olaraq qalır. Xarici psixoloqlar yaradıcı və produktiv təfəkkürü tədqiq edərkən onun mühüm xüsusiyyətindən biri kimi onun çevikliyini xüsusi vurğulayırlar. D.Gilford təfəkkür keyfiyyətlərini obyektin mövcud funksiyasını yenidən düşünmək, nəzərdən keçirməklə yeni keyfiyyət kimi istifadə etməyə qabiliyyət kimi təsvir edir (8, s.23).

Yeniyetməlik insan inkişafındakı psixoloji dəyişikliklərin ən vacib, lakin çətin mərhələlərindən biri hesab olunur. Bu mərhələdə beynin idrak funksiyalarının, xüsusən də təfəkkür keyfiyyətlərinin sürətli inkişafı baş verir, çünki yeniyetmələr yeni məlumatları müstəqil şəkildə təhlil etmək və problemləri hərtərəfli öyrənmək qabiliyyətinə yiyələnməyə başlayırlar. Eyni zamanda, onların emosional sahəsində və davranışlarında dəyişikliklər ortaya çıxır və bu da onların düşüncə proseslərinə birbaşa təsir göstərir. Psixoloqların fikrincə, yeniyetməlik dövründə prefrontal korteksdəki neyrobioloji dəyişikliklər təfəkkür keyfiyyətlərini və qərar qəbul etmə qabiliyyətlərini gücləndirir. Bu baxımdan, təfəkkür keyfiyyətləri yeniyetmələrdə mürəkkəb düşüncə bacarıqlarının və reallığın tənqidi qavranılmasının formalaşmasında əsas rol oynayır. Təfəkkür keyfiyyətləri problemi tərkib hissələrinə ayırmaq, dərinlən təhlil etmək və məntiqi əlaqələrə əsaslanaraq həll yolları tapmaq qabiliyyətidir. Yeniyetmələrdə bu qabiliyyət əsasən orta məktəbdə akademik fəaliyyətlər vasitəsilə inkişaf edir. Psixoloji tədqiqatlar göstərir ki, təfəkkür keyfiyyətlərinin inkişafı yalnız məlumat qavrayışını deyil, həm də yeni biliklərin yaradılması və inkişaf etdirilməsi proseslərini əhatə edir. Bu proseslərin yeniyetmələrdə uğurla inkişaf etməsi üçün effektiv təhsil mühiti yaratmaq, yüksək motivasiyanı qorumaq və yaradıcılığı və müstəqil düşüncəni təşviq etmək vacibdir. Buna görə də, şagirdləri problemləri birdən çox perspektivdən nəzərdən keçirməyə sövq edən tədris metodları xüsusi əhəmiyyət kəsb edir.

N.A.Mençinskayanın təfəkkürün çevikliyi anlayışına verdiyi izahı daha tam və dolğun hesab etmək olar. O hesab edir ki, təfəkkürün çevikliyi fəaliyyətin müxtəlif faydalı variasiyalarında təzahür edir. Bizim təfəkkürün çevikliyi haqqında anlayışımız obyektin xassələrinin interpretasiyasının dəyişməsi, intellektual məsələlərin həlli vəziyyətində obyektin keyfiyyət transformasiyası ilə əlaqədardır (6, s. 56). Fikrimizcə, təfəkkürün çevikliyinin əsasını vasitəçilik mexanizmləri təşkil edir. Əgər L.S.Viqotskinin işlərində universal vasitə qismində sözlər (işarələr) nəzərdən keçirilirdisə, daha sonralar nəinki sözlü, eyni zamanda obrazlı vasitələr də öyrənilməyə başladı. Məktəb yaş dövründə bu keyfiyyətə sahib olmaq şagirdə obyektlər arasında kifayət qədər mürəkkəb gizli əlaqə və münasibətləri əks etdirən intellektual məsələləri həll etməyə imkan verir. Böyük məktəblilərdə təfəkkürün çevikliyinin təzahürünü öyrənmək üçün psixoloqlar növbəti işlərində şagirdlərdə çevik təfəkkürün obrazlı vasitələrini- kompleks təsəvvürləri tədqiq edirdilər (3, s. 235). Bura biz obyektlərin elə obrazlarını aid edirik ki, onlar öz xüsusiyyətlərinin məcmusu daxilində əks olunurdular. Bu cür təsəvvürlərin birinin hüdudları çərçivəsində şagird çevik təfəkkür nümayiş etdirərək obyektin bir xassəsinin analizindən digər xassələrinə keçə bilər. Kompleks təsəvvürlər zamanı obyektin müxtəlif xassələri heç bir halda kənarda qalmır, hətta situasiya qarşıya obyektə bir xassəni ön plana çıxarıb digərinə maneə yaradaraq müəyyən interpretasiya vəziyyətini çıxardıqda belə.

Yeniyetmələrdə təfəkkür keyfiyyətlərinin inkişafına dair

## XÜLASƏ

Məqalədə qeyd olunur ki, təfəkkür inkişafın müəyyən səviyyəsində ziddiyyətli münasibətlərdə təzahür edir. Buna sübut olaraq qeyd edək ki, psixoloji ədəbiyyatlarda təfəkkür keyfiyyətləri yaradıcı təfəkkürün xüsusiyyətlərindən biri kimi nəzərdən keçirildiyi şəraitlərin əsasını problemli situasiyaların produktiv qurulması təşkil edir. Tədqiqatlar göstərir ki, yeniyetmələrin təfəkküründə elə mexanizmlər mövcuddur ki, onlar məsələ həlli zamanı obyektin qurulması və inkişafını ziddiyyətlərə münasibətin köməyi ilə təsvir edirlər.

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# ASSESSING THE LEVEL OF INDEPENDENCE OF LEARNERS WITH INTELLECTUAL DISABILITIES IN WORK-RELATED INSTRUCTION

**Martina Magová**

Catholic University, Faculty of Education, Ružomberok, Slovakia, orcid.org/0000-0002-6664-6299

**Barbora Kováčová**

Catholic University, Faculty of Education, Ružomberok, Slovakia, orcid.org/0000-0002-6728-4904

## Abstract

*The paper focuses on assessing the level of independence of learners with intellectual disabilities during work-related instruction. The aim of the study was to identify the level of independence in performing selected work-related activities and to compare it according to the type of activity performed. The study was conducted using participatory observation in two special primary schools and included 12 seventh-grade learners educated according to Variant A. The learners' level of independence was assessed using a structured observation sheet comprising 15 indicators covering individual aspects of the work process, from preparing the workplace to completing the work activity. Observation was conducted across three types of work-related activities: working with paper, clay processing, and food preparation in the school training kitchen. The collected data were analysed using descriptive statistical procedures, and differences among the three independent groups were assessed using the Kruskal–Wallis test. Descriptive results showed the highest mean level of independence for working with paper ( $M = 3.97$ ), followed by clay processing ( $M = 3.80$ ) and food preparation in the school training kitchen ( $M = 3.68$ ). However, the differences among the groups were not statistically significant,  $H(2) = 1.473$ ;  $p = 0.479$ , and the effect size was negligible ( $\epsilon^2 \approx 0.00$ ). The findings highlight the importance of systematically monitoring and developing independence in work-related instruction, which may contribute to gradually reducing the need for external support and promoting the functional independence of learners with intellectual disabilities.*

## Keywords:

*intellectual disabilities, independence, work-related instruction, work-related activities, participatory observation, functional independence*

## Independence as an Area of Development in Learners with Intellectual Disabilities

The development of independence represents an important component of support for individuals with intellectual disabilities, as it influences their ability to manage everyday activities, make decisions about their own lives, and actively participate in their social environment. The acquisition of practical and self-care skills contributes to reducing dependence on assistance from others and creates the prerequisites for a greater degree of autonomy (Kováčová & Hančárová, 2023). Independence should therefore not be viewed solely in terms of mastering a particular

activity, but also as an important factor contributing to quality of life, social participation, and the successful integration of an individual into everyday life.

Weber, Kozinka, and Winkler (In Kováčová, 2014) identify two specific levels of independence that should be observed in the development of every child. The first is the initial level of independence, which emerges towards the end of the third year of life and during the first half of the later preschool period. At this level, independence is manifested through compliance with established rules and routines set by adults. For example, a child may already be able to change their shoes independently after returning from outdoor activities. This routine is also reinforced in kindergartens, where not all children may yet be fully proficient in performing the activity itself, but the habit of changing shoes upon arrival and departure is gradually established and regularly supported.

A further indicator of a higher developmental level of independence is the child's ability to perform familiar activities spontaneously, without instructions or assistance from an adult. An acquired behavioural characteristic, such as the child's sense of order, is manifested not only at home but also in other environments, for example when visiting grandparents or attending a summer camp. In such situations, the child is able to independently put away toys or other materials used during an activity without being prompted to do so (Kováčová, 2014; Kováčová & Hančárová, 2023).

Kuld et al. (2023) conceptualise independence not merely as a person's ability to perform all activities without assistance from others. An important component of independence is the opportunity to make choices, express personal preferences, make decisions, and influence one's everyday life. Support may therefore include providing opportunities for choice, assisting with decision-making, developing communication skills, and creating an environment in which a person can actively influence their own life. The independence of a person with intellectual disabilities does not depend solely on their individual abilities. The way in which support is provided is also of crucial importance. When support is flexible and respects the person's choices and decision-making, it can strengthen their autonomy and promote independent living. Conversely, overly directive or rigid forms of support may restrict their independence (Fullana, Pallisera, & Díaz-Garolera, 2025).

Shepley et al. (2018) conducted a study focusing on the development of independence in everyday activities among learners with intellectual disabilities. The researchers used video-based instructions presented through a mobile device. The aim was to teach learners to independently perform functional activities required in everyday life. The intervention also included teaching learners how to independently operate the mobile device and locate the appropriate video instruction. One of the practical tasks involved preparing a snack. The learner gradually followed the individual steps of the activity and subsequently performed them independently. The study thus connects the acquisition of practical skills with the development of the ability to initiate and complete an activity independently. Importantly, the intervention was not limited to acquiring a specific skill but also aimed to support the learner's independent functioning. This approach may be applicable to teaching self-care, household, and other functional activities. The findings indicate that systematic instruction in practical tasks can contribute to the development of independence among learners with intellectual disabilities.

Panerai, Catania, Rundo, and Ferri (2018) focused on the development of functional skills necessary for independent living among adolescents and young adults with intellectual disabilities. The training incorporated virtual reality technologies and applications accessible through tablets. The aim was to examine the feasibility of home-based training in functional living skills. The significance of the study lies in the fact that the training was not conducted exclusively in a specialised setting but directly within the participants' home environment. The researchers examined whether the acquired skills could be transferred to real-life situations. The findings indicated that the use of virtual technologies may be an appropriate approach to training

functional skills. An important aspect was the promotion of independence without the need for continuous direct assistance from another person. The study highlights the importance of practically oriented education during the transition to adulthood. During this period, functional skills are particularly important for the gradual development of independence and the individual's progression towards independent living.

Furthermore, when considering the independence of learners with intellectual disabilities, it is important to examine the relationship between motor abilities and performance in everyday activities. Endo, Asano, and Asai (2024) specifically focused on static and dynamic balance. Balance represents an important component of motor functioning required for the performance of everyday activities. Their research indicates that motor abilities cannot be considered separately from the learner's functional performance. When performing activities of daily living, learners need to coordinate their movements, maintain postural stability, and adapt their movements to the specific requirements of the activity. Limitations in the motor domain may therefore affect the level of independence. The study is also relevant from the perspective of special education, as it connects motor performance with the individual's practical functioning. The findings support the importance of assessing functional abilities when evaluating the independence of individuals with intellectual disabilities.

### **Skill Automatization in Work-Related Skills**

Skill automatization represents a level at which an activity is performed fluently, efficiently, and with minimal cognitive effort. At this stage, the learner no longer needs to consciously consider every individual step of the activity, which allows attention to be directed towards other aspects of the task or the surrounding environment (Vargová, 2007).

A characteristic feature of skill automatization is that a skill becomes increasingly automatic and can be performed with less fatigue and greater accuracy. In learners with intellectual disabilities, complete automatization in terms of speed or absolute error-free performance may not always be achieved. The aim, however, is to enable the learner to approach the highest level of automatization possible in relation to their individual abilities and potential (Jankovský, 2012).

Automatized skills are particularly important for promoting independence and independent living. They enable learners to perform self-care activities, such as dressing and personal hygiene, as well as to prepare food, maintain order, and perform other household and practical activities with a reduced need for assistance from others. The acquisition of such skills therefore contributes directly to reducing the learner's dependence on support from their environment (Vargová, 2007). The consolidation of automatized skills requires long-term and systematic practice in authentic or realistically simulated everyday situations. Repeated practice enables learners to gradually transfer acquired skills from guided learning situations to practical contexts in which the skills are required. According to Bárťová (2004), project-based learning and simulations that imitate real working conditions can be particularly effective at this stage, as they provide opportunities for learners to apply skills in meaningful and functionally relevant situations.

From the perspective of special education, skill automatization can therefore be understood as a gradual transition from conscious and guided practice towards the increasingly natural and independent application of acquired skills in everyday life (Čarnická, 2026). The level of automatization is not determined solely by the speed or error-free performance of an activity, but rather by the extent to which the learner can perform the activity with an appropriate degree of independence, accuracy, and reduced need for external support.

### **Research Design**

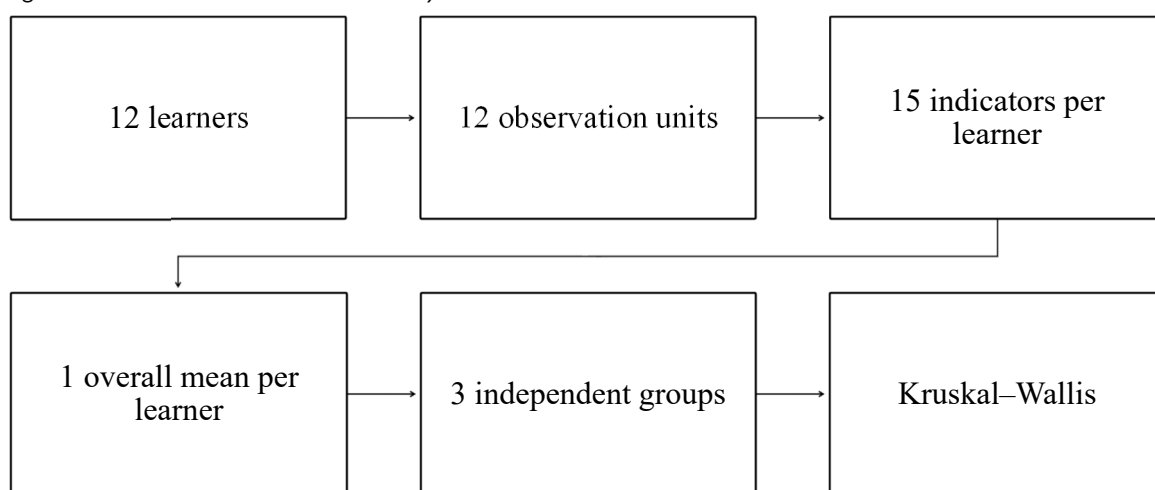
The aim of the present study was to identify the level of independence of learners with intellectual disabilities during work-related instruction. Particular attention was paid to the extent to which

learners were able to perform individual practical activities independently and to the degree of assistance required during their completion. The study also focused on selected aspects of learners' functional performance that may contribute to their ability to perform work-related tasks with a reduced need for external support.

### Participatory Observation

Participatory observation was used as one of the methods for collecting data on the level of independence of learners with intellectual disabilities directly within the natural conditions of the school environment. The observations were conducted during work-related instruction in school workshops and training kitchens. This setting made it possible to observe learners while performing authentic work-related activities and to capture their level of independence in situations requiring them to follow instructions, use work tools and materials, adhere to a prescribed work procedure, and respond appropriately to the course of a particular work task. The observation was conducted in **two special primary schools**, with one class of learners educated according to **Variant A** observed in each school. The research sample consisted of **12 seventh-grade learners with intellectual disabilities**. The learners were observed during selected work-related activities and were subsequently classified into three groups according to the type of activity performed: **clay processing (n = 3)**, **food preparation in the school training kitchen (n = 4)**, and **working with paper (n = 5)**. The activities were selected to capture the learners' level of independence in work situations involving different demands related to material handling, adherence to work procedures, concentration, organisation of activities, and the need for pedagogical support.

*Figure 1: Data Structure and Analytical Procedure*



The focus of the observation was not solely on the final product of the work activity but primarily on the **process of its implementation**. Attention was paid to the extent to which learners were able to perform individual work steps independently, how they responded to the teacher's instructions, whether they were able to follow the sequence of steps according to the prescribed work procedure, use work tools appropriately, maintain attention, and, when necessary, identify and correct errors in their own performance. The observation also included organisational and social aspects of the work activity, such as preparing the workplace, putting away tools and materials, cleaning the work area, communication, and cooperation with other learners.

A **structured observation sheet** consisting of 15 indicators of the level of independence was used to record the observed behaviours. The indicators were formulated to cover the individual stages of the work process, from preparing the workplace and tools, through understanding the

instructions and performing individual work steps, to checking the outcome and completing the work activity. The learners' concentration, communication, cooperation, and ability to respect the designated work area were also assessed.

Each indicator was assessed using a **five-point rating scale**, which made it possible to capture differences in the level of support required when performing a particular task. A higher score represented a higher level of learner independence, whereas a lower score indicated a greater need for support, guidance, or assistance from the teacher. The assessment therefore focused not only on whether the learner completed the task, but also on the level of independence demonstrated during its performance.

A total of **12 observation units** were obtained, with each observation unit representing one learner assessed across all 15 indicators of independence. For each learner, an **overall mean score** was calculated from the 15 indicators, representing their overall level of independence during the respective work-related activity. The resulting individual mean scores ranged from 3.27 to 4.40.

The collected data were analysed using descriptive statistical procedures. For the overall mean scores, the arithmetic mean, median, minimum and maximum values, and standard deviation were calculated. The overall level of learner independence was subsequently compared across the three groups according to the type of work-related activity. Given the small sample size within the individual groups and the ordinal nature of the rating scale, a non-parametric **Kruskal–Wallis test** was used to examine differences in the level of independence across the three groups.

Participatory observation thus enabled the researchers to capture the learners' level of independence within a natural work-related environment and to identify specific areas in which learners demonstrated a higher level of independence, as well as areas in which pedagogical support remained necessary. The data obtained provided a more comprehensive perspective on learner independence than an assessment of the final work product alone.

The observation sheet was adapted from Krolčík (2026), who developed a structured observation sheet comprising 15 indicators as part of field-based research. The observation sheet was used to individually assess the level of independence of the learners (N = 12) during work-related instruction.

*Table 1: Observation Sheet Used in Study 1*

| Learner code |                                                                           | Date | Activity |   |   |   |  |
|--------------|---------------------------------------------------------------------------|------|----------|---|---|---|--|
| Step         | Indicator                                                                 | 1    | 2        | 3 | 4 | 5 |  |
| 1            | Prepares the workplace according to instructions..                        |      |          |   |   |   |  |
| 2            | Prepares the necessary tools and materials..                              |      |          |   |   |   |  |
| 3            | Becomes familiar with the task (understands the purpose of the activity). |      |          |   |   |   |  |
| 4            | Follows the teacher's instructions throughout the entire process.         |      |          |   |   |   |  |
| 5            | Performs the first work step (ability to initiate the activity).          |      |          |   |   |   |  |
| 6            | Proceeds logically according to the prescribed procedure (sequencing).    |      |          |   |   |   |  |
| 7            | Uses tools and materials in a technically appropriate manner.             |      |          |   |   |   |  |
| 8            | Accuracy and quality: Pays attention to the precision of the work.        |      |          |   |   |   |  |
| 9            | Concentration: Works without unnecessary distractions.                    |      |          |   |   |   |  |
| 10           | Completes the product/task within the specified time.                     |      |          |   |   |   |  |
| 11           | Self-monitoring: Is able to identify an error in the outcome.             |      |          |   |   |   |  |
| 12           | Cleans and organises the workplace.                                       |      |          |   |   |   |  |
| 13           | Returns tools and materials to their designated place.                    |      |          |   |   |   |  |
| 14           | Communication: Is able to appropriately request assistance or materials.  |      |          |   |   |   |  |
| 15           | Cooperation: Respects the workspace of other learners.                    |      |          |   |   |   |  |

*Source: Krolčík (2026)*

*Table 2. Rating Scale for the Observation Sheet*

| Level of support |                          | Description                                                                                      |
|------------------|--------------------------|--------------------------------------------------------------------------------------------------|
| 5                | Completely independently | Performs the task without any prompting or assistance.                                           |
| 4                | Verbal prompting         | Requires only brief verbal guidance or a reminder.                                               |
| 3                | Visual prompting         | Needs to see a model, diagram, or demonstration provided by the teacher.                         |
| 2                | Physical assistance      | Requires partial hand-over-hand guidance or direct intervention by the teacher.                  |
| 1                | Not completed            | Did not complete the task even with maximum support (refused or was unable to perform the task). |

*Source: Krolčík (2026)*

## Research Findings

The results of the participatory observation provided data on the level of learner independence during the performance of selected work-related activities within work-related instruction. The collected data were analysed using descriptive statistical indicators and subsequently compared according to the type of work-related activity performed. The following tables present the findings for the individual indicators of learner independence and across the three types of work-related activities.

*Table 3: Descriptive Analysis of Individual Independence Indicators*

| Indikátor                                                                    | Mean        | Median | Minimum. | Maximum | SD          |
|------------------------------------------------------------------------------|-------------|--------|----------|---------|-------------|
| 1. Prepares the workplace according to instructions..                        | 4,25        | 4,00   | 4        | 5       | 0,45        |
| 2. Prepares the necessary tools and materials..                              | 4,00        | 4,00   | 3        | 5       | 0,43        |
| 3. Becomes familiar with the task (understands the purpose of the activity). | 3,75        | 4,00   | 3        | 4       | 0,45        |
| 4. Follows the teacher's instructions throughout the entire process.         | 3,67        | 4,00   | 3        | 4       | 0,49        |
| 5. Performs the first work step (ability to initiate the activity).          | 4,00        | 4,00   | 4        | 4       | 0,00        |
| 6. Proceeds logically according to the prescribed procedure (sequencing).    | 3,50        | 3,50   | 3        | 4       | 0,52        |
| 7. Uses tools and materials in a technically appropriate manner.             | 4,00        | 4,00   | 3        | 5       | 0,43        |
| 8. Accuracy and quality: Pays attention to the precision of the work.        | 3,58        | 4,00   | 3        | 4       | 0,52        |
| 9. Concentration: Works without unnecessary distractions.                    | 3,08        | 3,00   | 2        | 4       | 0,52        |
| 10. Completes the product/task within the specified time.                    | 4,17        | 4,00   | 4        | 5       | 0,39        |
| 11. Self-monitoring: Is able to identify an error in the outcome.            | <b>2,92</b> | 3,00   | 2        | 3       | <b>0,29</b> |
| 12. Cleans and organises the workplace.                                      | <b>4,42</b> | 4,00   | 4        | 5       | 0,52        |
| 13. Returns tools and materials to their designated place.                   | 4,25        | 4,00   | 4        | 5       | 0,45        |
| 14. Communication: Is able to appropriately request assistance or materials. | 3,75        | 4,00   | 3        | 4       | 0,45        |
| 15. Cooperation: Respects the workspace of other learners.                   | 4,17        | 4,00   | 4        | 5       | 0,39        |

*Zdroj: Krolčík & Magová (2026)*

The results revealed several noteworthy findings concerning the learners' performance across the individual work-related indicators. The highest mean score was recorded for the **organisation of the workplace** (M = 4.42; SD = 0.52), indicating a very good level of performance in this area among

the observed learners. High mean scores were also recorded for **preparing the workplace** ( $M = 4.25$ ) and **returning tools and materials to their designated place** ( $M = 4.25$ ). Relatively high performance was also observed in **completing the task** ( $M = 4.17$ ) and **cooperation** ( $M = 4.17$ ). These findings indicate that the learners performed particularly well in activities related to organising the work environment, completing work-related tasks, and cooperating with others. In contrast, the lowest mean score was recorded for **self-monitoring** ( $M = 2.92$ ;  $SD = 0.29$ ), representing the weakest area among the assessed indicators. Lower performance was also observed in **concentration** ( $M = 3.08$ ;  $SD = 0.52$ ) and **logical sequencing of work steps** ( $M = 3.50$ ;  $SD = 0.52$ ). These findings suggest that the learners experienced greater difficulty particularly in processes related to self-regulation, maintaining attention, and independently organising individual work steps in a logical sequence.

A particularly noteworthy finding was observed for **Indicator 5 – initiating the first work step**, for which the mean score was  $M = 4.00$  and the standard deviation was  $SD = 0.00$ . This indicates that **all 12 observed learners received exactly 4 points on this indicator**. The finding demonstrates complete consistency in the learners' performance with regard to their ability to initiate the first work step and represents one of the most stable indicators assessed. The absence of variability among the learners on this indicator is therefore a noteworthy finding that should be highlighted in the interpretation of the results.

*Table 4: Comparison of the Three Work-Related Activities*

| Work-related activity | Learners code | n | Mean | Median | Minimum | Maximum | SD   |
|-----------------------|---------------|---|------|--------|---------|---------|------|
| Clay processing       | P1–P3         | 3 | 3,80 | 3,87   | 3,53    | 4,00    | 0,24 |
| Food preparation      | P4–P7         | 4 | 3,68 | 3,77   | 3,27    | 3,93    | 0,29 |
| Working with paper    | P8–P12        | 5 | 3,97 | 3,87   | 3,60    | 4,40    | 0,32 |

*Source: Author's own processing*

The results of the comparison of the three observed work-related activities indicate that the learners' overall mean scores across all 15 indicators differed slightly between the individual activities. The highest mean score was achieved by learners in **working with paper** ( $M = 3.97$ ;  $SD = 0.32$ ), indicating a relatively higher level of performance in meeting the assessed work-related requirements in this activity. This was followed by **clay processing** ( $M = 3.80$ ;  $SD = 0.24$ ), while the lowest mean score was recorded for **food preparation in the school training kitchen** ( $M = 3.68$ ;  $SD = 0.29$ ). However, the differences between the individual work-related activities were not pronounced, as all mean scores fell within a relatively narrow range from 3.68 to 3.97.

In terms of variability in performance, the lowest standard deviation was recorded for **clay processing** ( $SD = 0.24$ ), indicating relatively consistent learner performance within this activity. In contrast, the highest variability was observed in **working with paper** ( $SD = 0.32$ ). The overall mean score for learners P1–P12 was  $M = 3.83$ , with all three work-related activities achieving mean scores above 3.50. Overall, the findings indicate a relatively good and consistent level of performance across the assessed work-related activities, with the most favourable results observed for working with paper and the least favourable results for food preparation in the school training kitchen.

Based on the descriptive characteristics of the data, the comparison involved **three independent groups** according to the type of work-related activity: clay processing ( $n = 3$ ), food preparation in the school training kitchen ( $n = 4$ ), and working with paper ( $n = 5$ ). Given the small sample sizes within the individual groups and the ordinal nature of the rating scale, the **Kruskal–Wallis test** was

selected as an appropriate non-parametric method for examining differences in the level of learner independence across the three groups.

The analysis was based on the **overall mean score of each learner calculated from all 15 observed indicators**. Thus, each learner contributed one overall score to the analysis, resulting in 12 individual observations distributed across the three independent groups.

Table 5: Individual Overall Score

| Work-related activity | Learner code | Overall Mean (M) |
|-----------------------|--------------|------------------|
| Clay processing       | P1           | 3,87             |
| Clay processing       | P2           | 3,53             |
| Clay processing       | P3           | 4,00             |
| Food preparation      | P4           | 3,80             |
| Food preparation      | P5           | 3,73             |
| Food preparation      | P6           | 3,27             |
| Food preparation      | P7           | 3,93             |
| Working with paper    | P8           | 3,87             |
| Working with paper    | P9           | 3,80             |
| Working with paper    | P10          | 4,20             |
| Working with paper    | P11          | 3,60             |
| Working with paper    | P12          | 4,40             |

Source: Author's own processing

To assess differences in the level of independence among learners performing different types of work-related activities, a non-parametric **Kruskal–Wallis test** was used due to the small sample size and the non-normal distribution of the ordinal data. The analysis included the **overall mean score for each learner**, calculated from all 15 assessed indicators.

Table 6: Kruskal–Wallis Test Results

|                     |                                 |                                                                                             |
|---------------------|---------------------------------|---------------------------------------------------------------------------------------------|
| Kruskal-Wallis Test | $H(2) = 1,473$ ;<br>$p = 0,479$ | At the significance level of $\alpha = 0.05$ , the result is not statistically significant. |
|---------------------|---------------------------------|---------------------------------------------------------------------------------------------|

Source: Author's own processing

Descriptive results showed the highest mean level of independence for **working with paper** ( $M = 3.97$ ;  $n = 5$ ), followed by **clay processing** ( $M = 3.80$ ;  $n = 3$ ), while the lowest mean value was recorded for **food preparation in the school training kitchen** ( $M = 3.68$ ;  $n = 4$ ). However, the Kruskal–Wallis test did not indicate statistically significant differences among the three observed work-related activities,  $H(2) = 1.473$ ;  $p = 0.479$ .

The result therefore does not provide evidence that the type of work-related activity was associated with statistically significant differences in the overall level of learner independence within the observed research sample. The differences between the mean values should therefore be interpreted primarily at the descriptive level. The higher mean score observed for working with paper may indicate better performance in activities involving a more structured work material, whereas the lower mean score observed for food preparation in the school training kitchen may be related to the more complex nature of the work situation. Given the small number of observed learners, however, these differences cannot be generalised to the broader population of learners with intellectual disabilities.

To assess the practical significance of the differences among the three work-related activities, an additional analysis of **effect size using epsilon squared ( $\epsilon^2$ )** was performed. The analysis yielded  $\epsilon^2 = -0.059$ . As negative values of epsilon squared do not have a substantive interpretation as an effect, the result indicates a **negligible practical effect**. Thus, both the non-significant Kruskal–Wallis test and the effect size suggest that the observed differences in the overall level of learner independence across the three work-related activities were not practically meaningful within the observed sample.

Table 7: Formula for Calculating the Epsilon-Squared ( $\epsilon^2$ ) Effect Size

| Formula                          | Interpretation of Values                                                                                                                                                                                                                                                                                                                                                   |
|----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\epsilon^2 = H - k + 1 / N = k$ | <p>The result ranges from <b>0</b> to <b>1</b>.<br/> <b>0</b> indicates no group effect.<br/> <b>1</b> indicates complete separation of values between groups.</p> <p>Effect size thresholds:<br/>           &lt; 0.01: Negligible effect<br/>           0.01 – 0.06: Small effect<br/>           0.06 – 0.14: Moderate effect<br/>           &gt;= 0.14: Large effect</p> |

Source: Author's own processing

Based on the calculated H statistic,  $H = 1.473$ , with  $k = 3$  groups and a total sample size of  $N = 12$  learners, the epsilon-squared effect size was calculated as  $\epsilon^2 = -0.059$ . Since epsilon squared may yield a negative value when H is very small, such a value is interpreted as **0**, that is,  $\epsilon^2 \approx 0.00$ . The result therefore indicates a **negligible effect** of the differences among the three types of work-related activities. In other words, not only was no statistically significant difference identified ( $H(2) = 1.473$ ;  $p = 0.479$ ), but the effect size also provides no evidence of a meaningful difference in learner independence between clay processing, food preparation in the school training kitchen, and working with paper.

### Summary of Findings

To assess the practical significance of the differences among the three work-related activities, an additional analysis of effect size using the epsilon-squared coefficient ( $\epsilon^2$ ) was performed. With  $H = 1.473$ , three comparison groups, and a total of 12 learners, the effect size was  $\epsilon^2 \approx 0.00$ . This result indicates a **negligible effect** of the differences among the individual work-related activities. The finding is consistent with the results of the Kruskal–Wallis test, which did not indicate statistically significant differences among the groups ( $H(2) = 1.473$ ;  $p = 0.479$ ). Although the highest descriptive mean score was observed for working with paper ( $M = 3.97$ ), followed by clay processing ( $M = 3.80$ ) and food preparation in the school training kitchen ( $M = 3.68$ ), the observed differences can, in light of the inferential analysis, be considered small and practically negligible. The interpretation should also take into account the very small number of learners in the individual groups ( $n = 3-5$ ), which substantially limits the statistical power of the analysis.

### Discussion and Implications of the Findings

From a descriptive perspective, differences were observed among the individual work-related activities; however, these differences were not statistically significant, and the effect size was negligible.

The results of assessing the learners' level of independence indicated that the level of independent performance of work-related activities differed descriptively across the individual types of work-related activities. The highest mean score was recorded for working with paper, followed by clay processing, while the lowest mean score was observed for food preparation in the school training

kitchen. However, the Kruskal–Wallis test did not indicate statistically significant differences among the groups ( $H(2) = 1.473$ ;  $p = 0.479$ ). This result needs to be interpreted in the context of the very small sample size and the unequal number of learners in the individual groups. The absence of statistical significance therefore does not necessarily imply the absence of differences in learners' practical performance; rather, it indicates that, given the size of the observed sample, the identified differences could not be statistically confirmed.

From a pedagogical perspective, however, the findings highlight the importance of monitoring and systematically developing independence among learners with intellectual disabilities. Independence in work-related activities should not be understood merely as the ability to complete a particular task without assistance, but as a complex competence involving preparation for the activity, understanding the work procedure, carrying it out, responding appropriately to emerging situations, monitoring one's own performance, and completing the work activity. These components create the prerequisites for the gradual transfer of responsibility for the performed activity from the teacher to the learner.

The findings also point to a distinction between organisational and routine activities that were relatively well mastered and activities requiring a greater degree of independent decision-making, sustained concentration, and self-monitoring. From this perspective, the development of independence remains an important objective of work-related instruction, even though the differences among the observed work-related activities were not statistically significant.

The value of the observation therefore lies not only in identifying differences between individual work-related situations but, above all, in its potential to identify specific areas in which learners demonstrate independence and areas in which they continue to require support. The information obtained in this way can be used to individualise pedagogical guidance, establish an appropriate level of assistance, and gradually reduce external support. The development of independence thus remains an essential component of work-related instruction, as its aim is not merely to enable learners to complete a specific work task, but also to gradually create the prerequisites for the highest possible level of functional independence in their everyday lives and future working lives.

## Conclusion

The independence of a learner with intellectual disabilities should therefore not be assessed solely on the basis of whether the learner is able to complete a work-related task. Of particular importance is the extent to which the learner can independently initiate, perform, monitor, and complete individual steps of a work-related activity with the minimum possible need for external support. From this perspective, work-related instruction acquires a broader significance, becoming a context for the systematic development of competencies that extend beyond the specific work task itself and create the prerequisites for achieving the highest possible level of functional independence in the learner's future life.

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**Text reviewed by:**

Prof. PhDr. Stanislav Benčíč, CSc.

Mgr. Lucia Plavec

**Contacts:**

doc. PaedDr. Barbora Kováčová, PhD.

Catholic University, Faculty of Education, Department of Special Education,  
Hrabovská cesta 1, Ružomberok, Slovakia

PaedDr. Martina Magová, Ph.D.

Catholic University, Faculty of Education, Department of Special Education,  
Hrabovská cesta 1, Ružomberok, Slovakia

# WORK EDUCATION OF PUPILS WITH INTELLECTUAL DISABILITIES FROM THE PERSPECTIVE OF TEACHERS

**Martina Magová**

Catholic University, Faculty of Education, Ružomberok, Slovakia, [orcid.org/0000-0002-6664-6299](https://orcid.org/0000-0002-6664-6299)

**Kristián Krolčík**

Workplace focusing on penitentiary and post-penitentiary prevention, intervention, and resocialization, Levoča, Slovakia

## Abstract

*The paper focuses on the importance of work education in the education of pupils with intellectual disabilities from the perspective of teachers. The aim of the research was to identify and characterize teachers' experiences with work education, with a focus on its educational and therapeutic significance, as well as the specific characteristics and needs of pupils. The research was conducted using a qualitative research design, with a semi-structured interview with eight participants as the main data collection method. The data obtained were processed using open coding and thematic analysis. The results highlighted the importance of work education in developing pupils' practical competencies, independence, motivation, and self-confidence. At the same time, its potential to support emotional stability, coping with failure, and the development of frustration tolerance was identified. Work education can therefore be viewed as an important means of providing comprehensive support for the psychosocial development of pupils with intellectual disabilities.*

**Keywords:** work education, intellectual disability, psychosocial development, emotional stability, independence, teachers

## Introduction

Work education represents an important component of the education of pupils with intellectual disabilities, as it combines the development of practical skills with the promotion of independence and social and emotional development. Through concrete work activities, pupils gain direct experience with the outcomes of their own actions, which may positively influence their motivation, self-evaluation, and sense of competence (Kováčová & Harčárová, 2023). The importance of work education should therefore not be viewed solely in terms of acquiring work procedures and skills, but also as a space for supporting the pupil's overall personal development. Particular attention should be paid to how teachers perceive the potential of work education when working with pupils requiring different levels of support (Čarnická et al., 2026). Their experiences may highlight the benefits of work activities, as well as the specific needs of pupils and the conditions that influence their engagement in activities (Kováčová & Harčárová, 2023). For this reason, the paper focuses on teachers' experiences with the implementation of work education for pupils with intellectual disabilities.

## Pupil with Mild Intellectual Disability

An individual with mild intellectual disability should be guided and educated in a way that provides opportunities to participate in various activities and to establish and develop social relationships

and connections beyond the family environment. In general, through their activities, particularly in the work and social domains, they can contribute to the development of their family and the community in which they live. Some pupils with mild intellectual disability are able to travel independently, whereas others require support and assistance when using public transportation, handling money, and planning and organizing their daily lives (Čarnická et al., 2026).

Most pupils with mild intellectual disability are able to work. Some may be employed with a certain level of personal or workplace support, while others may be able to work without such support. In the Slovak context, employment opportunities may include various cafés, shops, sheltered workshops, or the arts, such as theatre groups, where individuals can apply their work-related competencies despite their intellectual disability (Kováčová, 2025, Kováčová et al., 2026).

It should be emphasized, however, that having mild intellectual disability does not necessarily mean that all individuals have fully developed academic skills, such as reading, writing, and numeracy. This may also affect their ability to complete documentation related to a particular work activity. In such situations, support and clarification of individual items may be necessary (Pudišová, 2013). Many individuals with mild intellectual disability establish intimate relationships, and some marry and raise children with varying levels of support. International studies also point to differences in how individuals with mild intellectual disability understand interpersonal relationships and social rules, particularly in terms of their ability to realistically and appropriately evaluate specific situations (Kováčová et al., 2026). In some cases, this may result in an unintentional violation of ethical or social norms.

### **Motivation and Assessment in Work Education**

Motivation and assessment in work education form a complementary cycle that fundamentally determines the extent to which a pupil with intellectual disabilities engages in the educational process. Regarding motivational strategies, experts agree on the importance of experiencing success, although they emphasize different stimuli. While Valášek (2014) identifies the potential of the aesthetics and attractiveness of materials, Kunák (2019) and Honzíková (2015) emphasize the sense of technical competence and the need for immediate positive reinforcement. This approach is particularly important given the reduced frustration tolerance of pupils described by Švarcová (2006), as well as the need to understand the practical meaning of work highlighted by Vagnerová (2014). In the area of assessment, special education practice has shifted from rigid standards towards an individualized relational framework. Kováčová and Harčárová (2023) and Leonhardt et al. (2007) agree on the importance of formative and continuous assessment, which prioritizes the effort invested, the degree of progress, and independence over the aesthetic quality of the final product. In line with this approach, Honzíková (2015) advocates broader use of verbal assessment and self-assessment through visual scales, which can reduce stress and strengthen pupils' self-awareness. The comprehensiveness of assessment is further enhanced by Šesták (2015) and Kocurová (2002), who also incorporate indicators of social behavior, perseverance, and responsibility into the assessment process. As stated by Kožuchová et al. (2011), the overall aim of these strategies is to transform external stimulation into intrinsic enjoyment of creative activity. A system of motivation and assessment designed in this way does not merely serve a classificatory function but becomes a formative tool that supports pupils' self-image and prepares them for successful social integration.

### **Research Design**

The aim of the research was to identify and characterize the participants' experiences with the implementation of work education for pupils with special educational needs, with a focus on its educational and therapeutic significance, the specific characteristics of pupils, and the conditions for implementing work activities.

A semi-structured interview was used as the main data collection method. The interview protocol consisted of 17 open-ended questions based on the specific research objectives. The interviews were conducted directly in the school environment, recorded with the participants’ consent, and subsequently transcribed verbatim.

The research sample consisted of eight participants (R1–R8) who work as teaching staff in special primary schools. Their length of teaching experience ranged from 3 to 20 years, with the sample including participants with both shorter and extensive teaching experience. In terms of the primary educational program variant they taught, variants A, B, and C were represented, with some participants working simultaneously across several variants. The most common combinations were variants A and B, and variants A, B, and C.

This research sample makes it possible to capture the experiences of teaching staff with different lengths of teaching experience and working within individual educational program variants of special primary schools.

Table 1: Summary of Research Sample Characteristics

| Participant code | Length of teaching experience (years) | School type    | Primary educational program variant |
|------------------|---------------------------------------|----------------|-------------------------------------|
| R1               | 13                                    | special school | A                                   |
| R2               | 7                                     | special school | A, B, C                             |
| R3               | 20                                    | special school | A                                   |
| R4               | 16                                    | special school | A, B                                |
| R5               | 4                                     | special school | B, C                                |
| R6               | 3                                     | special school | A, B                                |
| R7               | 15                                    | special school | A, B                                |
| R8               | 20                                    | special school | A, B, C                             |

Source: Own research data, Krolčík & Magová (2025)

The data obtained were processed using open coding in accordance with the principles of thematic analysis. In the first phase, meaning units were identified and initial codes were created, such as “hand-in-hand method,” “low frustration tolerance,” and “lack of consumable materials.” Subsequently, semantically related codes were grouped into subcategories and then into broader categories. The categories thus created made it possible to systematically capture recurring themes and experiences of the participants.

The research was conducted in accordance with ethical principles. Participation in the research was voluntary, and all participants provided informed consent. To ensure anonymity, identifying information was replaced with codes R1–R8, and the names of the institutions were not disclosed. Photographic documentation was obtained in a manner that prevented the identification of individual pupils (Krolčík & Magová, 2025).

Data Analysis

For the purposes of this paper, two of the most numerous categories identified in the overall dataset were selected. These categories also most strongly reflected the research focus:

- 1. Educational and therapeutic significance of work education
- 2. Specific characteristics and needs of pupils in work activities

Both categories are subsequently characterized through individual subcategories and participants’ statements.

### Category 1: Educational and Therapeutic Significance of Work Education

Work education is not perceived merely as a subject focused on acquiring manual skills, but primarily as a comprehensive intervention tool with a significant therapeutic dimension. Based on the semantic similarity of the identified codes, the first category was divided into three in-depth subcategories.

Table 2: Coding of the First Category

| CATEGORY                                                   | SUBCATEGORY                    | CODES                                                                                                                               |
|------------------------------------------------------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| EDUCATIONAL AND THERAPEUTIC SIGNIFICANCE OF WORK EDUCATION | Psychosocial development (1.1) | building self-confidence, a sense of usefulness, immediate results of work, joy of success, elimination of fear of making mistakes. |
|                                                            | Functional literacy (1.2)      | self-care, meal preparation, financial literacy (shopping), orientation in time and space, hygiene.                                 |
|                                                            | Rehabilitation (1.3)           | development of fine motor skills, hand-eye coordination, sensory activation, basal stimulation.                                     |

Source: Own research data

Subsequently, we provide a more detailed characterization of the individual subcategories, which were designated as 1.1 to 1.3.

#### Subcategory 1.1: Psychosocial Development and Emotional Stability

The analysis of the interviews indicates that practical education fulfils an important **psychosocial and compensatory function** in the education of pupils with intellectual disabilities (ID). Respondents do not perceive it merely as a space for developing practical skills, but also as an environment in which pupils can experience success, recognition of their own efforts, and a sense of competence. This function is particularly important for pupils who repeatedly experience failure in academically and cognitively oriented subjects, which may negatively affect their self-esteem, motivation, and willingness to engage in further activities.

Respondent R3 states in this regard: *"Pupils who do not experience a sense of success while sitting at their desks and reading see an immediate, tangible result of their work during practical education, which significantly boosts their self-confidence."* This statement points to the importance of **immediate feedback**, which practical activities naturally provide. The outcome of the activity is concrete, visible, and often usable, distinguishing it from tasks in which the result is mediated by a symbolic system or depends on mastering more cognitively demanding operations. The tangible nature of the outcome enables pupils to more easily connect their own effort with the achieved result and creates opportunities for experiencing personal success.

The phenomenon of the **immediate result** can therefore be considered an important motivational mechanism of practical education. Through their own activity, pupils can develop the experience that they are capable of creating something, completing a task, or managing a practical activity. Such experiences may support the development of a more positive self-image and strengthen their perception of their own usefulness. In this context, practical education does not merely

provide opportunities for practising work procedures, but also contributes to **building a sense of competence and autonomy**.

An in-depth analysis of the statements further showed that the meaning and form of experienced success differ according to the individual abilities and degree of disability of the pupil. For pupils in Variant A, the source of success may be the creation of an aesthetically valuable product, mastery of a particular work technique, or independent completion of an assigned task. For pupils in Variants B and C, success often has a more basic and functional character. Success may consist of mastering a simple work-related action, completing a partial stage of an activity, responding appropriately to an instruction, or performing an element of self-care. Respondent R5 metaphorically compares this difference to elite sporting performance: *“For a pupil with a severe disability, mastering basic self-care is equivalent to winning an Olympic gold medal.”* This statement emphasizes the need to **individualize the criteria of success** and not assess pupils' performance exclusively according to standards typical of their typically developing peers.

An important component of psychosocial development identified by the respondents is also **strengthening independence and a sense of personal usefulness**. Practical education provides situations in which pupils can gradually assume responsibility for individual stages of the work process – from preparing the workplace and selecting tools to carrying out and completing the task itself. Even partial independence may be significant from the perspective of psychosocial development, as pupils gain the experience that they are not merely recipients of assistance but can be active participants in an activity and contribute to its outcome.

Another important finding within this subcategory concerns the **management of fear of making mistakes and the development of tolerance towards failure**. Respondents R3 and R5 point to the low frustration tolerance of some pupils, which, in situations of failure, may manifest itself through refusal to participate, affective reactions, or premature termination of an activity. According to their experience, however, practical education provides an appropriate context for gradually developing a more positive attitude towards mistakes. Respondent R3 describes this approach as the strategy **mistakes are our friends**. Its essence is to avoid perceiving a mistake as definitive failure and instead regard it as a natural part of the learning and creative process.

Such an approach may enable pupils to experiment, repeatedly try individual work procedures, and accept correction without immediately experiencing failure. **A mistake is thus transformed from a threat to one's self-image into an opportunity for further learning**. Gradually gaining experience that failure does not necessarily lead to rejection or negative evaluation may support the development of frustration tolerance and the ability to regulate one's emotional responses.

The respondents' statements also highlight the importance of a **safe and supportive atmosphere**, in which pupils are provided with adequate time, assistance, and encouragement. Positive feedback does not necessarily have to focus exclusively on the final product, but may also address the process itself – the pupil's effort, perseverance, independent decision-making, or successful completion of a particular work-related step. Such an approach to assessment makes it possible to recognize small individual improvements that might otherwise remain unnoticed if attention were focused exclusively on the final performance.

Thus, according to the respondents, practical education creates a **multifunctional space that integrates work activity, learning, social interaction, and emotional experience**. Success in a work-related task may serve as a source of positive feedback that supports self-confidence and motivation; repeated experiences of successfully completing tasks may strengthen independence and a sense of competence; and gradually accepting mistakes may contribute to the development of frustration tolerance and emotional regulation. From this perspective, practical education can be understood not only as a means of developing work-related and self-care competencies, but also as an **important tool for psychosocial support for pupils with intellectual disabilities**.

The overall interpretation of the respondents' statements therefore suggests that **the value of practical education does not lie exclusively in the quality of the product created or in the degree to which a particular work technique is mastered**. Equally important is the process through which pupils gain experiences of success, learn to cope with failure, accept mistakes, cooperate with others, and gradually assume responsibility for their own activities. These aspects can be considered important determinants of psychosocial development and emotional stability among pupils with intellectual disabilities.

#### **Subcategory 1.2: Functional Literacy and Preparation for Independent Living**

In this subcategory, teachers emphasize the transition from school-based theory to practical life competence. The analysis confirmed that PE in special education primarily addresses areas that are generally considered to be acquired naturally within the family environment by the typically developing population. Respondent R3 emphasizes the direct impact of PE on the quality of family life: *"When a pupil learns to spread butter correctly on bread, for the family it means that the child is able to have breakfast independently in the morning without parental assistance."* This shift towards functional independence is crucial for reducing the pupil's social dependence. **literacy** (practising shopping), **orientation in time and space** (following a work schedule), and **hygiene habits**. A critical point emerging from the interview with respondent R7 is the fact that pupils from socially disadvantaged backgrounds enter school without basic everyday habits. In such cases, PE compensates for the absence of preschool preparation, placing increased demands on teachers in the area of developing basic hygiene and self-care skills.

#### **Subcategory 1.3: Rehabilitation and Sensory Stimulation**

The final subcategory focuses on the physiological and neurological aspects of PE. Respondents R2, R5, and R7 perceive this subject as a form of **occupational therapy**. The primary objective is not the final product itself, but rather the process, which stimulates the development of **fine motor skills and bilateral coordination**.

Respondent R5, who works with pupils in Variant C, emphasizes the importance of **basal stimulation and sensory perception of materials**: *"We teach pupils to perceive the material itself – that this is warm, this is cold, this is smooth... it is more therapy than conventional teaching."* From a rehabilitation perspective, teachers particularly emphasize the development of **visual-motor skills (hand-eye coordination)** and **grip**.

Synthesizing these findings, we conclude that the educational and therapeutic significance of PE is perceived in practice as a **holistic process**: successful motor rehabilitation creates the prerequisites for mastering self-care skills, which subsequently contributes to strengthening the pupil's self-confidence and psychosocial stability.

#### **Category 2: Specific Characteristics and Needs of Pupils in Work Activities**

Based on the semantic similarity of the codes, the second category was divided into three in-depth subcategories.

Table 3: Coding of the Second Category

| CATEGORY                                                   | SUBCATEGORY                               | CODES                                                                                                                                          |
|------------------------------------------------------------|-------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| SPECIFIC CHARACTERISTICS AND NEEDS OF PUPILS IN ACTIVITIES | Psychomotor Barriers (2.1)                | Impaired fine motor skills, muscle stiffness, hand tremors, weak grip, coordination difficulties, motor restlessness                           |
|                                                            | Cognitive and Emotional Limitations (2.2) | Low attention span (10-minute blocks), low frustration tolerance, rigidity, affective reactions to failure                                     |
|                                                            | Strengths and Potential (2.3)             | A preference for stereotypical and mechanical activities, visual memory, precision in routine tasks, sincerity, enthusiasm for tactile stimuli |

Source: Own research data

Subcategory 2.1: Psychomotor Barriers and Motor Clumsiness

From the perspective of manual activities, teachers identified psychomotor functioning as the most significant barrier. Respondents R3, R5, and R6 consistently reported that pupils with ID predominantly experience impaired fine motor skills and a low level of bilateral coordination (coordination of both hands). In this context, respondent R3 draws attention to a critical lack of grip strength: *“Many pupils are unable to exert sufficient pressure on a tool, whether they are sawing or simply holding a ruler correctly while drawing.”* This deficit directly limits the selection of technical procedures.

Respondent R5 adds that pupils with more severe disabilities (Variants B and C) frequently experience muscle stiffness or hand tremors, which requires the use of ergonomically adapted aids, such as spring-assisted scissors or thick grips for writing implements. The analysis indicates that motor clumsiness is not merely a physical limitation but may also become a source of secondary frustration when a pupil is unable to perform a movement that they have cognitively planned.

The respondents further emphasized that the degree of motor difficulty varies considerably between individual pupils, which makes a uniform approach to practical activities inappropriate. The same task may therefore be relatively easy for one pupil but require significant adaptation, additional time, or direct assistance for another. Teachers consequently need to adjust not only the difficulty of the task but also the size, weight, shape, and functional properties of the materials and tools used. An important element is also the gradual development of motor skills through repeated practice, whereby the pupil is provided with sufficient opportunities to repeat a movement and consolidate the acquired motor pattern. Repetition is particularly important in activities requiring precision, coordinated use of both hands, or controlled application of force. The analysis also showed that motor limitations may affect the pupil's ability to maintain attention and motivation during an activity. When a task is consistently experienced as physically demanding or difficult to complete, the pupil may lose interest or avoid further attempts. For this reason, teachers consider it important to structure tasks into smaller, manageable steps and to provide immediate positive feedback for partial achievements. Such an approach allows pupils to experience success even when they are unable to complete the entire activity independently.

At the same time, the findings indicate that assistance should be provided in a way that supports, rather than replaces, the pupil's own activity. Excessive physical assistance may reduce opportunities for developing independence, whereas appropriately timed support can facilitate successful completion of a task and gradually lead to greater autonomy. The teacher therefore plays an important role in identifying the boundary between necessary assistance and the space that should be left for the pupil's own motor exploration and problem-solving.

This finding is consistent with the theory of Valášek (2014), who emphasizes the need to adapt materials in order to compensate for the pupil's motor limitations. From this perspective, adaptation should not be understood merely as a technical modification of tools, but as part of a broader individualized pedagogical approach that takes into account the pupil's motor abilities, functional potential, pace of work, and level of independence. Psychomotor barriers therefore represent an important factor influencing not only the performance of individual work tasks but also the pupil's motivation, emotional experience, and opportunities for developing functional independence.

### **Subcategory 2.2: Cognitive and Emotional Limitations in the Work Process**

An in-depth analysis of the interviews revealed that success in PE is limited not only by motor skills but also by executive functions and emotional stability. Attention concentration: Respondents R2 and R5 report that the average period of full concentration on a task does not exceed 10 minutes. *"After ten minutes of monotonous work, the pupil loses interest, starts looking around or disturbing others,"* states R5. This fact requires the teacher to constantly alternate activities and divide the lesson into smaller, dynamic blocks. Frustration tolerance: A key finding is the pupils' low tolerance for failure. Respondent R3 describes situations in which pupils react affectively to even a minor mistake (e.g., an uneven cut): *"They tend to tear up their work immediately or start crying."* This highlights the importance of the "mistakes are our friends" strategy discussed in the first category. Rigidity and fear of novelty: Pupils with ID, particularly those with a co-occurring autism spectrum disorder (R6), demonstrate pronounced rigidity. Any change in an established work procedure may cause uncertainty and even resistance to the activity.

These findings indicate the need for a predictable structure of the work process, in which a new or modified procedure is introduced gradually and supported by clear visual instructions. The teacher must therefore simultaneously respect the pupil's need for routine while creating a safe environment in which tolerance for change can gradually be expanded. An important prerequisite for successful participation in work activities is therefore an appropriate degree of differentiation that takes into account not only the pupil's cognitive abilities, but also their current emotional state and individual pace of work.

### **Subcategory 2.3: Strengths and Specific Potential of Pupils**

Despite numerous limitations, teachers identified in the interviews areas in which pupils with intellectual disabilities demonstrate strengths and which may represent their potential for future employment. Preference for routine and stereotypical activities: Respondent R3 highlights the pupils' excellent ability to perform mechanical and repetitive activities (e.g., sanding wood, weaving carpets, pulling weeds). *"They find a sense of calm in stereotypical activities; they are precise and persistent in them, which is a great asset for their future employment in sheltered workshops,"* explains R3.

Visual memory and sincerity: Respondent R5 points to the strong visual orientation of pupils. When provided with a clear pictogram or a visual step-by-step procedure, they are able to work with surprising consistency and accuracy. At the same time, respondents R3 and R8 emphasize their emotional sincerity and enthusiasm for tactile stimuli (working with clay, dough, or water), which makes PE one of the most popular subjects in the pupils' timetable.

The analysis further indicates that pupils' strengths are particularly evident when the structure of the activity corresponds to their individual abilities and preferred ways of processing information. Predictable sequences of steps allow pupils to anticipate what will happen next and reduce the cognitive demands associated with planning and organizing the activity. Repetitive activities may therefore provide not only a sense of security but also opportunities to consolidate specific practical skills through repeated practice. In this context, routine should not be interpreted merely as a limitation of flexibility, but also as a potential resource that can be purposefully used in educational and pre-vocational preparation.

The respondents also point out that the ability to remember visually presented procedures can facilitate the gradual transition from direct teacher assistance towards greater independence. Once a pupil has mastered a visual sequence, they may be able to perform the activity with reduced verbal guidance and, in some cases, independently. This creates opportunities for developing functional autonomy and increasing the pupil's confidence in their own abilities. Similarly, precision and persistence in repetitive tasks may represent valuable qualities in future work environments where reliability, consistency, and adherence to established procedures are important.

Tactile and sensory activities represent another significant area of potential. Working with materials such as clay, dough, wood, textiles, or water provides pupils with immediate sensory feedback and allows them to engage in activities through direct experience. Such activities may simultaneously support motivation, attention, sensory exploration, and the development of practical skills. The positive emotional response associated with these activities can also facilitate longer-term engagement and willingness to repeat and practise individual procedures.

The synthesis of findings in this category indicates that the characteristics of pupils in practical activities form a complex profile in which motor and cognitive deficits need to be compensated for through methodological structure (visualization, task segmentation into small steps) and by making use of their natural inclination towards routine-based algorithms. At the same time, the findings demonstrate that these characteristics should not be viewed exclusively as limitations. In an appropriately structured environment, certain characteristics may become functional strengths that support learning, independence, and future vocational participation.

PE, in this sense, does not work with "disability" as a deficit alone, but with the individual potential of the pupil, which becomes visible through specific practical activities. The teacher's role is therefore not only to identify what the pupil cannot do, but also to recognize the conditions under which the pupil can perform successfully. Such an approach shifts the focus from limitations towards functional abilities and creates opportunities for meaningful participation in educational, social, and future vocational contexts.

## Conclusion

The results of the qualitative analysis highlight the significant position of practical education in the education of pupils with intellectual disabilities. The respondents' statements confirm that its importance extends beyond the acquisition of work-related, practical, and self-care skills. Practical education creates a natural space for experiencing success, strengthening self-confidence, developing independence, and building a sense of personal competence. In particular, the opportunity to see a concrete and immediate outcome of one's own activity emerges as an important motivational factor that may positively influence the pupil's attitude towards learning and their perception of their own abilities.

The findings also highlight the need to perceive pupil success individually and in the context of their current abilities. For pupils requiring a higher level of support, the decisive outcome does not necessarily have to be the creation of a complex product, but may instead involve mastering a simple work-related task, a partial activity, or an element of self-care. Such an achievement

nevertheless has significant psychosocial value, as it provides the pupil with an experience of mastery and personal usefulness.

Another important aspect of practical education is its potential to support emotional stability and the development of frustration tolerance. Creating an environment in which a mistake is not perceived as failure but as a natural part of the learning process enables pupils to gradually develop more positive experiences of failure. Practical education thus becomes a space in which the development of practical competencies can be combined with the development of emotional and social skills.

Based on the findings obtained, it can be concluded that practical education represents an important means of comprehensive support for pupils with intellectual disabilities. Its benefits can be identified not only in the areas of work readiness and practical independence, but also in self-esteem, motivation, social functioning, and emotional regulation. From the perspective of special education, practical education therefore cannot be reduced to the acquisition of individual work procedures. Its potential lies primarily in its ability to create situations in which every pupil can experience success appropriate to their individual abilities and, through their own activity, gradually develop the experience: *"I can do it myself."*

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**Text reviewed by:**

PaedDr. Silvia Tuláková, PhD.

Mgr. Alžbeta Matulová

**Contacts:**

PaedDr. Martina Magová, Ph.D.

Catholic University, Faculty of Education, Department of Special Education,  
Hrabovská cesta 1, Ružomberok, Slovakia

Mgr. Kristián Krolčík

Workplace focusing on penitentiary and post-penitentiary prevention, intervention, and resocialization, Levoča, Slovakia

# INCLUSION OF INTELLECTUALLY GIFTED LEARNERS IN FOREIGN LANGUAGE EDUCATION IN SLOVAK PRIMARY SCHOOLS

Viera Rassu Nagy

Catholic University, Faculty of Education, Ružomberok, Slovakia, [orcid.org/0009-0003-6212-034X](https://orcid.org/0009-0003-6212-034X)

## Abstract

*This study analyses the limitations of inclusive education for intellectually gifted learners with specific linguistic talent in Slovak primary schools. The findings reveal a significant discrepancy between legislative declarations and actual educational practice: giftedness is predominantly developed outside the school environment, while the school system is unable to respond flexibly to the specific educational needs of gifted learners. In most cases, individualised education programmes remain largely formal, while instructional differentiation is reduced to quantitative enrichment and an increase in the amount of learning material. At the same time, a rigid curriculum limits opportunities for vertical acceleration. A qualitative analysis of interviews with teachers (N = 8) also reveals a high risk of misdiagnosis, particularly when manifestations of cognitive frustration are incorrectly interpreted as symptoms of ADHD or autism spectrum disorder (ASD). The study highlights the need for a fundamental transformation of curricular flexibility, methodological support, and the integration of diagnostic processes with instructional practice in order to enable the effective development of the linguistic talent of intellectually gifted learners.*

## Keywords

*Intellectually gifted learner; linguistic giftedness; inclusive education; curriculum rigidity; diagnosis*

## Introduction to the Issue and the Limits of Inclusion of Intellectually Gifted Learners

The current discourse in Central and Southern European educational sciences places strong emphasis on the implementation of the principles of inclusive education. In its contemporary understanding, inclusion represents an effort to transform the school environment so that it can respond flexibly to the diverse needs of all learners. As Kováčová (2019) argues, discussions about what constitutes inclusion, what does not, and whether inclusion exists at all in our conditions are constrained by one fundamental issue: a lack of preparedness – the unpreparedness of the educational environment, the surrounding community, and all those involved.

In Slovak primary education, however, this concept has been translated into educational practice in a considerably asymmetric manner. Foreign language education has undergone, and continues to undergo, a long process of development. It is a highly dynamic and multidimensional phenomenon, which makes it particularly challenging and, at the same time, interesting. It requires an innovative approach, creativity, and continuous adaptation of teaching methods and techniques so that teachers are able not only to engage learners and motivate them to participate actively in classroom activities, but also to foster their independence and autonomous learning (Kuchárová, 2018). Systematic attention and the allocation of educational resources are primarily directed towards learners with disabilities, specific learning difficulties, or those from socially disadvantaged backgrounds.

Learners with giftedness – and, more specifically, learners with exceptional linguistic talent – remain at the margins of institutional attention. This issue also concerns learners with different

types of giftedness, including artistic, physical, and cognitive giftedness (Valachová et al., 2019). Although legislative documents declare the need to create conditions for the identification, development, and support of gifted learners, these requirements are not necessarily reflected in specific educational approaches and conditions in everyday pedagogical practice. This creates a certain discrepancy between what is formally declared in the field of gifted education at the legislative level and the extent to which the actual educational needs of these learners are addressed within primary school settings (Duchovičová, 2007; Pokrivčáková, 2013).

### The Legislative Framework versus Barriers in Educational Practice in Slovakia

From a *de jure* perspective, the status of intellectually gifted learners in the Slovak Republic is established by Act No. 245/2008 Coll. on Education and Training (the School Act), which defines gifted learners as learners with special educational needs (SEN). The legislation formally guarantees their right to education adapted to their abilities, primarily through the provision of an Individualised Education Programme (IEP).

In actual educational practice in mainstream primary schools in both countries, however, this framework encounters substantial institutional barriers. Schools often perceive the development and ongoing qualitative evaluation of IEPs/Individual Development Plans (IDPs) for intellectually gifted learners as an additional administrative burden rather than as a functional tool for the personalisation of instruction. In both the Slovak and Italian mainstream education systems, which have historically been shaped by standardisation and uniformity, there is a lack of mechanisms providing foreign language teachers with meaningful methodological and material support when working with this target group. Although the diagnostic processes conducted by Slovak counselling and prevention centres (CPP) or Italian clinical centres can identify high cognitive potential, the link between diagnostic assessment and its practical implementation in language classroom instruction remains discontinuous.

### Systemic Limitations of Inclusion in Foreign Language Education

Slovak primary schools remain largely constrained by linear and chronologically structured national curricula. When a learner enters primary education with partially or fully developed linguistic talent and their foreign language communication skills, most commonly in English, have already reached the A2 or B1 level, the standard curriculum may constitute a form of cognitive deprivation. While the majority of the class is acquiring basic lexical units and isolated grammatical structures, the gifted learner is required to follow the same pace of instruction. The Slovak education system does not readily allow a learner to move flexibly, either horizontally or vertically, to a higher grade in a particular subject without undergoing demanding formal examinations.

The concept of inclusion presupposes the teacher's ability to differentiate the educational process in terms of both content and learning processes. In Slovak schools, however, inclusion as implemented by foreign language teachers often takes the form of so-called **quantitative saturation**. When a gifted learner completes a standardised task more quickly than their peers, the teacher typically assigns additional tasks of the same cognitive level – for example, another worksheet focused on the mechanical completion of grammatical exercises. What is lacking is a qualitative transformation of instruction that would take into account the specific cognitive needs of gifted learners, such as deep conceptualisation and the identification of logical patterns within grammatical systems (Reid, 2019).

The current generation of intellectually gifted learners acquires foreign languages in ways that are closely connected to immersive exposure to language within the digital ecosystem. Gifted children demonstrate a high degree of self-directed learning; they absorb language both passively and actively through exposure to authentic video content, participation in global gaming platforms, and engagement with highly specialised and non-linear texts (Pokrivčáková, 2013). Formal

language instruction in primary schools, however, often remains disconnected from this dimension of the learner's world. It is still heavily dependent on printed textbook sets whose thematic content may be outdated and insufficiently responsive to contemporary learners. This creates a profound risk of demotivation, as intellectually gifted learners may perceive formal language education as an artificial and rigid system, potentially leading to a decline in intrinsic motivation and the development of apathy towards formal schooling.

### **Pedagogical Assessment and the Specifics of Asynchronous Development**

One of the specific manifestations of intellectual giftedness may be asynchronous development, in which different areas of a child's development do not progress at the same pace. A high level of cognitive abilities may therefore not be accompanied by a comparable degree of social, emotional, or motor maturity (Valachová et al., 2019). For example, an intellectually gifted learner may demonstrate an excellent level of abstract thinking and foreign language competence while simultaneously requiring greater support in areas such as fine motor skills, emotional regulation, or social interaction with peers. Such developmental unevenness may present a challenging situation from the perspective of educational assessment, particularly when teachers lack sufficient knowledge of the specific characteristics of giftedness and its manifestations in the school environment.

At the same time, undergraduate teacher education programmes for future foreign language teachers at Slovak and Italian universities devote relatively limited attention to giftedness and its psychological and pedagogical specificities. Insufficient knowledge of the manifestations of giftedness may subsequently complicate the appropriate interpretation of a learner's behaviour in the classroom. Manifestations such as low tolerance for repetition of previously acquired material, loss of interest in simple or stereotypical tasks, impatience with a slower pace of work, or an increased need for intellectual stimulation may be interpreted in educational practice as disinterest, disruptive behaviour, arrogance, or a lack of respect for teacher authority. In some cases, such behaviours may also prompt consideration of other developmental or behavioural difficulties, although these manifestations alone may not provide sufficient grounds for diagnostic assessment.

### **Methodological Approaches to Foreign Language Education for Gifted Learners**

The effective development of the linguistic potential of intellectually gifted learners requires a substantial reconsideration of traditional approaches to instruction. In Slovak primary schools, however, the application of specific methodological approaches often conflicts with standardised teaching strategies primarily designed for the average achievement level of the mainstream learner population.

Instructional differentiation represents a key principle of inclusive education and involves adapting the **content, process, and product** of learning. In practice, however, qualitative differentiation is frequently replaced by so-called **quantitative saturation**. When an intellectually gifted learner completes a standardised task ahead of their peers, they are typically given additional work of the same cognitive level, such as another worksheet involving mechanical vocabulary or grammar exercises. As Pokrivčáková (2014) points out, such an approach may become demotivating and may encourage gifted learners to reduce their performance in order to conform to the pace of the class.

A qualitative alternative is represented by the approach developed by Laznibatová (2013) within the APROGEN Programme (Alternative Programme for the Education of Gifted Learners). Two principles are particularly relevant: **curriculum compacting**, in which previously mastered content is identified and repetitive practice is reduced, and **enrichment**, which provides opportunities for more cognitively demanding activities. In foreign language education, this may include working

with authentic texts, exploring linguistic parallels and etymologies, and engaging in problem-based or project-based tasks requiring higher-order thinking. However, implementing such approaches in mainstream Slovak classrooms remains challenging due to relatively large class sizes and the limited availability of methodological resources specifically designed to support differentiated foreign language instruction for gifted learners.

### **CLIL and Modern Technologies in Foreign Language Education for Gifted Learners**

Content and Language Integrated Learning (CLIL) represents a particularly suitable approach to foreign language education for intellectually gifted learners, as it combines language learning with cognitively stimulating subject content. Rather than treating the foreign language as an end in itself, CLIL enables learners to use it as a means of accessing information related to their specific interests, such as science, information technology, or history (Pokrivčáková et al., 2010). The potential of CLIL can be further enhanced through digital technologies. Contemporary gifted learners often acquire language through authentic digital environments and demonstrate a high degree of autonomous learning (Mistrík, 2019). However, the educational value of technology depends on how it is integrated into instruction. When digital tools merely reproduce traditional teaching practices, their potential to provide cognitive challenge and support learner autonomy remains limited.

### **Psychopedagogical Challenges and Risks of Misinterpretation**

The specific developmental characteristics of intellectually gifted learners also create challenges for educational assessment. Asynchronous development may contribute to behaviours that are difficult to interpret in a classroom setting, particularly when instruction does not correspond to the learner's cognitive level. Frustration caused by a slow pace of instruction may manifest itself through restlessness, seeking alternative sources of stimulation, or verbally correcting the teacher (Dočkal, 2011). Without sufficient knowledge of giftedness, such behaviours may be interpreted as disinterest, disruptive behaviour, or may raise concerns about attention or behavioural difficulties.

A further challenge arises when exceptional foreign language competence is accompanied by difficulties in peer interaction. Such a combination may sometimes lead to consideration of autism spectrum disorder, although the observed behaviour alone does not constitute sufficient evidence for such a diagnosis. Appropriate interpretation therefore requires a comprehensive assessment that takes into account the learner's cognitive profile, developmental characteristics, social functioning, and educational context.

These challenges are closely related to the limited attention devoted to giftedness in the pre-service preparation of foreign language teachers. Since intellectually gifted learners may require specific methods and strategies for acquiring new knowledge and skills (Magová, 2024), teacher education should provide greater emphasis on differentiation, enrichment, and the pedagogical interpretation of gifted learners' behaviour. Without such preparation and appropriate support from school-based support teams, teachers may rely on strategies that address classroom management rather than the effective development of the learner's potential.

### **Research Methodology**

The aim of the study is to examine the theoretical assumptions presented in the preceding sections through a qualitative empirical inquiry into the experiences and perspectives of foreign language teachers working with intellectually gifted learners in Slovak primary schools. Given the complex and highly individualised nature of giftedness and its manifestations in the language classroom, a qualitative research design was adopted (Szombatová, 2016).

Data were collected through semi-structured interviews, which enabled the researchers to address predefined thematic areas while allowing participants to elaborate on their individual experiences and perspectives (Kováčiková & Prokeínová, 2007). The research sample consisted of eight English language teachers (N = 8) working at mainstream state primary schools in different regions of Slovakia, each with at least three years of teaching experience. Inclusion criteria comprised current or previous experience of teaching a learner with formally identified general intellectual giftedness or exceptional linguistic talent.

The interviews were conducted either in person or online, audio-recorded with participants' informed consent, and subsequently transcribed verbatim. All data were anonymised. The interview protocol was structured around the key research areas identified in the theoretical framework, including curricular rigidity, asynchronous development, the educational needs of intellectually gifted learners, and the risk of diagnostic misinterpretation.

### **Interview Protocol for Foreign Language Teachers**

#### *Block A: Identification and Educational Assessment of Giftedness*

##### *Focus: manifestations of giftedness in the learner*

1. **Question:** Can you recall a learner from your teaching practice who demonstrated exceptionally advanced foreign language skills upon entering primary school? How did these abilities manifest themselves in classroom activities?
2. **Question:** How did you, as a teacher, determine whether the learner's performance reflected intellectual or linguistic giftedness rather than simply more extensive preparation at home? Did you cooperate with the school support team or a counselling and prevention centre (CPP) in this regard?

#### *Block B: Teaching Practice and Differentiation*

##### *Focus: limitations of a standardised educational system*

3. **Question:** How do you address situations in which a gifted learner completes a standardised task, such as a textbook exercise, significantly earlier than the rest of the class?
4. **Question:** What specific methods do you use with such learners, for example content enrichment, project-based learning, digital technologies, or CLIL? What material, organisational, or time-related constraints do you encounter in Slovak schools?

#### *Block C: Legislation, Support, and Administration*

##### *Focus: systemic aspects*

5. **Question:** What has been your experience with developing and implementing an Individualised Education Programme (IEP) for a gifted learner in the foreign language classroom? Do you perceive it primarily as a useful support tool or as an administrative burden?
6. **Question:** Do you feel that you receive sufficient support from the education system, such as methodological resources, curricular flexibility, and funding for educational materials, when working with learners with linguistic talent? What do you consider to be the most significant gaps in the Slovak system?

#### *Block D: Psychosocial Aspects and Risks of Misinterpretation*

##### *Focus: learner behaviour and diagnostic considerations*

7. **Question:** Have you encountered manifestations of frustration, boredom, apathy, or disruptive behaviour in gifted learners that you associated with a slow pace of instruction? How did school management or parents respond to these situations?

8. **Question:** Have you encountered situations in which behaviours associated with intellectual frustration in a gifted learner were interpreted by teachers or other professionals as indicating attention, behavioural, or autism spectrum difficulties? If so, how was the situation addressed?

Summary Table of Qualitative Research Findings

The table below presents the responses of individual participants (T1–T8) to the key thematic areas addressed in the interviews. The findings indicate that digital self-directed language learning, particularly through online games and video content, as well as boredom associated with insufficient cognitive challenge, were recurring themes across the participants’ accounts.

Table 1: Overview of Qualitative Research Findings

| Teacher Code | Region of Practice     | Identified Source of Learner’s Giftedness                   | Observed Classroom Behaviour                                 | Differentiation Method Applied                               | Practical Functionality                                               | Experience with Risk of Misdiagnosis (ADHD/ASD)                |
|--------------|------------------------|-------------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------------------|-----------------------------------------------------------------------|----------------------------------------------------------------|
| T1           | Bratislava Region      | <i>Extramural English</i> (YouTube, TikTok)                 | Passivity, ignoring assigned tasks, silent drawing           | Enrichment (reading a self-selected book)                    | <b>Formal</b> (implemented mainly on paper for inspection purposes)   | Yes (colleagues suggested assessment for Asperger syndrome)    |
| T2           | Bratislava Region      | Bilingual family environment                                | Correcting the teacher’s pronunciation, disruptive behaviour | Quantitative differentiation (additional worksheet)          | <b>Ineffective</b> (difficult to implement in a class of 24 learners) | Yes (the school advocated ADHD assessment due to restlessness) |
| T3           | Nitra Region           | Digital self-directed learning (gaming)                     | Speaks only English, ignores Slovak                          | CLIL projects (IT topics using a tablet)                     | <b>Partially functional</b> (supported by the school psychologist)    | Yes (suspected autism spectrum disorder)                       |
| T4           | Žilina Region          | Combined factors (high intellectual ability + computer use) | Apathy, head on desk, refusal to write                       | Peer-support role (“teacher assistant”)                      | <b>Ineffective</b> (formal goals created without substantive content) | No (the learner was perceived simply as idle and lazy)         |
| T5           | Banská Bystrica Region | <i>Extramural English</i> (games and videos)                | Hyperactivity, frequent unsolicited verbal responses         | Quantitative differentiation (additional textbook exercises) | <b>Formal</b> (perceived primarily as an administrative burden)       | Yes (the primary teacher was convinced the learner had ADHD)   |

|           |                |                                            |                                                        |                                                                |                                                                         |                                                                            |
|-----------|----------------|--------------------------------------------|--------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------|
| <b>T6</b> | Prešov Region  | Spontaneous reading from the age of four   | Interrupting, demanding attention                      | Content enrichment (creating comics)                           | <b>Ineffective</b> (insufficient funding for educational materials)     | No (mainly conflicts with school management concerning perceived rudeness) |
| <b>T7</b> | Košice Region  | Digital self-directed learning (streaming) | Social withdrawal, quietly speaking to self in English | None (the learner is required to follow the pace of the class) | <b>Ineffective</b> (the counselling recommendation was not implemented) | Yes (the school support team considered referral for ASD assessment)       |
| <b>T8</b> | Trenčín Region | Above-average memory and parental support  | Excellent performance, perfectionism, stress           | Curriculum compacting (working on tasks intended for Grade 8)  | <b>Functional</b> (due to strong teacher initiative)                    | No (the learner was considered unproblematic, although somewhat anxious)   |

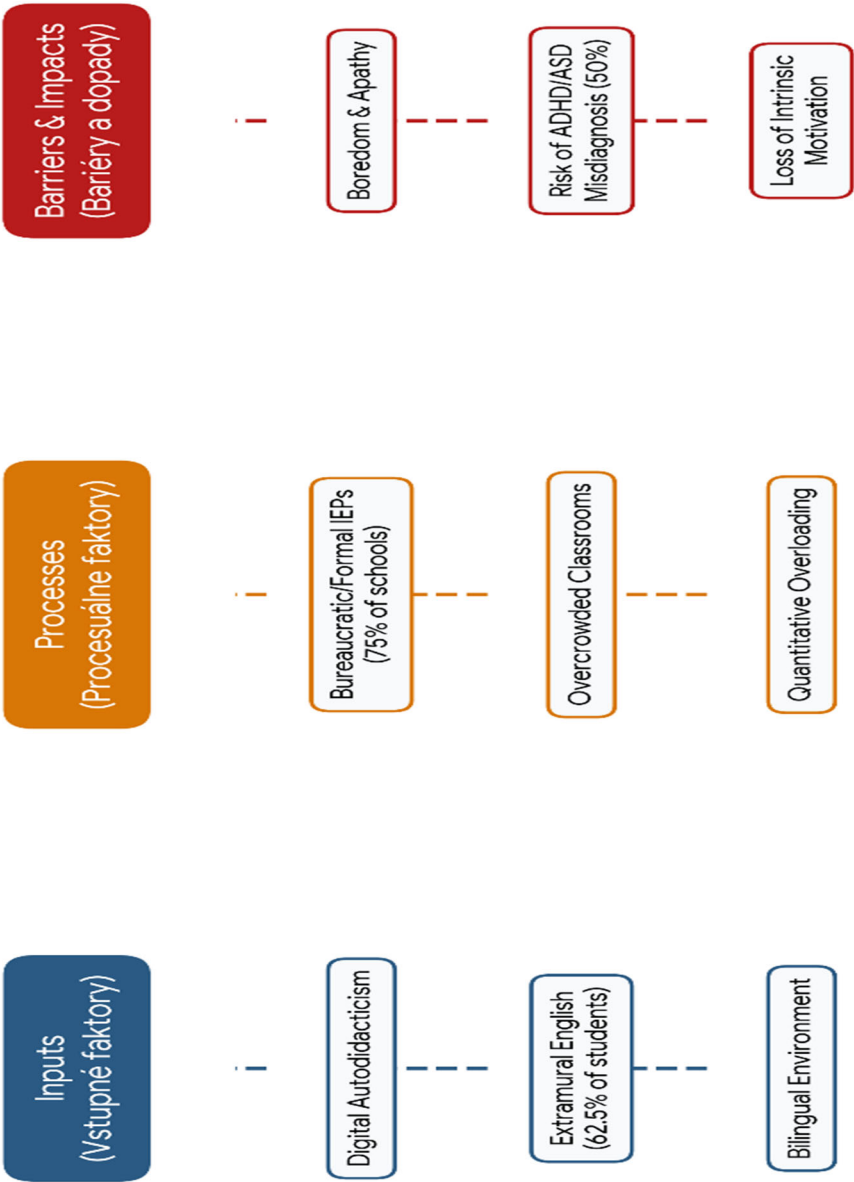
*Source: Author's own elaboration*

The Figure 1 below illustrates a **negative feedback loop within the Slovak inclusive education system**, showing how systemic limitations may contribute to learner frustration and, in some cases, to the misinterpretation of gifted learners' behaviour as indicative of other developmental or behavioural difficulties.

- **Origin of giftedness:** 62.5% of the teachers (5 out of 8) reported cases of *Extramural English*, indicating that learners had acquired substantial foreign language skills independently through digital environments outside formal instruction.
- **Limitations of IEP implementation:** In 75% of cases (6 out of 8), teachers described the Individualised Education Programme (IEP) as either largely formal or ineffective in practice. Reported barriers included administrative demands and insufficient resources for differentiated educational materials.
- **Risk of diagnostic misinterpretation:** 50% of teachers (4 out of 8) reported experiences in which manifestations associated with cognitive frustration – such as withdrawal into English, refusal of standardised tasks, or restlessness related to boredom – contributed to consideration of ADHD or autism spectrum disorder rather than being interpreted primarily in the context of giftedness.

The model organises the interview findings from Slovak teachers (U1–U8) into three analytical dimensions: **Inputs** (the sources and development of giftedness), **Processes** (the ways in which the school responds to gifted learners), and **Barriers and Outcomes** (systemic limitations and their potential consequences for the learner).

Figure 1: Hierarchical Components of Inclusion of Intellectually Gifted Learners in Slovakia



Source: Author's own elaboration

The main findings of the study lead to three key conclusions:

1. **Acceleration of giftedness outside school (Inputs):** Contemporary linguistic giftedness is no longer developed primarily within structured school environments. Phenomena such as *digital self-directed learning* and *Extramural English* (identified in 62.5% of the participants) indicate that some learners enter formal education with substantial prior exposure to the language and with linguistic competences that may exceed the expectations of the national curriculum.
2. **Formalisation of inclusive instruments (Processes):** The systemic response to such giftedness remains limited. Individualised Education Programmes (IEPs) were described as ineffective or predominantly bureaucratic in 75% of cases. Educational differentiation was more often characterised by quantitative increases in workload than by qualitative enrichment, with gifted learners being assigned additional tasks of a similar level of cognitive complexity.

3. **Pathologisation of boredom (Barriers and Outcomes):** The most critical finding concerns the potential psychosocial consequences for learners. Prolonged cognitive under-stimulation and boredom may contribute to behavioural responses such as apathy or disruptive behaviour. In 50% of cases, teachers reported experiences in which such manifestations were interpreted in terms of attention, behavioural, or autism spectrum difficulties, potentially contributing to inappropriate diagnostic considerations rather than supporting the development of the learner's actual potential.

## Conclusion

The inclusion of intellectually gifted learners in foreign language education in Slovakia should not remain merely a formal declaration in educational documentation. Moving from a standardised model of schooling towards a more personalised approach requires a fundamental paradigm shift: giftedness should be understood not simply as an advantage that a learner can develop independently, but as a specific educational need requiring appropriate stimulation and support. The present study examined the realities of inclusive education for linguistically gifted learners in Slovak primary schools from the perspective of teachers (U1–U8). The findings, synthesised into a three-dimensional model of **Inputs, Processes, and Barriers**, reveal a substantial gap between learners' cognitive potential and the capacity of the educational system to respond to their specific needs.

Based on the identified limitations, several measures can be recommended at different levels of the education system. At the **system level**, greater curricular flexibility is needed to enable schools to implement vertical acceleration for learners who demonstrate advanced foreign language competence without unnecessarily demanding administrative procedures. For example, learners who demonstrate a foreign language competence substantially above the expected level should have access to more flexible forms of progression. Systemic support should also include freely accessible digital repositories of differentiated learning materials based on principles such as curriculum compacting, enrichment, and CLIL.

At the level of **counselling and prevention centres**, psychological assessment reports should provide not only psychometric results but also pedagogically applicable recommendations for teachers. These may include information on the learner's learning characteristics, suitable forms of enrichment, and suggestions for differentiated tasks. Greater interdisciplinary cooperation between counselling services, school support teams, and teachers could also contribute to more effective implementation and evaluation of individualised education programmes.

At the level of **school management and foreign language teachers**, quantitative increases in repetitive tasks should be replaced by qualitative differentiation. Once a learner has demonstrated mastery of a particular learning objective, subsequent activities should provide greater cognitive challenge through enrichment, project-based learning, CLIL, authentic language materials, and interest-based tasks. The teacher's role should increasingly shift from that of the primary source of information towards that of a mentor and facilitator who supports learner autonomy and takes individual developmental characteristics into account.

Ultimately, inclusive education for intellectually gifted learners should not be understood as an additional burden placed on teachers, but as a systematic adaptation of educational content, methods, and learning opportunities to individual potential. As Kováčová (2019) emphasises, genuine inclusion requires a change in the way learners and their individual needs are understood. Such a shift is essential if Slovak primary schools are to create conditions in which linguistic talent can be identified, supported, and developed rather than left outside the scope of systematic educational provision.

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## Text reviewed by:

Prof. PhDr. Stanislav Benčíč, CSc.  
PaedDr. Beata Kozmonová

## Contacts:

PaedDr. Viera Rássu Nagy, PhD.  
Catholic University, Faculty of Education, Department of Special Education,  
Hrabovská cesta 1, Ružomberok, Slovakia

# Contextualization and Scaffolding in Professional Vocabulary Development: Toward a Pedagogical Framework for Tertiary Language Education

Борисенко Олександра Анатоліївна

Кандидат філологічних наук, доцент кафедри іноземних мов економічного факультету, Київський національний університет імені Тараса Шевченка

**Oleksandra Borysenko**

PhD in Philology, Associate Professor, Foreign Languages Department, the Faculty of Economics, Taras Shevchenko National University of Kyiv

## Abstract

Structural change in higher professional education demands a rethink of specialized foreign language instruction in economics, marketing, and analytics, where graduates must navigate hybrid communicative spaces blending data reporting, marketing concepts, and macroeconomic frameworks. This paper examines the challenges of acquiring professional vocabulary, focusing on *semantic drift*: how polysemous terms (*elasticity*, *conversion*, *yield*, *pipeline*) shift meaning across domains.

Drawing on Vygotsky's Zone of Proximal Development, Bruner's scaffolding theory, and Halliday's Systemic Functional Linguistics, the study proposes an integrated linguo-pedagogical matrix mapping three levels of contextualization (micro-textual, meso-situational, macro-discursive) onto corresponding scaffolding types (hard, soft, procedural). The resulting three-tiered model shows how structured support reduces cognitive load, resolves interference between competing domain meanings, and guides learners toward independent, discourse-level mastery.

**Keywords:** professional vocabulary development, instructional scaffolding, contextualization, semantic drift, tertiary language education, linguodidactics, economics, marketing, business analytics

## 1. Introduction

### 1.1 Background and Institutional Context

Higher education worldwide is undergoing rapid structural change, driven by digital integration and the growing overlap between academic disciplines. This shift calls for a serious rethink of how specialized foreign language instruction, Content and Language Integrated Learning (CLIL) are approached. In today's tertiary institutions, especially within faculties of economics, business administration, and the social sciences, the old boundary between pure language learning and subject-specific content has largely disappeared. Graduates in Economics, Marketing, and Business Analytics no longer work within isolated linguistic silos. Instead, they need to navigate complex, hybrid communicative environments where quantitative data interpretation, financial compliance frameworks, empirical market modelling, and strategic negotiation all intersect on a regular basis.

Traditional approaches to English for Specific Purposes (ESP), which have historically relied on grammar drills, passive translation exercises, and static, single-domain glossaries, simply aren't

enough to prepare students for the realities of multinational corporate environments, international regulatory bodies, or global academic discourse. Conventional language teaching tends to treat vocabulary as a fixed set of dictionary definitions to be memorized, but real-world professional communication demands something more: higher-order discursive, pragmatic, and analytical competence. It isn't enough for learners to know what a word means in a generic sense. They also need to understand how its meaning, pragmatic force, typical word combinations, and register shift depending on the professional context in which it is used.

## 1.2 The Problem of Semantic Drift and Cross-Disciplinary Word Confusion

One of the biggest challenges in teaching is what we might call *semantic drift*: the way common, multi-purpose words shift in meaning as they move between fields. A word can mean one thing in everyday English and something quite different, even contradictory, once it lands in a specific discipline. This is a particular headache in economics education, where students are constantly tripped up by terms that look familiar but behave differently depending on whether they're encountered in microeconomics, digital marketing, or business analytics.

A few examples illustrate this well:

### Conversion

1. *In digital marketing*, conversion is a key performance indicator (KPI): the percentage of prospective leads who move through the sales funnel to complete a desired action, such as going from an ad click to an actual purchase.
2. *In business analytics*, it refers to something quite different: transforming raw data, casting it into new types, or migrating it through a database schema as part of an ETL (Extract, Transform, Load) pipeline.
3. *In international economics*, conversion typically means currency exchange, capital account convertibility, or the transformation of asset liquidity under global trade regimes.

### Elasticity

1. *In microeconomics*, elasticity is a precise mathematical measure of how sensitive quantity is to changes in price, income, or the price of related goods, expressed as a coefficient along a supply or demand curve.
2. *In strategic marketing*, the same word describes something more qualitative: how loyal customers are to a brand, how sensitive they are to price changes during a promotion, or how the market responds to competitors' positioning.
3. *In business data systems*, elasticity refers to something else entirely: how well a system architecture scales, how cloud computing infrastructure adjusts to demand, or how storage allocation flexes dynamically.

### Pipeline

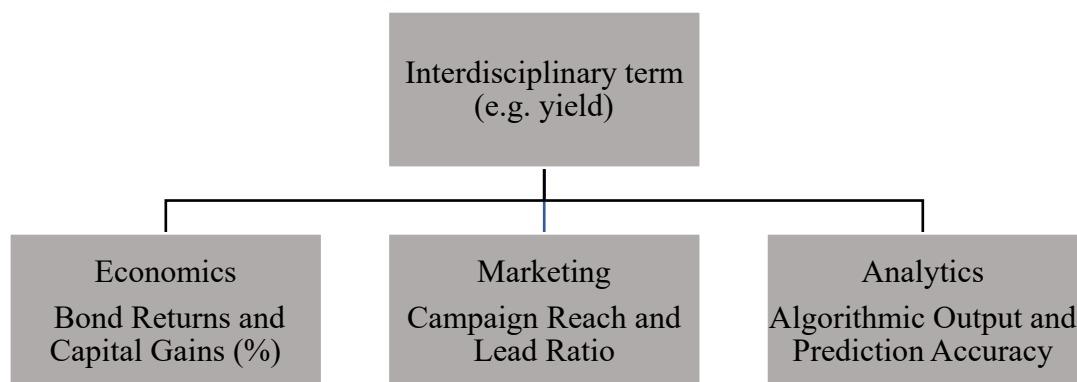
1. *In marketing and sales*, a pipeline visualizes the stages of customer acquisition, lead qualification, and deal management within a CRM system.
2. *In business analytics*, it refers to automated data processing workflows, such as sequences for feature extraction or CI/CD (continuous integration/continuous deployment) chains.
3. *In macroeconomics*, pipeline can mean something physical or financial: energy infrastructure corridors, capital project funding mechanisms, or strategic supply lines for resources.

### Yield

1. *In financial economics*, yield refers to real return on investment, coupon rates, bond yields, or capital gains as a percentage.
2. *In marketing*, it describes how efficiently a campaign reaches its audience, measured through impression-to-lead ratios or engagement rates.

3. *In business analytics*, yield can refer to the output of an algorithmic model, the prediction accuracy of a decision tree, or the volume of data extracted per query cycle.

Diagram1. Interdisciplinary Semantic Mapping of Professional Discourse in Higher Education



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When tertiary students encounter these polysemous terms without explicit, structured support, they often run into real cognitive friction. It is common for learners to fall into inter-domain lexical interference, carrying a term's meaning over from one field into another where it simply does not apply, or worse, where it actively misleads. A student might know the dictionary definition of *yield* or *conversion* perfectly well, yet still struggle to use it correctly when auditing an econometric forecast, drafting a marketing plan, or documenting a data pipeline.

### 1.3 Theoretical Solution: Contextualization and Scaffolding

Overcoming semantic drift and lexical interference calls for uniting two foundational paradigms in modern language pedagogy: contextualization and instructional scaffolding.

Contextualization acts as the primary anchor for resolving semantic ambiguity. It rests on the idea that specialized vocabulary cannot be learned in isolation from the social and discursive environments where it's actually used (Halliday & Matthiessen, 2014). Within this framework, contextualization operates across three distinct levels:

1. **Micro-level context** (syntagmatic/textual): the immediate grammatical patterns, syntactic constraints, and register-specific collocations a word appears in.
2. **Meso-level context** (case-based/situational): authentic problem-solving tasks, simulated department meetings, case studies, and business negotiation scenarios.
3. **Macro-level context** (discursive/sociocultural): institutional norms, global regulatory frameworks, trade compliance standards, and the broader socio-economic policy environment.

Instructional scaffolding, grounded in Vygotsky's (1978) socio-constructivist theory and later formalized by Wood, Bruner, and Ross (1976), works alongside contextualization to give students the adaptive support they need to work through these layers of complexity. Scaffolding offers temporary, targeted help, such as syntax matrices, Socratic questioning, or genre templates, that eases the burden on working memory, allows learners to build up cognitive schemas, and is gradually withdrawn as learners become more independent (Sarmiento-Campos et al., 2022).

### 1.4 Research Purpose and Structural Organization

This paper sets out to build a theoretical and methodological framework for developing professional vocabulary in tertiary language education, with a specific focus on economics, marketing, and business analytics. More specifically, the study aims to:

1. Bring together socio-constructivist, cognitive, and systemic-functional theories into a single, integrated pedagogical model;

2. Explain how semantic drift and inter-domain lexical interference operate cognitively across specialized disciplines;
3. Develop an operational matrix that maps micro-, meso-, and macro-level contextualization against hard, soft, and procedural scaffolding;
4. Offer practical task examples and assessment approaches that curriculum designers and ESP/CLIL practitioners can put to use.

## 2. Methodology of the Review

The literature search covered four major databases: Scopus, Web of Science (Core Collection), ERIC, and Google Scholar, spanning publications from 2015 to 2026. A small number of seminal historical works, Vygotsky (1978), Wood, Bruner, and Ross (1976), Halliday (1985), and Sweller (1988), were added manually, since these predate the search window but remain foundational to the paper's theoretical grounding.

Search terms were organized around four conceptual pillars, and records were retained only if they touched on all four areas simultaneously. The first pillar covered the instructional context: terms such as *English for Specific Purposes*, *ESP*, *CLIL*, *tertiary language education*, and *linguodidactics*. The second focused on the linguistic phenomenon under study: *vocabulary acquisition*, *lexical development*, *semantic drift*, *polysemy*, and *interference*. The third addressed the pedagogical mechanism: *scaffolding*, *instructional support*, *Zone of Proximal Development* (Vygotsky, 1978), and *Cognitive Load Theory* (Sweller, 1988). The fourth narrowed the search to the relevant professional fields: *economics*, *marketing*, *business analytics*, and *interdisciplinary pedagogy*.

This search strategy surfaced a body of recent empirical work directly relevant to the review's aims. Hrdličková (2020) examined how business and law vocabulary is acquired in ESP classrooms, highlighting how terms with everyday meanings (such as *capital*) take on far more precise, field-specific senses once students encounter them in a specialized context. Related work on Business English pedagogy has likewise stressed that vocabulary instruction needs to be scaffolded and revisited over time rather than delivered as a single exposure, since deeper cognitive processing and repeated engagement are what make specialized terms stick (Namwong et al., 2022). Within CLIL research more specifically, Castellano-Risco et al. (2020) found that the instructional context itself, rather than the sheer volume of vocabulary input, was the strongest predictor of second-language vocabulary gains, a finding that lends direct empirical support to this paper's emphasis on contextualization over rote exposure.

Search terms within each pillar were treated as interchangeable alternatives, while all four pillars had to be represented for a record to be considered relevant. This layered structure allowed the search to remain broad enough to capture interdisciplinary work, while staying focused on studies genuinely relevant to professional vocabulary development in tertiary education.

## 3. Literature Review

The theoretical foundation for professional vocabulary acquisition in tertiary education draws on three traditions: cognitive psychology, socio-constructivist pedagogy, and systemic functional linguistics. Bringing these traditions together offers a robust framework for understanding how specialized lexical knowledge is mentally built, cognitively processed, and put to use in real professional settings.

### 3.1 Socio-Constructivism, Scaffolding, and the Zone of Proximal Development

#### *Vygotsky's Socio-Constructivist Framework*

The pedagogical foundation of this study rests on Lev Vygotsky's socio-constructivist theory of cognitive development (Vygotsky, 1978). Vygotsky argued that higher psychological functions, including language processing, conceptual categorization, and abstract reasoning, do not develop in isolation within an individual's mind. Instead, they are shaped through social interaction,

cultural tools, and symbolic systems. Learning, in this view, is fundamentally social: knowledge is built together before it becomes internalized.

At the centre of Vygotsky's model is the Zone of Proximal Development (ZPD), which he defined as the gap between what a learner can achieve independently and what they can achieve with guidance from an adult or a more capable peer (Vygotsky, 1978, p. 86).

In tertiary foreign language education, particularly within ESP and CLIL settings, upper-intermediate learners (roughly B2/C1 level) consistently run into a specialized version of this gap. They may have solid general linguistic competence, yet still struggle badly when faced with authentic, unscaffolded professional texts in economics, marketing, or analytics. They can read the individual words, but they can't bridge the distance between knowing a dictionary definition and applying a term the way an expert would.

#### *Bruner's Instructional Scaffolding and Fading*

Jerome Bruner and his colleagues turned Vygotsky's ZPD into the practical educational concept of instructional scaffolding (Wood, Bruner, & Ross, 1976). Scaffolding refers to the temporary support an instructor, peer, or pedagogical tool provides so a learner can accomplish a task that would otherwise be beyond their unassisted ability.

Wood et al. (1976) identified six functions that effective scaffolding tends to serve: drawing the learner's interest and keeping them oriented toward the task; simplifying the task by reducing the number of steps needed to reach a solution; keeping the learner focused on the goal; highlighting the features that matter most; managing frustration so the task doesn't become overwhelming; and modelling an ideal or expert solution.

Crucially, scaffolding isn't meant to be permanent. Van de Pol, Volman, and Beishuizen (2010), in their widely cited review of a decade of scaffolding research, identify contingency, fading, and the gradual transfer of responsibility as the three defining features of genuine scaffolding. In practice, this means an instructor diagnoses where the learner currently stands, offers support suited to that moment, and steadily withdraws it as the learner grows more capable. As learners internalize structures and build independent competence, the support is dismantled step by step.

#### *Contemporary Applications in ESP and CLIL*

In today's university language teaching, scaffolding has grown beyond simple peer tutoring into more structured instructional design. Researchers generally distinguish between two modes of delivering it. Hard scaffolding refers to pre-planned, fixed instructional materials, such as sentence frames, graphic organizers, vocabulary co-occurrence charts, or text-structure templates, that support lower-level decoding and organization. Soft scaffolding, by contrast, is more dynamic and responsive: Socratic questioning, real-time feedback, communicative prompts, and peer negotiation that instructors deploy spontaneously as problems arise.

In specialized vocabulary instruction, combining hard and soft scaffolding keeps tertiary learners from falling back on rote memorization. It gives them structural support for processing complex registers while still building the independence they'll eventually need to function professionally on their own.

### **3.2 Cognitive Load Theory and Lexical Processing Architecture**

#### *Human Cognitive Architecture*

While socio-constructivism explains how learning is socially shaped, John Sweller's Cognitive Load Theory (CLT) explains the underlying cognitive mechanism behind why unassisted exposure to specialized texts so often fails as a learning strategy (Sweller, 1988). CLT rests on a model of human cognitive architecture built around two memory systems. Working memory has extremely limited capacity and duration when it comes to processing new, unorganized information: Miller's (1956) classic account put the limit at roughly seven items, plus or minus two, while Cowan's (2001) later, more rigorous review argued that the true limit, once rehearsal and

long-term memory support are controlled for, is closer to about four chunks. Long-term memory, by contrast, has virtually unlimited storage, and information there gets organized into complex, automated knowledge structures called schemas.

#### *The Three Dimensions of Cognitive Load*

Sweller's framework describes the total cognitive load a learner experiences as the sum of three components: intrinsic load, extraneous load, and germane load.

Intrinsic load reflects the inherent difficulty of the material itself, driven by how many elements need to be held in mind and processed together. Polysemous professional terms (think of *elasticity* meaning different things in microeconomics, marketing, and cloud infrastructure) carry high intrinsic load, because the learner has to juggle syntax, domain knowledge, and context all at once.

Extraneous load is the mental effort wasted on poor instructional design: split attention, unguided searching, or badly structured tasks. When tertiary students are left to decipher specialized vocabulary from raw, unscaffolded academic texts with no support, their working memory gets swamped by this kind of unproductive processing, leaving little capacity left for actual learning.

Germane load, finally, is the productive mental effort that goes into building, refining, and automating long-term schemas. The whole point of good instructional design is to cut down on extraneous load so that working memory capacity can go toward this more productive, germane processing instead.

#### *Cognitive Load Reduction Through Scaffolding*

Instructional scaffolding acts directly on this cognitive architecture. Hard scaffolding (sentence frames, data-commentary templates, syntactic matrices) works as a kind of external cognitive offloading: by handling low-level structural and syntactic demands for the learner, it substantially reduces extraneous load. That, in turn, frees up working memory for germane schema-building, allowing learners to store richer, multi-domain lexical knowledge in long-term memory.

### **3.3 Systemic Functional Linguistics and Register Theory**

#### *Halliday's Metafunctional Model*

To round out the constructivist and cognitive perspectives, Michael Halliday's Systemic Functional Linguistics (SFL) offers the socio-linguistic grounding for contextualization (Halliday, 1985; Halliday & Matthiessen, 2014). SFL treats language not as a passive set of abstract rules, but as a dynamic resource people use to make meaning within specific social situations.

Halliday identifies three core functions language performs at once: the ideational function, which constructs experience and logical relationships (what the text is actually about); the interpersonal function, which enacts social relationships, roles, and stances (who is speaking to whom, and how); and the textual function, which organizes language into a coherent, cohesive text (how the message is put together).

#### *Register Variables: Field, Tenor, and Mode*

Central to SFL is the idea of register: the way language choices shift systematically depending on three situational variables. Field, tied to the ideational function, refers to the institutional domain or subject matter at hand; in specialized tertiary education, field is what determines domain-specific terminology, whether that's econometric regression or customer churn modelling. Tenor, tied to the interpersonal function, refers to the social roles and relationships between the people communicating, and it shapes things like formality, hedging, and politeness, such as an analyst presenting a risky forecast to senior executives versus peers reviewing each other's code. Mode, tied to the textual function, refers to the channel or medium of communication, and it shapes how a text is structured and how dense or cohesive it is, as in the difference between a written legal brief and an interactive slide presentation.

### *SFL as a Lens for Contextualization*

SFL helps explain why traditional vocabulary teaching, which treats words as static, isolated dictionary entries, tends to fail in tertiary professional education. A specialized term shifts in pragmatic force, syntactic behaviour, and meaning as field, tenor, and mode change around it.

Contextualization puts SFL into practice across three levels: micro-textual (field-specific collocations and syntactic patterns), meso-situational (case-based role-plays that adjust for tenor), and macro-discursive (mastering the genre conventions tied to a given mode). Scaffolding is what guides tertiary learners through these shifts in register, helping them adapt their vocabulary choices to the standards expected across economics, marketing, and business analytics.

## **4. Theoretical Foundations and Domain-Specific Pedagogical Matrix**

### **4.1 Operationalizing Contextualization Across Specialized Domains**

Resolving semantic drift in a systematic way means building contextualization into instruction at three distinct levels, each targeting a different scale of meaning-making.

#### **A. Micro-Level Context (Syntagmatic/Textual Scale)**

At this level, the focus narrows down to the immediate grammatical environment a word lives in: what it typically combines with, what structures it fits into, and how those patterns shift by register. This is precision work at the level of the phrase.

In business analytics, terms like *variance*, *skew*, or *pipeline* can be scaffolded through syntax matrices and technical commentary templates, helping learners see how a term like "pipeline" behaves differently in "pipeline architecture" versus "feature variance." In economics, the same approach applies to structural collocations built around systemic mechanisms, phrases like "elasticity of substitution" or "fiscal consolidation measures." And in marketing, learners work on mapping the syntactic patterns that surround performance indicators, such as "conversion funnel efficiency" or "customer acquisition cost reduction."

#### **B. Meso-Level Context (Case-Based/Situational Scale)**

At the next level up, vocabulary gets anchored in something closer to real professional life: authentic problem-solving tasks, department-style role-plays, and simulated business scenarios where a term stop being an abstract label and starts functioning as a working tool.

In marketing, this might look like a simulated product launch audit, where *conversion* shifts from a textbook definition into a decision-making metric that students actually weigh against ad spend and customer retention figures. In business analytics, learners might work through churn-prediction datasets, interpreting outputs like *yield*, *precision*, and *recall*, and then translating those findings into recommendations a non-technical stakeholder could actually use. In economics, students might simulate a central bank committee deliberating on interest rate policy in the middle of an inflationary shock, forcing them to use economic vocabulary the way policymakers actually do, under pressure and with real consequences on the table.

#### **C. Macro-Level Context (Discursive/Sociocultural Scale)**

At the broadest level, specialized vocabulary connects to industry-wide standards, international regulatory frameworks, socio-economic policy, and the realities of cross-border trade.

In economics, this could mean working through the language of international trade policy, for instance, analysing how the EU's Carbon Border Adjustment Mechanism ripples through global supply chains. In marketing, it might involve weighing the trade-offs between localizing a brand for different markets and keeping it standardized worldwide, across cultures and regulatory environments that don't always agree. In business analytics, it could mean grappling with international data privacy regimes like GDPR and CCPA, along with the broader conversation around ethical AI governance in how data gets reported and used.

Table 1. A Pedagogical Matrix for Contextualized Scaffolding

| Professional Domain | Contextual Level                       | Scaffolding Type                                                                             | Example Term& Meaning Shift                                                                 | Learner Autonomy Stage                                                                       |
|---------------------|----------------------------------------|----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| Business Analytics  | Micro-Level (Syntagmatic/Textual)      | Hard Scaffolding: syntax matrices, code-commentary frames, and technical reporting templates | "Pipeline" → workflow/ETL automation; "Yield" → algorithmic output accuracy                 | Tier1: Guided Acquisition (decoding technical terms and building structured reports)         |
| Marketing           | Meso-Level (Situational/Case-Based)    | Soft Scaffolding: Socratic questioning, negotiation templates, and peer-led pitch feedback   | "Conversion" → funnel progression/KPI tracking; "Elasticity" → brand promotion sensitivity  | Tier2: Collaborative Application (shaping strategic messages and defending campaign choices) |
| Economics           | Macro-Level (Sociocultural/Discursive) | Procedural Scaffolding: genre analysis guides, policy brief frames, and peer audit rubrics   | "Yield" → bond return/asset valuation; "Elasticity" → price/income sensitivity coefficients | Tier3: Autonomous Mastery (synthesizing policy and forecasting at a strategic, macro level)  |

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5. Domain-Specific Instructional Applications and Task Examples

To show how the Integrated Pedagogical Matrix works in practice, this section walks through three classroom-tested examples. Each one shows how a particular level of contextualization, micro, meso, or macro, pairs naturally with a particular type of scaffolding, hard, soft, or procedural, across business analytics, marketing, and economics.

5.1 Business Analytics Example: Micro-Level Hard Scaffolding for Data Reporting

This example sits within business analytics and data science communication, focusing on terms like *pipeline*, *variance*, *yield*, *feature extraction*, and *overfitting*. The goal is simple in principle but tricky in practice: help students write precise, technical commentary on statistical model outputs without accidentally slipping into the general business meanings of these same words.

The scaffolding tool is a syntax matrix paired with sentence frames for code commentary, a textbook case of what Wood, Bruner, and Ross (1976) call hard scaffolding: a fixed, pre-built structure that carries the learner through a task they couldn't yet manage alone. The matrix offers three interchangeable pieces students can mix and match: a subject (say, "the predictive pipeline" or "the model"), a verb phrase ("demonstrates significant," "yields an accuracy rate of," "exhibits severe overfitting in"), and a statistical outcome to round out the sentence ("variance across validation folds," or "feature coefficients, with an R-squared of 0.89").

In the classroom, this unfolds in three steps. Students first review a raw output log from a machine learning model, showing its performance across ten cross-validation folds. Then they use

the matrix to build a well-formed technical sentence, something like: "The machine learning pipeline yields an accuracy rate of 87.4%, while exhibiting minor variance across validation folds." Finally, once the pattern feels familiar, they write a 150-word summary evaluating the model's deployment risks entirely on their own, with the matrix quietly fading into the background.

### 5.2 Marketing Example: Meso-Level Soft Scaffolding for Campaign Pitch Defence

This example moves into digital marketing and brand strategy, working with terms like *conversion rate optimization (CRO)*, *customer acquisition cost (CAC)*, *elasticity*, *omnichannel reach*, and *value proposition*. The aim is to help students defend strategic budget decisions in front of an executive audience, using precise marketing vocabulary while under real pressure to think on their feet.

Here the scaffolding is soft rather than fixed, closer to a live conversation than a template. Student teams take on the role of a digital marketing agency proposing a \$500,000 reallocation of an e-commerce platform's campaign budget. As teams present, the instructor challenges them with spontaneous, Socratic-style questions, echoing the same kind of contingent, in-the-moment questioning Wood et al. (1976) identified as central to effective scaffolding. A typical prompt might be: "You've increased budget allocation for social media channels by 30%. How does this affect your overall customer acquisition cost, and what's your projected conversion threshold?" Students respond with the same precision they'd need in an actual boardroom: "While initial CAC may rise by 5%, our targeted CRO strategy will lift top-of-funnel conversion rates from 1.8% to 2.4%, offsetting the added channel costs."

After each pitch, peer groups step in with an evaluation rubric, rating the presenter's tone, register, and lexical precision under questioning, layering peer feedback on top of the instructor's live scaffolding.

### 5.3 Economics Example: Macro-Level Procedural Scaffolding for Policy Brief Writing

This example shifts into macroeconomics and international trade policy, targeting terms like *fiscal consolidation*, *price elasticity of demand*, *trade balance*, *regulatory compliance*, and the EU's Carbon Border Adjustment Mechanism (CBAM). The goal is for upper-level students to work through complex trade regulations and produce a formal macroeconomic policy brief written for government stakeholders.

The scaffolding tool here is a structured genre template, a form of procedural scaffolding that guides students through the expected shape of this kind of writing. The executive summary asks them to define the economic shock or regulatory shift at hand, using expected phrases like "inflationary pressures," "fiscal consolidation," and "trade balance volatility." The empirical analysis section asks them to present elasticity metrics and supply chain data, following a pattern along the lines of: "Assuming high price elasticity of demand, where the coefficient exceeds 1.0, foreign import substitution would likely..." The policy recommendations section calls for three concrete legislative proposals, written in the confident, formal register typical of policy writing: "the Ministry must implement...", "it is imperative that..."

The task unfolds across three phases. Students first deconstruct an authentic policy brief from a body like the IMF or the European Central Bank, using the template to see how real policy writing is put together. They're then given a simulated trade disruption, such as the introduction of EU CBAM tariffs on imported steel, and draft their own 500-word brief using the same template. Finally, students carry out a double-blind peer review using a rubric grounded in Halliday's (1985) systemic functional linguistics, assessing each other's writing across the same three dimensions introduced in Section 3.3: how accurately the content is conveyed, what stance the writer takes toward the reader, and how well the text holds together as a whole.

## 6. Pedagogical Implications, Assessment, and Limitations

### 6.1 Implications for ESP/CLIL Curriculum Design

The framework proposed here points to several concrete changes that business and economics faculties could implement in curriculum design.

The first concerns the co-design of language instruction. Language courses are typically developed independently by language departments, with limited input from subject-matter faculty. A more effective model would involve ESP instructors and economics or marketing faculty jointly designing at least one instructional unit per semester around an authentic disciplinary artifact, such as an earnings call transcript, an anonymized marketing dashboard, or a central bank statement. For instance, a first-year economics-track language course might replace a generic business vocabulary unit with a joint session in which students annotate an authentic Federal Reserve press release alongside their economics instructor, then analyse its collocational patterns and register choices with their language instructor. This represents a modest but meaningful shift away from invented textbook examples and toward the language students will encounter in professional practice.

The second concerns course sequencing. Rather than treating "Business English" as an undifferentiated course delivered uniformly across four years, a program could align its structure explicitly with the three-tier model proposed in this study. Years 1–2 would emphasize brief, frequent hard-scaffolding exercises, such as the data-commentary syntax task described in Section 5.1, integrated into regular class sessions rather than delivered as isolated units. Year 3 could introduce a single recurring simulation extending across the semester, for example, a simulated consultancy project in which student teams present a marketing budget proposal to a panel of instructors acting as clients, revisited at intervals to provide repeated, low-stakes practice in defending decisions under questioning, consistent with the pitch scenario outlined in Section 5.2. By Year 4, students would work toward a single capstone deliverable, such as a policy brief addressing a current trade issue (for example, EU carbon tariffs or a recent monetary policy decision), produced and defended with minimal scaffolding, in line with the exemplar presented in Section 5.3.

With respect to polysemy, one concrete instructional tool would be a cumulative glossary documenting semantic drift, compiled collaboratively by students across all four years rather than provided in advance by instructors. Each time a familiar term is found to shift meaning across a new disciplinary context, students would record the term, the relevant domain, and a brief definition. By the final year, a cohort would have constructed its own reference resource tracking how terms such as *pipeline*, *yield*, *elasticity*, and *conversion* function differently across analytics, finance, and marketing contexts. This approach renders the phenomenon of semantic drift observable and self-documented, rather than something instructors merely describe in lectures.

### 6.2 Scaffolding-Aligned Assessment Framework

Assessment should mirror the same three-tier progression underlying the instructional design, ensuring that evaluation methods remain consistent with pedagogical practice.

At Tier 1 (Guided Acquisition), a practical approach involves brief, weekly commentary exercises: students are presented with an unfamiliar dataset or output log and given a short window to produce a single accurate technical sentence using the syntax matrix, consistent with the task described in Section 5.1. Such assessments are low-stakes and frequent, appropriate given that the instructional objective at this stage is the development of accurate, automatized usage rather than high-pressure evaluation.

At Tier 2 (Collaborative Application), assessment shifts to recorded, interactive tasks, such as a brief team presentation defending a marketing or business decision, evaluated not only on the proposal itself but on the team's capacity to respond to unscripted follow-up questions, consistent with the CAC/CRO defence scenario described in Section 5.2. An appropriate rubric

would assess register maintenance under pressure, lexical accuracy when responding to unplanned challenges, and the ability to recover appropriately from errors, criteria that more closely resemble professional evaluation than conventional written examination.

At Tier 3 (Autonomous Mastery), assessment appropriately consists of a substantial independent task, such as a policy brief, analytical report, or research paper, completed with minimal instructor support during the drafting process. One concrete implementation would involve providing students with a current, authentic event, such as a recent tariff announcement or interest rate adjustment, and requiring a policy brief of approximately 1,000 words within a defined timeframe, evaluated according to the three systemic functional linguistics dimensions introduced earlier: accuracy of content, appropriateness of stance toward the reader, and overall textual cohesion.

### **6.3 Limitations and Directions for Future Research**

This framework represents a theoretical starting point rather than an empirically validated model, and several limitations warrant acknowledgment.

The most significant limitation concerns the absence of empirical validation. The proposed framework is currently grounded in theoretical reasoning and instructional design logic rather than empirical evidence. An appropriate initial study would compare two sections of the same first-year business English course, one employing the proposed scaffolding matrix and one following standard departmental practice, assessing vocabulary retention and writing quality through a pre/post-test design at the conclusion of the semester. Such a study would provide preliminary evidence before undertaking larger-scale or longitudinal research.

A further limitation concerns instructor preparation. Implementing Socratic scaffolding around marketing decisions, or assessing systemic functional linguistics-based register shifts in an economics policy brief, presumes a degree of subject-matter familiarity that many language instructors may not currently possess. A practical response would involve structured, recurring interdisciplinary workshops, for example, an economics faculty member leading a session each term on the structure and evaluation criteria of authentic policy briefs, rather than expecting language instructors to acquire this expertise independently.

Future research would also benefit from more rigorous cognitive measures. Employing eye-tracking or electroencephalography to compare working memory load during scaffolded versus unscaffolded vocabulary tasks would provide more direct evidence for the cognitive load claims outlined in Section 3.2, rather than relying on classroom performance as an indirect proxy. Longitudinal corpus-based studies tracking individual students' writing development across a full four-year program would further clarify whether learners progress through the proposed three tiers as the model suggests, or whether actual developmental trajectories are considerably less linear than the tiered structure implies.

## **7. Conclusion**

This review and the conceptual framework it suggests indicate that mastering professional vocabulary in higher education, particularly across economics, marketing, and business analytics, cannot be achieved through isolated lexical memorization or unguided communicative immersion alone. Addressing the challenges of semantic drift and inter-domain lexical interference requires a systematic, theory-driven alignment between the level of contextual complexity involved in a given task (micro, meso, or macro) and the corresponding form of pedagogical scaffolding provided (hard, soft, or procedural).

By integrating Socio-Constructivism, Cognitive Load Theory, and Systemic Functional Linguistics within a single, actionable pedagogical matrix, this framework reconceives tertiary language education as an active process of cognitive and discursive development, rather than a passive exercise in vocabulary instruction. In doing so, it seeks to equip future economists,

marketers, and analysts with the linguistic precision, pragmatic flexibility, and analytical autonomy necessary to function effectively within contemporary global professional discourse.

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# Philological Sciences

## Causes of Language Change

Tamar Tsulaia

Akaki Tsereteli State University, Kutaisi, Georgia, PH doctor of philology

The presented study addresses one of the fundamental issues in linguistics — language change, its causes, and the theoretical models proposed by various scholars. The paper discusses both internal structural factors and external sociocultural and economic factors that influence language transformation or its complete replacement.

The study notes that language change is a long-term and hardly noticeable process. It also emphasizes that the primary condition for language shift and development is social bilingualism, which manifests itself in the process of intergenerational transmission.

The paper concludes that, despite the existence of numerous theoretical models, it is impossible to determine in advance exactly which combination of factors will cause language change or preservation. However, in most cases, the decisive role is played by the sociopolitical and economic environment.

Keywords: language change, bilingualism, sociopolitical and economic factors.

### Causes of Language Change

For centuries, people have speculated about the causes of language change. The main problem in determining these causes lies in deciding which of the possible explanations should be taken seriously. Scholars are overwhelmed by the number of potential theories that emerge during the research process. They formulated countless hypotheses before reaching conclusions about what had actually occurred

In the past, language change was attributed to an astonishing variety of factors encompassing almost every aspect of human life — physical, social, mental, and environmental. Like a traffic accident, linguistic changes may have multiple causes. A car crash is rarely caused by a single major factor, such as the sudden loss of steering control or the driver falling asleep. More often, there is a combination of factors contributing to the overall catastrophe. Similarly, linguistic changes are also likely caused by a combination of factors.

Given the confusion and contradictions surrounding the causes of language change, it is not surprising that some well-known linguists consider the entire field to be something of a disaster zone. Leonard Bloomfield (1933) argued that the causes of sound change are unknown. In a similar tone, Robert D. King (1969) noted that many linguists — probably the majority — had long abandoned the search for the causes of phonological change. Furthermore, pessimism is reflected in Zellig Harris's (1969) statement that explaining the causes of language change goes far beyond any theory ever developed. However, such pessimism is unjustified. Even if we are unable to examine every possible cause, we can still consider the explanations proposed over the years and evaluate their relative significance.

Jean Aitchison (2004: 135–150) lists four general causes of language change:

1. Fashion and random fluctuation
2. Foreign elements
3. Social needs
4. Politeness

In addition, Sarah G. Thomason (2003) argues that foreign material transferred from one language to another also involves three distinct types of change. First, some changes that occur in cases of gradual language death belong to the category of attrition — the loss of linguistic material — but they do not necessarily make the dying language resemble the language replacing it. Second, deliberately implemented linguistic changes, such as cases in which a speech community intentionally distances its language from neighboring languages, are contact-induced but do not involve diffusion. Third, some changes occur as a result of indirect interference, usually when a borrowed morpheme triggers a chain reaction that disrupts the structure of the recipient language.

It is important to note that language shift or death, as well as language maintenance, are long-term collective outcomes of language choice. There are a number of conditions that compel people to abandon one language in favor of another.

The most fundamental condition is social bilingualism. Research has shown that in almost all cases, language shift within a community occurs through intergenerational transition. Typically, one generation is bilingual but transmits only one of the two languages to the next generation. The language of a monolingual community is generally maintained as long as monolingualism itself is preserved. It should also be noted that the existence of social bilingualism does not necessarily mean that language shift will occur. It is a necessary, but not sufficient, condition.

Other studies have demonstrated that migration is another cause of language change. When members of a small group migrate to a particular region, they often shift to the dominant language of the host community. It is also possible that, as a result of large-scale migration, the local population may shift to the language of the migrants. This is especially common in situations where the local population has been militarily defeated by the migrating group.

Language shift may also be determined by the level of prestige associated with a language and by the number of its speakers. If a language enjoys higher prestige, speakers of other languages may replace their own language with the more prestigious one. Likewise, a population with a relatively small number of speakers may shift to the language of a numerically larger group.

Although all of the conditions discussed above have been widely studied, there has been no significant success in using any combination of these factors to reliably predict either language shift or language maintenance. It should also be noted that there are numerous cases in which a speech community is exposed to the same conditions but nevertheless maintains its language.

Thus, despite the existence of many theoretical models, language change remains a slow process, and the factors influencing it may not be easily predictable or readily identifiable in advance. However, in most cases, language change is driven by sociopolitical and socioeconomic factors.

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# Linguistic Challenges in Intercultural Communication

**Medea Imnadze**

PhD, Assistant Professor, Batumi State Maritime Academy

## Introduction

Intercultural, or so-called intercultural communication involves direct communication between representatives of different cultures. It is well known how diverse the cultural backgrounds of crew members can be. They differ in cultural values, national traditions, clothing, behavior, diet, living environment, views, etc.

Even in this area, maritime communication is a peculiar phenomenon. Because of international crews, it has been quite a considerable amount of time since, according to the International Maritime Convention, seafarers had a common language, English. Moreover, English is an essential part of educational programs for training maritime personnel of any specialization; seafarers have to pass an English language exam several times.

The above situation does not deny the intercultural nature of maritime communication ; official-business relations may be monolingual, but they are based on different cultural cognitive bases of communicants; therefore, they have all the characteristic features of intercultural communication. Moreover, we should not forget that the English language certificate obtained in different countries is proof that the sailor has passed the appropriate language level test; however, speaking practice still involves many “underlying” and invisible problems, including:

- 1) inaccuracies and misunderstandings caused by phonetic nuances;
- 2) lack of speech practice;
- 3) very different “variants” of the English language;
- 4) lack of knowledge of cultural background information, etc.

Particular importance should be attached to the final point when the ship's crew, upon entering a foreign port, has to communicate with representatives of that port's service (the port master, customs officers, the pilot). Maritime literature documents numerous cases in which failures in professional communication are attributed to linguo-ethnic barriers.

## Discussion

In 1973, the international community raised the issue of adopting standardized, universally accepted English-language terminology and phraseology, driven by the bitter experience of humanity, particularly the serious consequences of misunderstandings. Language misunderstanding has repeatedly become a direct cause of border disasters.

In this regard, we present several examples:

In New Orleans in 1996, the naval vessel BRIGHT FIELD lost its maneuverability due to a technical malfunction and crashed into a shopping center located on the coast.

Initially, the port captain and the ship's captain established communication without misunderstanding. After the ship encountered technical problems, the port captain naturally asked the question, "Do we have a problem?", to which the ship's captain did not answer, which ultimately led to a disaster:

*"After the main engine tripped, the crew noticed a drastic reduction in engine vibration, as the bow veered to port. At this point, the pilot (responsible for safely guiding the ship through congested waterways) asked the master (the ship's highest-ranking authority responsible for the operation and safety of the ship, crew, and cargo), "Do we have a problem?" By now, the Bright Field was on*

*its destructive path. The master didn't reply"* (James A. Ruggieri, P.E., *General Machine Corp*, September 01, 2002, <http://www.ecmweb.com/content/case-runaway-ship>).

It is noteworthy that the captain of the ship was Chinese, who, according to the port captain, spoke to him in quite "broken" English: *"The Pilot suggested that the Chinese master spoke only a 'kind of broken English' and that he had not received any response to his commands to put the engine full astern, away from the riverbank"* (Tores Evangelos, *Language Barriers and Miscommunication as a Cause of Maritime Accidents*).

Many other cases are the result of similar misunderstandings, for example, in 1996, the Chinese captain of the naval vessel WEALTHY RIVER was bringing the ship into the port of Charleston (South Carolina). He turned the ship in the opposite direction from the information received from the port, and as a result, the ship entered shallow water:

*"The Chinese captain, who spoke very little English, misinterpreted this as a command to turn to hard to port, and ordered the helmsman to do so. The vessel, which had been in the center of the channel, swung to port and proceeded towards the north edge of the channel. Before the situation could be corrected, the ship had left the dredged channel and grounded almost immediately"* (Tores Evangelos, *Language Barriers and Miscommunication as a Cause of Maritime Accidents*).

In 1973, the International Maritime Safety Committee (IMO) decided that in order to overcome language barriers, to assist in the greater safety of navigation and of the conduct of the ship, it was necessary to introduce a common language for navigation. According to the decision, this language is English. Accordingly, the Standard Marine Navigational Vocabulary (SMNV) was created, which was adopted in 1977. It was amended in 1985.

Taking into account the changes taking place in modern seafaring, the Maritime Safety Committee decided in 1992 to create a more comprehensive vocabulary than the SMNV, which later became known as the SMCP (Standard Marine Communication Phrases). In 2001, the IMO SMCP was compiled, and in 2002 it came into force.

The IMO SMCP meets the requirements of the STCW and of the SOLAS Conventions, covering the communication safety aspects laid down in these conventions. Use of the IMO SMCP should be made as often as possible; seafarers should adhere as closely as possible to it in relevant situations. The IMO SMCP offers a rich choice of situations covered by phrases well suited to meet the communication requirements of the STCW Convention.

The IMO SMCP reduces grammatical, lexical and idiomatic varieties to a tolerable minimum. The IMO SMCP helps maritime training institutions.

The need to standardize the language is of particular importance due to the increasing number of internationally trading vessels with crews speaking many different languages, since problems of communication may cause misunderstandings leading to dangers to the vessel, the crew, and the environment.

Knowledge of the existing document is required for certification for all officers working on ships more than 500 tonnage.

In Georgia, the relevant standards have been adopted in accordance with the above-mentioned international documents: see the "Georgian Maritime Code"

([http://www.economy.ge/uploads/kanonmdebloba/transporti/Sazgvao\\_kodeqsi.pdf](http://www.economy.ge/uploads/kanonmdebloba/transporti/Sazgvao_kodeqsi.pdf));

the Law of Georgia "On Education and Certification of Seafarers"

([http://www.economy.ge/uploads/kanonmdebloba/transporti/mezgvaurta\\_ganatileba\\_da\\_sertificireba.pdf](http://www.economy.ge/uploads/kanonmdebloba/transporti/mezgvaurta_ganatileba_da_sertificireba.pdf)). It is also worth considering that a number of articles and provisions have been added to the "Georgian Maritime Code" in accordance with the "International Convention on Standards of Training and Watchkeeping for Certified Seafarers" (International STCW Convention), which was revised in 2010 in Manila.

According to statistics, 20% of maritime accidents are related to language problems in intercultural communication. The vast majority of modern maritime crews are multilingual. Crew members come from diverse ethnic backgrounds, and they engage in professional dialogue with one another, where speech-related issues frequently arise. The need for intercultural communication in the maritime field is very high, since when entering different ports, crew members have verbal contact with port personnel, customs officers, pilots, etc. The ship's Captain and the pilot hired in the port must be able to establish effective communication for safety reasons. The issue is further complicated by the fact that during informal communication in microgroups, seafarers still speak their native language, and when addressed by a member of another microgroup, some have difficulty switching from one language code to another. This problem, in our opinion, has been almost not investigated in the specialized literature. Moreover, the "linguistic portrait" of working seafarers requires the following information:

- 1) Native language and knowledge of other languages (except English);
  - 2) Skills in switching from one language to another;
  - 3) Certificate of English language proficiency should reflect the following skills:  
a) Reading; b) Speaking; 3) Listening (auditing); 4) Writing; 5) Translation.
  - 4) Experience in using professional terminology and specialized phraseology.
- This information helps prevent or minimize emergencies caused by misunderstanding.

After analyzing the features of maritime communication, we can summarize the following :

Maritime communication takes place in two different modes: official and unofficial communication:

Official communication is conducted primarily in the international language of sailors-English-with rare exceptions.

Unofficial communication is multilingual, reflecting the diverse linguocultural backgrounds of international crews.

From a semiotic point of view, maritime communication includes both verbal and non-verbal methods. Direct verbal communication predominates, but in certain typical situations non-verbal signals, or a combination of verbal and non-verbal forms, are used.

In terms of scope, official maritime communication is local in nature, as it takes place within professional groups. Unofficial communication, on the other hand, is more intense, involving intragroup and interpersonal relations.

The status of the communicators and sailors' interactions is hierarchical, though they can also be democratic. The intercultural dimension of maritime communication is undeniable, and it remains highly specific in its characteristics- and restricted to a professional setting.

## Conclusion

All of this serves once again demonstrate that effective communication at sea is essential for ensuring safety, preventing accidents, and managing vessel traffic efficiently.

Moreover, navigational and safety communications (ship- to- shore; shore-to-ship; onboard ship) must be precise, simple, and unambiguous to avoid confusion and error.

In conclusion, using the IMO SMCP provides a clear and reliable system for communication at sea, ensures that vessels and shore authorities understand each other, reduces risks, and maintains safe and efficient maritime operations worldwide.

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## Geological and Mineralogical Sciences

УДК 528+550.837+553.98

# ПРОЕКТ РЕКОГНОСЦІРУВАЛЬНОГО ОБСТЕЖЕННЯ ТЕРИТОРІЇ УКРАЇНИ МОБІЛЬНИМИ ПРЯМОШУКОВИМИ МЕТОДАМИ З МЕТОЮ ВИЯВЛЕННЯ БЛОКІВ ДЛЯ ПОШУКІВ ВУГЛЕВОДНІВ, ВОДНЮ, РУДНИХ КОРИСНИХ КОПАЛИН ТА ВОДИ

**Якимчук М.А.**

Інститут прикладних проблем екології, геофізики і геохімії, пер. Лабораторний, 1, м. Київ, 01133, Україна

**Корчагін І.М.**

Інститут геофізики ім. С.І. Субботіна НАН України, просп. Акад. Палладіна, 32, м. Київ, 03680, Україна

**Соловйов В.Д.**

Інститут геофізики ім. С.І. Субботіна НАН України, просп. Акад. Палладіна, 32, м. Київ, 03680, Україна

**Анотація.** Представлено проект рекогносцирувального обстеження території України з метою виявлення перспективних блоків та ділянок для проведення детальних пошукових робіт на нафту, газ та природний водень. Підготовлений проект може бути оперативно реалізований з використанням мобільної прямопошукової технології, яка включає модифіковані методи частотно-резонансної обробки та декодування супутникових знімків та фотознімків, вертикальне електрорезонансне зондування розрізу, а також методику інтегральної оцінки перспектив нафтогазоносності великих пошукових блоків і ліцензійних ділянок. Для практичної реалізації проекту супутниковий знімок території України розбито на 180 окремих блоків (фрагментів), частотно-резонансну обробку яких доцільно проводити окремо. При обробці фрагментів знімків пропонується виконувати наступний комплекс вимірювальних процедур: а) фіксація відгуків на частотах нафти, конденсату і газу; б) реєстрація сигналів на частотах метаноокислювальних бактерій; в) встановлення наявності на глибині 57 км вулканічної структури, в якій є умови для синтезу вуглеводнів; додаткова фіксація відгуків нафти, конденсату і газу на цій глибині; г) фіксація сигналів на частотах нафти, конденсату і газу з нижньої частини розрізу на глибинах 5, 10, 15 км з метою оцінки перспектив виявлення нафти і газу в глибинних горизонтах розрізу. Перелічені процедури інструментальних вимірювань повною мірою показали свою ефективність та інформативність у процесі апробації прямопошукових методів на ділянках (майданчиках) буріння пошукових свердловин на суші та шельфі в різних регіонах земної кулі. У процесі проведення

експериментальних робіт отримано численні докази на користь глибинного (абіогенного) генезису вуглеводнів в рамках концепції водневої дегазації Землі. Апробована технологія дозволяє наповнювати досліджуваний розріз конкретними породами (осадовими, метаморфічними та магматичними), а також виділяти на поверхні ділянки та інтервали в розрізі, перспективні для пошуків рудних і горючих корисних копалин. Супер-мобільні методи доцільно використовувати для оцінки перспектив нафтогазоносності (рудоносності) великих пошукових блоків і локальних ділянок (у тому числі виставлених на аукціони), вибору оптимальних місць (майданчиків) для закладки розвідувальних і експлуатаційних свердловин, оцінки перспектив виявлення покладів нафти і газу в глибинних і надглибинних горизонтах розрізу, пошуків і локалізації зон розміщення глибинних каналів міграції хімічних елементів, флюїдів і мінеральної речовини у верхні горизонти розрізу. Застосування мобільної та малозатратної технології дозволить значно прискорити геологорозвідувальний процес на нафту, газ та природний водень, а також зменшити фінансові витрати на його реалізацію.

**Ключові слова.** Україна, нафта, газ, водень, вапняки, мергелі, доломіти, базальти, граніти, прямі пошуки, глибинна будова, вуглекислий газ, зондування розрізу, обробка даних ДЗЗ.

### Вступ

У 2019-2022 роках у різних регіонах земної кулі проведено значний об'єм експериментальних досліджень з метою апробації частотно-резонансних методів обробки та декодування супутникових знімків і фотознімків [6], а також розробки та вдосконалення методології їх практичного використання під час вирішення геолого-геофізичних задач різного характеру.

Результати апробації мобільної технології в режимі інтегральної оцінки нафтогазоносності (рудоносності) великих блоків (ліцензійних у тому числі) показали, що в такому режимі технологія може бути використана для оперативного обстеження територій окремих країн з метою виявлення (вибору) найбільш перспективних блоків (ділянок) для проведення детальних пошукових робіт на конкретні (різні) види корисних копалин. У зв'язку з цим у 2022 році були підготовлені та запропоновані проекти рекогносцирувального обстеження територій низки країн у різних регіонах земної кулі [22]. В даній статті описано особливості проектів рекогносцирувальних досліджень території України з метою виявлення найбільш перспективних блоків і ділянок для проведення детальних пошукових на нафту і газ, природний водень, рудні корисні копалини та воду.

### Методи досліджень

Експериментальні дослідження рекогносцирувального характеру проводяться з використанням мобільної прямопошукової технології, що включає модифіковані методи частотно-резонансної обробки та декодування супутникових знімків та фотознімків, вертикальне електрорезонансне зондування (сканування) розрізу та методику інтегральної оцінки перспектив нафтогазоносності (рудоносності) великих пошукових блоків і локальних ділянок [6]. Окремі компоненти використовуваної технології розроблені на принципах «речовинної» парадигми геофізичних досліджень, суть якої полягає в пошуку конкретної (потрібної в кожному конкретному випадку) речовини [2]. Розроблені методи засновані на стоячих електричних хвилях, відкритих Ніколою Тесла в 1899 році в глибинних горизонтах Землі [3, 4]. У модифікованих версіях методів частотно-резонансної обробки супутникових знімків і фотознімків, а також вертикального зондування (сканування) розрізу використовуються наявні бази даних (набори, колекції) осадових, метаморфічних і магматичних порід (<https://karpinskyinstitute.ru/ru/info/sprav/petro/petro-mobil.pdf>),

корисних копалин та хімічних елементів. Більш детально особливості та можливості використовуваних методів, а також методика проведення інструментальних вимірювань описані в [6-15].

На відміну від класичних геофізичних методів, використовувана технологія дозволяє в кожному конкретному випадку наповнювати досліджуваний розріз присутніми в ньому комплексами осадових, метаморфічних і магматичних порід, а також визначити в першому наближенні (і уточнювати на етапах деталізації) інтервали розрізу, перспективні на виявлення горючих і рудних корисних копалин, безпосередньо, в процесі проведення інструментальних вимірювань (реєстрації сигналів) розробленими апаратурно-вимірювальними комплексами (тобто без додаткових етапів моделювання та геологічної інтерпретації результатів інструментальних вимірювань).

Численні результати апробації та практичного застосування частотно-резонансних методів обробки супутникових знімків [6-15, 23] засвідчили, що цю супер-мобільну прямопошукову технологію можна успішно використовувати на наступних етапах геологорозвідувальних робіт на вуглеводні, природний водень, рудні корисні копалини і воду:

а) етап 1 (демонстраційний) – обробка супутникового знімка або фотознімка ділянки (майданчика) розташування відомих потенційному замовнику свердловини чи родовища для подальшої демонстрації працездатності та ефективності мобільної прямопошукової технології;

б) етап 2 (інтегральний) – детальна обробка супутникових знімків великих територій з метою визначення типів вулканічних структур, наявних у межах району обстеження, а також корисних копалин на які доцільно проводити детальні геологорозвідувальні роботи;

в) етап 3 (рекогносцирувальний) – розбивка супутникових знімків великих площ на послідовності фрагментів та їх детальна обробка з метою виявлення найбільш перспективних локальних блоків для проведення детальних пошукових робіт на шукані корисні копалини;

г) етап 4 (деталізаційний) – обробка в детальному режимі супутникових знімків найбільш перспективних локальних блоків, виявлених на попередньому етапі (рекогносцирувальному), з метою вибору ділянок для буріння пошукових та розвідувальних свердловин.

Зазначимо також, що в технології, що розробляється, використовується частотно-резонансний принцип реєстрації корисних сигналів [2]. Супутникові знімки чи фотознімки об'єктів дослідження, а також фотографії зразків порід, корисних копалин і хімічних елементів – це, у принципі, пучності стоячих електричних хвиль, виявлених Ніколою Тесла в 1899 р. в глибинних горизонтах Землі [3, 4].

При проведенні інструментальних вимірювань з використанням розроблених комп'ютеризованих комплексів послідовно зіставляються спектри супутникових або фотознімків об'єктів дослідження зі спектрами зразків порід, корисних копалин і хімічних елементів. У процесі зіставлення вимірювальним блоком реєструються резонанси (електромагнітні відгуки), які дозволяють зробити висновок про присутність (відсутність) конкретних порід, шуканих корисних копалин та хімічних елементів у розрізі об'єкта вивчення. Такі особливості методів обробки та декодування супутникових знімків, що розробляються, є підставою для використання термінів «частотно-резонансна технологія» («частотно-резонансні методи»).

Обробка супутникових знімків та фотознімків проводиться у лабораторних умовах, без організації та проведення польових геолого-геофізичних досліджень. Це надає можливість оперативно проводити дослідження в будь-якому регіоні земної кулі, а отже, прямопошукова технологія є супер-мобільною.

### Проекти рекогносцирувального обстеження території України

**Нафтогазовий проект.** Результати апробації та практичного застосування прямопошукової технології частотно-резонансної обробки супутникових знімків та фотознімків дозволяють достатньо обґрунтовано зробити висновок, що їх цілеспрямоване використання при пошуках і розвідці родовищ нафти та газу дозволяє значно прискорити та оптимізувати геологорозвідувальний процес. Додатковим підтвердженням потенційних можливостей мобільної прямопошукової технології можна вважати оперативно проведені рекогносцирувальні дослідження територій великих блоків у різних регіонах світу (в тому числі і в Україні). З іншого боку, результати обстеження великих блоків свідчать про потенційну можливість рекогносцирувального обстеження всієї території України з метою виявлення найбільш перспективних ділянок (блоків) для проведення детальних пошукових робіт на нафту і газ.

Для практичної реалізації цього проекту супутниковий знімок території України може бути розбитий на окремі блоки, частотно-резонансна обробка яких проводитиметься окремо. Один із можливих варіантів поділу супутникового знімка території України на окремі фрагменти наведено на рис. 1. На цьому зображенні з прямокутними контурами представлено 180 локальних фрагментів (блоків) для частотно-резонансної обробки.

Частотно-резонансну обробку всіх 180 фрагментів супутникового знімка України можна провести досить швидко. Під час обробки зображень може бути виконаний наступний комплекс вимірювальних процедур:

- а) фіксація з поверхні аномальних відгуків на частотах нафти, конденсату та газу;
- б) реєстрація сигналів на частотах метаноокислювальних бактерій (бактерії, популяції яких аналізуються в методі мікробіологічної розвідки на нафту і газ в Компанії MicroPro GmbH, Німеччина);
- в) встановлення наявності в районі досліджень вулканічних комплексів, в межах яких на глибині 57 км є умови для синтезу вуглеводнів; додаткова фіксація відгуків на частотах нафти, конденсату і газу на цій глибині;
- г) фіксація сигналів на частотах нафти, конденсату і газу з нижньої частини розрізу на глибинах 5, 10 і 15 км з метою оцінки перспектив виявлення нафти і газу в глибинних та надглибинних горизонтах розрізу.

Перелічені процедури інструментальних вимірювань в повній мірі показали свою ефективність та інформативність у процесі апробації прямопошукових методів на ділянках (майданчиках) буріння пошукових та розвідувальних свердловин на суші та шельфі в різних регіонах земної кулі та в районах розміщення базальтових вулканічних комплексів [7, 12-13, 15].

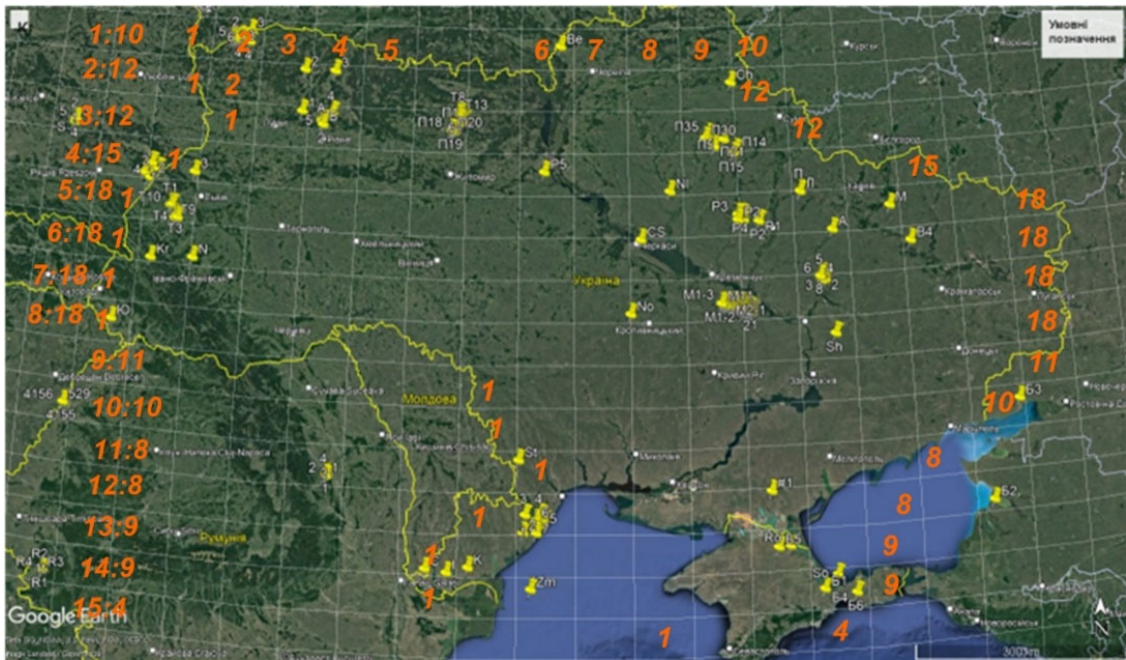


Рис. 1. Супутниковий знімок території України.

Fig. 1. Satellite image of Ukraine territory.

*Примітки.* Додаткові процедури інструментальних вимірювань та особливості їх проведення в рамках запропонованого проекту можуть бути сформульовані (уточнені), якщо буде визнано доцільність його реалізації в Україні.

У межах найбільш перспективних на нафту та газ блоків, виявлених в Україні, можна також достатньо оперативно провести детальні пошукові роботи з використанням методів частотно-резонансної обробки супутникових знімків і фотознімків. Підготовлені фрагменти супутникового знімка території України (рис. 1) можуть бути додатково оброблені в рекогносцирувальному режимі в рамках окремих проектів з метою виявлення блоків, перспективних для проведення детальних пошукових робіт на: а) природний водень; б) рудні корисні копалини; в) воду.

**Водневий проект.** При частотно-резонансній обробці кожного фрагмента зображення території України в рекогносцирувальному режимі з метою пошуків скупчень природного водню окремо може бути виконаний обмежений набір інструментальних вимірювань наступного характеру:

- а) процедура реєстрації сигналів (відгуків) на частотах 6-ї групи магматичних порід (базальти);
- б) процедура визначення глибини залягання кореня базальтового вулканічного комплексу (у разі фіксації відгуків з поверхні на частотах базальтів);
- в) процедури фіксації сигналів (відгуків) на частотах водню, фосфору (червоний) і водневих бактерій;
- г) інструментальні вимірювання для підтвердження (або встановлення відсутності) міграції водню в атмосферу.

Доцільність проведення переліченого комплексу процедур інструментальних вимірювань під час досліджень зумовлена результатами апробації прямопошукових методів в різних регіонах земної кулі. Матеріали численних досліджень дозволяють стверджувати наступне:

- а) під час інструментальних вимірювань в межах базальтових вулканічних комплексів практично повсюдно реєструються відгуки на частотах водню;
- б) червоний фосфор практично завжди присутній в базальтових вулканах;

в) водневі бактерії створюють свої колонії у верхній частині розрізу на ділянках міграції водню в атмосферу.

Для реалізації другого етапу проекту необхідно щоб виконувалися дві умови. По-перше, в межах хоча б одного обстеженого фрагмента території були виявлені базальтові вулканічні комплекси з воднем та зареєстровані відгуки на частотах червоного фосфору і водневих бактерій. Подальше продовження досліджень у межах перспективного блоку (блоків) можливе лише за участі хоча б однієї української (або іноземної) компанії в реалізації «проекту».

На другому етапі реалізації проекту в межах перспективного блоку можуть бути проведені дослідження наступного характеру:

а) проводиться частотно-резонансна обробка супутникового знімка блоку в детальному режимі з метою локалізації ділянок (зон) розташування базальтових вулканів та вибору найбільш перспективних ділянок для буріння розвідувальних свердловин на водень;

б) в контурах найбільш перспективних локальних зон виконується детальне сканування розрізу з метою визначення глибин і товщин резервуарів з воднем в розрізі над базальтами, а також безпосередньо в базальтах;

в) в межах перспективних локальних зон шляхом детального сканування також визначаються глибини і потужності колекторів з живою (цілющою) водою, та досліджуються лікувальні властивості живої води у виявлених колекторах розрізу.

За результатами детальної обробки супутникового знімка перспективного блоку приймається рішення про буріння пошукових свердловин на найбільш перспективних локальних ділянках. На початковій стадії буріння свердловини можуть проектуватися для дослідження колекторів з воднем у верхніх горизонтах розрізу. Під час буріння також можна також досліджувати колектори з живою водою. За результатами буріння перших свердловин можна прийняти рішення про наступні етапи досліджень для подальшої реалізації «проекту».

### **Апробація прямопошукової технології на території України**

У даній статті варто ще раз зазначити, що мобільна технологія пройшла широкі випробування в різних регіонах України. Інформація про ці пілотні дослідження може зацікавити компанії та інвестиційні центри, які розглядатимуть можливість участі у реалізації запропонованих проектів рекогносцирувальних досліджень території України.

Результати експериментальних робіт, проведених на території України, представлені в опублікованих статтях і матеріалах різноманітних конференцій, у тому числі зазначених у списку публікацій [7-14]. Деякі обстежені локальні ділянки та території на рис. 1 позначені жовтими маркерами. Крім того, звертаємо увагу на наступні матеріали експериментальних робіт.

**Південь України.** На території Придніпровської нафтогазоперспективної площі (рис. 2а) виявлено чотири вулканічні комплекси, в межах яких на глибині 57 км здійснюється синтез ВВ, а також базальтовий вулкан по якому відбувається міграція водню в атмосферу. В цілому, результати досліджень підтверджують припущення авторів геолого-геофізичних робіт в цьому районі Чорного моря про міграцію вуглеводнів на площі з глибинних горизонтів розрізу.

Чотири з п'яти обстежених локальних ділянок в межах Придністровської площі (рис. 2б) є перспективними для проведення детальних пошукових робіт з метою виявлення та локалізації промислових скупчень нафти і газу.

В контурах п'яти з дев'яти обстежених локальних ділянок на крупній території в районі розташування Олешкінських пісків в Херсонській області (рис. 3) за результатами проведених інструментальних вимірів прогнозується можливість виявлення покладів нафти і газу.

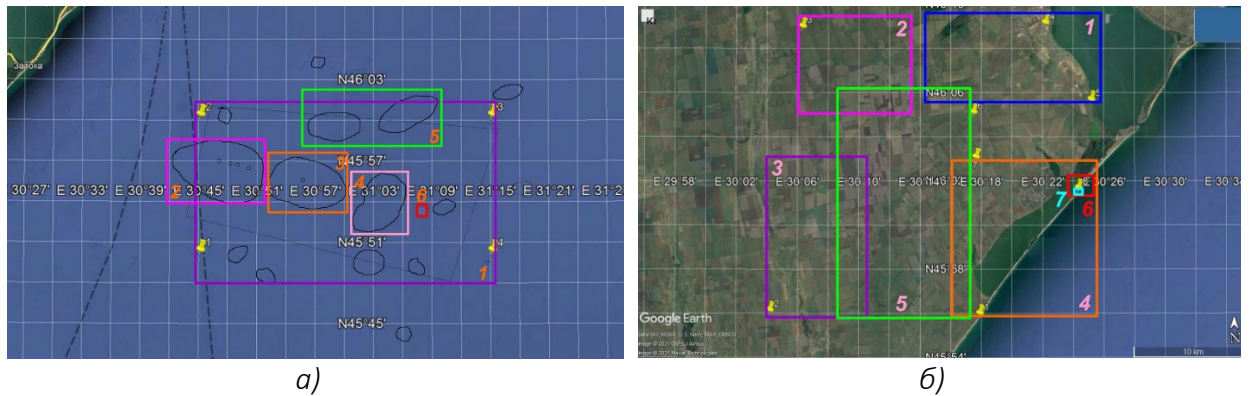


Рис. 2. Супутникові знімки зон розташування Придніпровської (а) і Придністровської (б) площ.

Fig. 2. Satellite images of the Prydniprovsk (a) and Prydnistrovsk (b) area's locations.

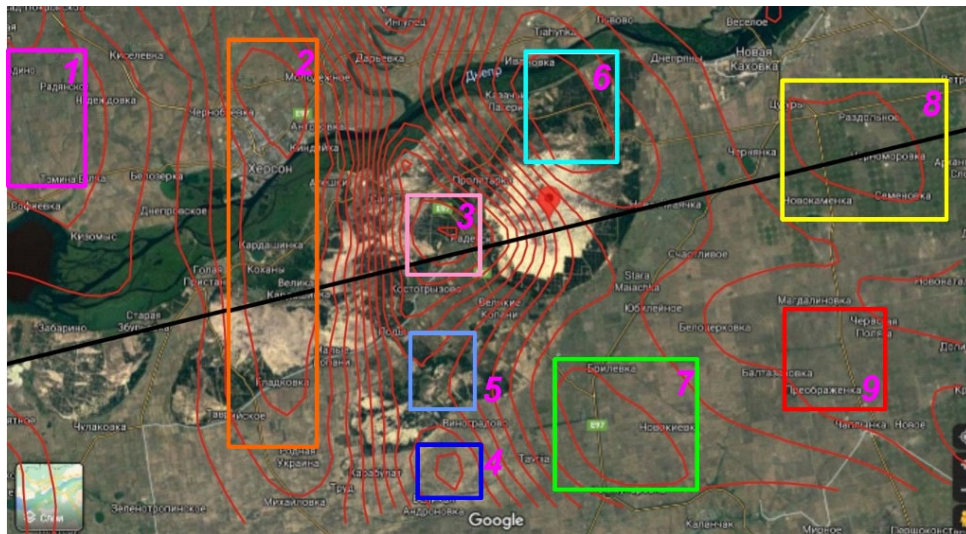


Рис. 3. Район розташування кільцевої структури «Олешкінські піски» на супутниковому знімку території.

Fig. 3. Location of the "Oleshkynsky sands" ring structure on a satellite image of the territory.

**Базальти Волині.** Значний об'єм експериментальних робіт проведено на окремих площах та кар'єрах у районі Волинської базальтової провінції. При частотно-резонансній обробці фотознімків кар'єрів (рис. 4) проводилося лише визначення глибини розташування коренів вулканічних структур, а також оцінювалася наявність у розрізі деяких хімічних елементів.

**Кар'єр-1 (рис. 4а).** Підтверджено наявність у розрізі фосфору (червоного та жовтого), водню, бактерій водневих та живої води. Корінь базальтового вулкана зафіксовано на глибині 470 км. З інтервалу 470-996 км отримані відгуки від гранітів. Зафіксовано сигнали на частотах **міді та літію**.

**Кар'єр-2 (рис. 4б).** Визначено базальтовий вулкан із коренем на глибині 723 км та отримано відгуки від фосфору, водню, бактерій водневих, живої води та гранітів з інтервалу 723-996 км. З поверхні зафіксовано відгуки від **міді (інтенсивні) та літію**.

**Кар'єр-3 (рис. 4в).** Над базальтовим вулканом з коренем на глибині 723 км отримані відгуки від фосфору, водню, бактерій водневих, живої води та гранітів з інтервалу 723-996 км. Зареєстровано відгуки на частотах **літію, нікелю, калію, скандію, титану, хрому**, а від міді та цинку сигнали були відсутні.

*Кар'єр-4 (рис. 4г).* Корінь базальтового вулкана визначено на глибині 470 км. З інтервалу 470-996 км отримані відгуки від гранітів, від живої води – на глибині 69 км, а від мертвої – на 71 км. З поверхні зафіксовано відгуки від **міді, літію та нікелю**.

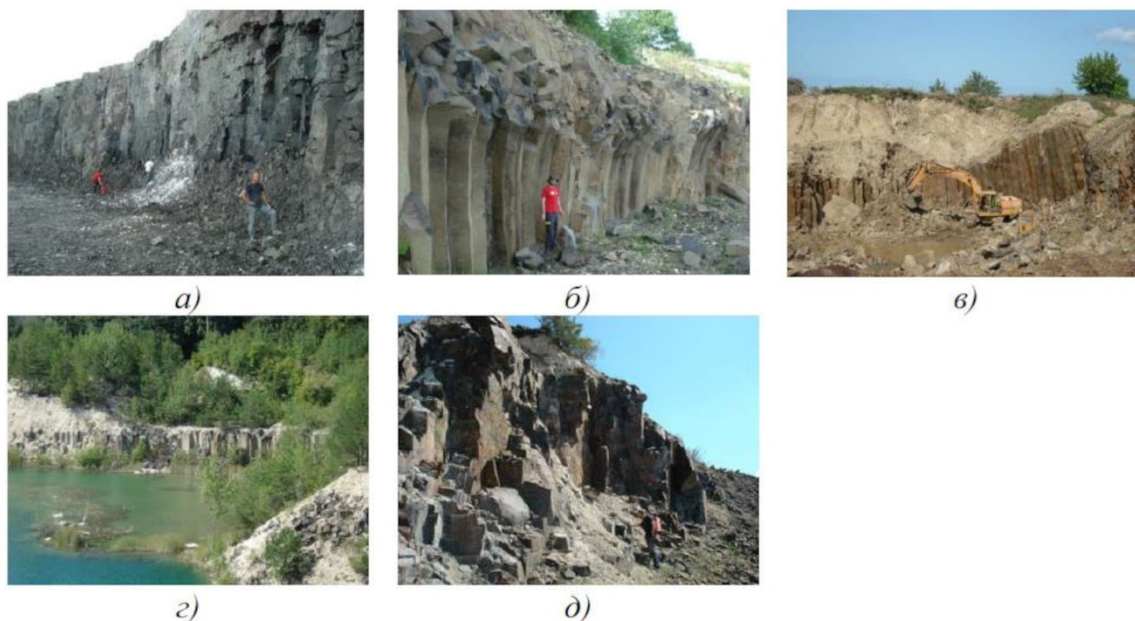


Рис. 4. Фотознімки ділянок з базальтових кар'єрів.

Fig. 4. Photographs of sites from basalt quarries.

*Кар'єр-5 (рис. 4д).* Корінь базальтового вулкана визначено на глибині 470 км. З інтервалу 470-996 км отримані відгуки від гранітів. З поверхні зафіксовано відгуки від **кобальту та літію (інтенсивні)**.

**Ділянки рекогносцирувального обстеження.** На рис. 5 наведено супутникові знімки шести ділянок обстеження в різних областях України. В процесі частотно-резонансної обробки супутникового знімка ділянки в районі н.п. Рудки (Самбірський район, Львівська область) (рис. 5а), розміщених в межах позитивної аномалії теплового потоку, зареєстровано відгуки на частотах нафти, газоконденсату, газу, лонсдейліту, калій-магнієві солі. Встановлено наявність вулканічного комплексу з коренем на глибині 723 км, заповненого 7-ю групою магматичних (ультрамафічних) порід. На поверхні синтезу ВВ 57 км зареєстровано відгуки на частотах нафти, газоконденсату та газу.

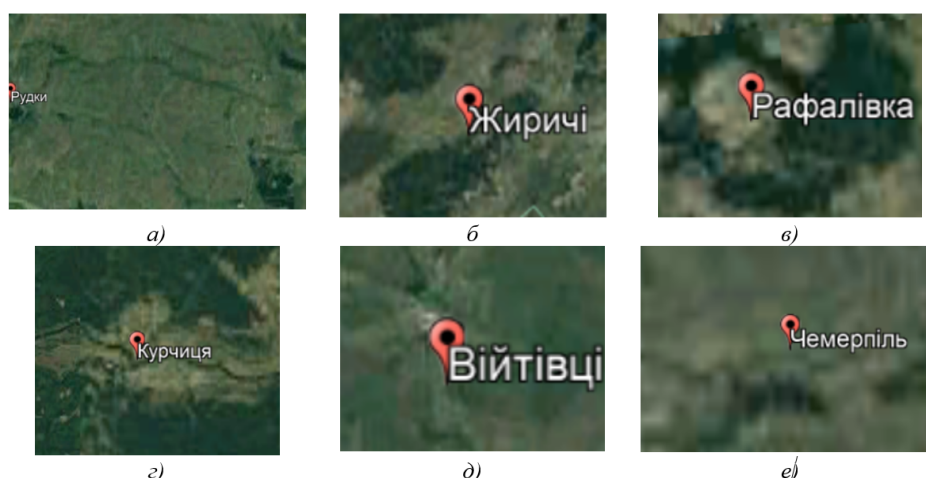


Рис. 5. Супутникові знімки ділянок рекогносцирувального обстеження прямопошуковими методами в різних регіонах України.

**Fig. 5.** Satellite images of areas of reconnaissance survey using direct-prospecting methods in various regions of Ukraine.

На всіх ділянках в районах населених пунктів. Жиричі (Волинська обл.), Рафалівка (Рівненська обл.), Курчиця (Житомирська обл.), Війтівці (Вінницька обл.), Чемерпіль (Кіровоградська обл.) (рис. 5б-е). інструментальними вимірами з поверхні зафіксовано відгуки на частотах водню, живої води та 6-ої (базальти) групи магматичних порід. Корені базальтових вулканів зафіксовано на глибинах 98 км, а із інтервалів 99-723 км отримано відгуки від 10-ої групи осадових (кременистих) порід.

**Обстеження ділянок з аномаліями теплового потоку.** Супутникові знімки двох зон з підвищеними значеннями теплового потоку в Карпатському регіоні представлені на рис. 6 і 7. Координати положення маркерів в межах цих зон надані чл.-кор. НАН України Р.І. Кутасом. Результати проведених інструментальних вимірювань зводяться до наступного.

*Ділянка обстеження на півночі.* В процесі частотно-резонансної обробки локального фрагмента знімка в районі точки (рис. 6, малий прямокутник, маркер - 49°00'N, 24°00'E) зареєстровані сигнали тільки від 7-ої (вапняки) групи осадових порід. Корінь вулкана вапняків зафіксований на глибині 470 км. З інтервалу 470-996 км отримані відгуки від «старих» гранітів. З усіх зразків вапняків сигнали зафіксовані тільки від лівосторонніх (зі зворотною поляризацією).

З поверхні отримані також сигнали на частотах нафти, конденсату, газу, бактерій метаноокислюючих, фосфору (жовтого). На поверхні 0 м з верхньої частини розрізу отримані відгуки від газу і фосфору (жовтого), що свідчить про їх міграцію в атмосферу.

На поверхні синтезу ВВ 57 км отримані відгуки від нафти, конденсату, газу, фосфору живої води (слабкої інтенсивності). Відгуки від мертвої води зафіксовано на глибині 59 км.

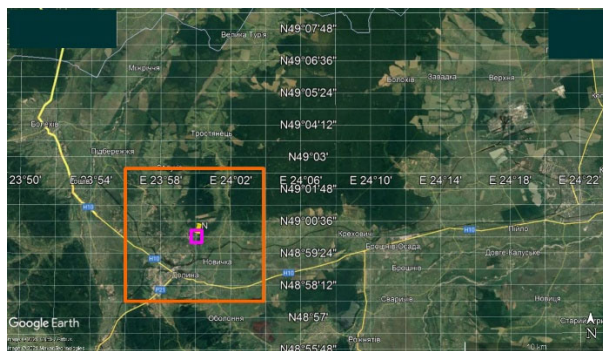
При обробці всього знімка (рис. 6, великий прямокутник) з поверхні зареєстровані сигнали від нафти, конденсату, газу, бурштину, бактерій метаноокислюючих, фосфору (червоного, коричневого, жовтого), горючого сланцю, газогідратів, льоду, антрациту, водню, бактерій водневих, живої води, базальтів глибинних, лонсдейліту.

Відгуки від мертвої води отримані на глибинах 13, 48, 59 і 71 км, а від живої - на 11, 46, 57 і 69 км. На поверхні зареєстровані сигнали від 1-6 і 7-ої (вапняки) груп осадових порід, 6-ої (базальти), 6А (долерити і андезити), 6Б (лампроїти), 7-ої (ультрамафічні), 8, 9, 10, 14, 15, 16 груп магматичних.

Фіксацією відгуків на різних глибинах визначені корені наступних вулканів: 7-а група магматичних (ультрамафічних) порід - 99 км; 7-а група осадових - 470 км; базальти - 723 км; граніти - 996 км. З інтервалу 99-723 км отримані відгуки від кременистих порід.

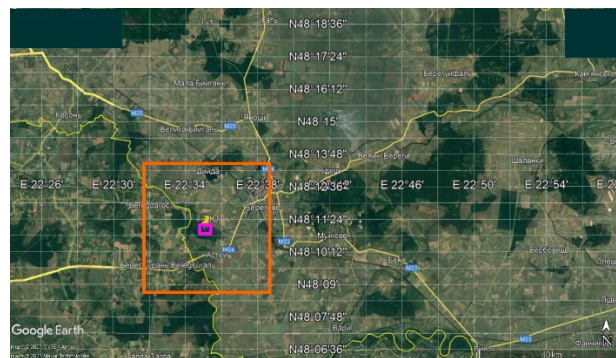
На поверхні 57 км отримані відгуки від нафти, конденсату, газу та бурштину, а також фосфору (червоного і жовтого), а на глибині 11 км - від нафти, конденсату та газу, сигнали від бурштину не отримані. Відгуки від вуглекислого газу на глибині 13 км були відсутні.

На поверхні 0 м з верхньої частини розрізу отримані відгуки від газу, вуглекислого газу і фосфору (жовтого і червоного), що свідчить про їх міграцію в атмосферу.



**Рис. 6.** Супутниковий знімок території в районі північної ділянки обстеження.

**Fig. 6.** Satellite image of the territory in the area of the northern part of the survey.



**Рис. 7.** Супутниковий знімок території в районі південної ділянки обстеження.

**Fig. 7.** Satellite image of the territory in the area of the southern part of the survey.

*Ділянка обстеження на півдні.* В процесі частотно-резонансної обробки локального фрагмента знімка в районі точки (рис. 7, малий прямокутник, маркер - 48°11'N, 22°35'E) з поверхні зафіксовані сигнали від фосфору (червоного), водню, бактерій водневих, живої води і базальтів. Корінь базальтового вулкана визначено на глибині 470 км, а з інтервалу 470-996 км отримані відгуки від «старих» гранітів. Верхня кромка базальтів зафіксована скануванням з кроком 50 см на глибині 450 м (сигнали простежено з різним кроком до 20 км). При аналізі зразків базальтів і габро сигнали отримані тільки від лівосторонніх (зі зворотною поляризацією).

Відгуки від живої води зареєстровані тільки на глибині 68 км; на глибинах 11, 46, 57 і 69 км сигнали були відсутні.

На поверхні 0 м з верхньої частини розрізу отримані відгуки від водню і фосфору (червоного), що свідчить про їх міграцію в атмосферу.

На глибині 450 м з верхньої частини розрізу отримані відгуки від 1-6 груп осадових порід, сигнали від водню і живої води були відсутні. Скануванням розрізу з 450 м, крок 5 см відгуки від живої води почали фіксуватися з 481 м, а від водню - з 463 м. В інтервалі 0-450 м сигнали від водню при скануванні не отримані.

При обробці супутникового знімка в великому прямокутнику на рис. 7 зафіксовані відгуки від нафти, конденсату, газу, вуглекислого газу, бактерій метаноокислюючих, фосфору (чорного, коричневого, червоного, білого, жовтого), горючих сланців, газогідратів, водню, живої води, льоду, ртуті, золота, коесіту, лонсдейліту (слабкої інтенсивності), солі калійно-магнієвої. Зареєстровані сигнали від солі, осадових порід 1-6 груп, 1-ої (граніти «молоді»), 2, 3, 5, 6-ої (базальти), 7-ої (ультрамафічні), 8, 9, 10, 15, 16 груп магматичних.

Корінь вулкана 1-6 груп осадових порід зафіксовано на глибині 99 км, базальтів і ультрамафічних порід - на 470 км, солі - на 723 км, гранітів - на 996 км. З інтервалу 99-723 км отримані відгуки від кременистих порід.

На поверхні 0 м з верхньої частини розрізу отримані відгуки від водню і фосфору (всі кольори), що свідчить про їх міграцію в атмосферу. На глибині 57 км зафіксовані відгуки від нафти, конденсату, газу, бурштину, фосфору (коричневого, чорного, жовтого).

На поверхні 11 км зафіксовані сигнали від нафти (слабкої інтенсивності), конденсату, газу і фосфору (жовтого). Відгуки від живої води отримані на глибинах 11 км, 57 км (слабкої інтенсивності) і 68 км.

*Короткі коментарі.* Обстежені ділянки є перспективними для пошуків корисних копалин, нафти, газу і природного водню в тому числі.

Отримано свідоцтва про можливий синтез нафти, конденсату та газу на межі 11 км.

Інструментальні виміри на ряді об'єктів обстеження дозволяють сформулювати припущення, що в складаючих розріз групах порід зі зразками зворотної поляризації (лівосторонніми) розподіл зарядів сприяє підвищенню температури на ділянці їх розміщення, а, отже, і теплового потоку.

**Обстеження ділянок водневої дегазації в Україні.** При аналізі супутникових знімків території України виявлені чисельні зони видимої водневої дегазації. В межах багатьох ділянок розташування зон дегазації проведені дослідження рекогносцирувального характеру.

**Район м. Бориспіль (Київська область).** Зони водневої дегазації можна спостерігати на знімках північніше аеропорту «Бориспіль» (рис. 8). В процесі частотно-резонансної обробки супутникового знімка на рис. 8а з поверхні зареєстровані відгуки від фосфору (червоного і жовтого), водню, бактерій (водневих), живої води, базальтів (старих), золота (слабкої інтенсивності), коеситу (слабкої інтенсивності). Сигнали від ВВ, алмазів, мертвої води, солі калійно-магнієвої і солі натрій-хлористої не отримані.

Зафіксовані відгуки від 1-6 груп осадових порід, гранітів (слабкої інтенсивності) і базальтів. Корені вулканів, заповнених осадовими породами 1-6 групи, а також базальтами, визначені на глибині 723 км, а гранітами - на 996 км. Скануванням розрізу з поверхні з кроками 1 м і 1 см верхня кромка базальтів зафіксована на глибині 298 м.

На поверхні 298 м з верхньої частини розрізу зареєстровані сигнали від 1-6 груп осадових порід і водню (слабкої інтенсивності). Скануванням розрізу з 298 м, крок 10 см відгуки від водню з базальтів почали фіксуватися з 340 м, а живої води - з 362 м.

Скануванням розрізу з поверхні, крок 10 см, відгуки на частотах водню з 2-ої групи осадових порід (псаміти) отримані з інтервалів 62-107 м і 240-260 м, а від фосфору (червоного) з 63-108 м і 240-260 м. Такі результати свідчать про те, що фосфор (червоний) міститься в водні.

На поверхні 0 м з верхньої частини розрізу отримані відгуки слабкої інтенсивності від водню і фосфору (жовтого), що свідчить про їх міграцію (слабку) в атмосферу.

На поверхні синтезу ВВ 57 км сигнали від нафти і бурштину не отримані. Відгуки від живої води зафіксовані на глибинах 57 км і 46 км.

Сигнали від живої води отримані тільки з псамітів, з гранітів та базальтів відгуки були відсутні. Сигнали живої води з базальтів зафіксовані на поверхні 69 км.

Відгуки від мертвої води зареєстровані на глибинах 48 км і 71 км.



**Рис. 8.** Супутникові знімки ділянок водневої дегазації в районі м. Бориспіль.

**Fig. 8.** Satellite images of hydrogen degassing sites near Boryspil.

При обробці знімка з локальною зоною водневої дегазації (рис. 8б) з поверхні зареєстровані відгуки від водню, водневих бактерій, фосфору (червоного і жовтого) і живої води. Відгуки від ВВ, вуглекислого газу, метаноокислюючих бактерій і солі не отримані.

Зареєстровані сигнали від базальтів. Верхня кромка базальтів визначена скануванням з кроками 1 м і 10 см на глибині 120 м. На поверхні 120 м з верхньої частини розрізу отримані сигнали від 8-ої (доломіти), 2-ої (псаміти) груп осадових порід і водню

При скануванні розрізу з 120 м, крок 10 см, відгуки від водню з базальтів почали фіксуватися з 145 м, а від живої води - зі 156 м. А при скануванні з поверхні, крок 10 см, відгуки від водню з доломітів (або псамітів) зафіксовані з інтервалу 47-107 м.

На поверхні 0 м зафіксовані сигнали (слабкої інтенсивності) від водню з верхньої частини розрізу, що свідчить про його міграцію в атмосферу.

*Ділянки обстеження в Рожищенському районі Волинської області.* При обробці знімка локальної ділянки водневої дегазації (рис. 9а) з поверхні зафіксовані відгуки від фосфору (червоного і жовтого), водню, водневих бактерій, живої води.

Встановлено наявність базальтового вулкана, який перекрито зверху вапняками. Фіксацією відгуків на різних глибинах (50, 99, 218, 480, 700, 724 км) корінь базальтового вулкана визначено на глибині 723 км, а верхня кромка базальтів встановлена скануванням розрізу з кроком 1 м на глибині 270 м. На поверхні 270 м з верхньої частини розрізу фіксувалися відгуки тільки від 7-ої групи осадових порід (вапняки).

При скануванні розрізу з 270 м, крок 10 см, відгуки від водню з базальтів почали фіксуватися з 300 м, а від живої води - з 320 м.

На поверхні 0 м відгуки від водню зафіксовані з верхньої частини розрізу, що свідчить про його міграцію в атмосферу. Скануванням розрізу з кроком 5 мм відгуки від водневих бактерій фіксувалися з поверхні до глибини 530 см.

В процесі обробки супутникового знімка відносно великої площі (рис. 9б) зареєстровані відгуки від 1-6, 7 (вапняки) і 8-ої (доломіти) груп осадових порід, а також 1-ої (граніти), 2, 3, 6-ої (базальти), 7-ої (ультрамафічні), 8, 9, 10, 11-ої (кімберліти), 12, 13 груп магматичних порід. Корені вулканів, заповнених осадовими породами 1-6 групи і гранітами зафіксовані на глибині 470 км, а вапняками, базальтами і кімберлітами - на 723 км. З інтервалів 99-470 км і 218-723 км зафіксовані відгуки від солі і кременистих порід відповідно.



**Рис. 9.** Супутникові знімки ділянок водневої дегазації в Рожищенському районі Волинської області.

**Fig. 9.** Satellite images of hydrogen degassing sites in the Rozhishchensky district of the Volyn region.

З поверхні зафіксовані відгуки від лонсдейлітів, солі калій-магнієвої, базальтів (глибинних), золота, ртуті, алмазів (слабкої інтенсивності), живої води, водню, антрациту, горючих сланців, газогідратів, фосфору (білого, чорного, коричневого, червоного), бактерій, вуглекислого газу, бурштину, газу, конденсату, нафти, водневих бактерій. Зареєстровані також відгуки від літію, від нікелю і міді сигнали не отримані.

При скануванні розрізу з поверхні, крок 1 м, відгуки від нафти зафіксовані з інтервалу 480- (600 - інтенсивний) -1000 м. Далі сканування не проводилося.

При скануванні розрізу з 0 м, крок 1 м, відгуки від газу почали фіксуватися з 260 м, водню - з 230 м, живої води - з 320 м, золота - з 620 м, алмазів - з 780 м. Відстеження інтервалів відгуків не проводилося.

В процесі частотно-резонансної обробки знімка території на рис. 10 з поверхні зафіксовані відгуки від нафти, конденсату, газу, водню, води (глибинної), а також від 7-8 груп осадових і 1-6 груп магматичних порід.

Фіксацією відгуків на різних поверхнях корені каналів (вулканів) 7-8 груп осадових і 6-ої групи магматичних порід визначені на глибині 723 км.



**Рис. 10.** Супутниковий знімок ділянки водневої дегазації в Рожищенському районі Волинської області.

**Fig. 10.** Satellite image of the hydrogen degassing site in the Rozhishchensky district of the Volyn region.

На поверхні 57 км отримані відгуки від нафти, конденсату, газу та води; від води отримані також сигнали на поверхні 69 км. На глибині 68 км відгуки від води отримані з осадових порід 7-8 груп, а також з 6-ї групи магматичних.

Вода в базальтах почала фіксуватися з 120 м, відгуки простежено до 69 км.

При скануванні з поверхні, крок 1 м відгуки від базальтів отримані зі 120 м, а від водню - з 260 м і простежені до 723 км.

Фіксація відгуків від нафти на різних поверхнях показала, що прогнозні колектори можуть бути розташовані в інтервалі глибини 4-9 км. Скануванням розрізу з 4000 м, крок 1 м сигнали від нафти отримані з інтервалів: 1) 4215-5010 м; 2) 5325- (інтенсивний) (6000-інтенсивний) (дуже інтенсивний) -6910 м; 3) 7080- (інтенсивний) (8000-інтенсивний) -8570 м (до 9 км простежено).

Відгуки від газу при скануванні з поверхні, крок 1 м зареєстровані в інтервалах: 1) 470- (1000 - інтенсивний) -1280 м; 2) 1600-1700 м; 3) 2660- (інтенсивний) (3000-інтенсивний) -3220 м; 4) 5010- (інтенсивний 5600) -5730 м; 5) 6835- (7200-інтенсивний) (7500-інтенсивний) (інтенсивний) -8400 м.

**Опубліковані матеріали.** У статтях [8-10] представлені результати досліджень, проведених на локальних ділянках уздовж профілів в межах Українського щита та в Карпатському регіоні.

Досить цікаві й у певному сенсі несподівані результати отримані під час проведення обстеження 21 локальної ділянки вздовж п'яти сейсмічних профілів ДДЗ [14]. Так, на п'яти обстежених ділянках виявлено базальтові вулкани з воднем та живою (цілющою) водою, у межах трьох – алмазонасні кімберлітові вулканічні структури. Відгуки на частотах нафти, конденсату та газу зареєстровані у контурах трьох вулканів, заповнених осадовими породами 1-6 груп, одного гранітного вулкана та одного вулканічного комплексу з

вапняками. На площі ще одного вулкана з 1-6 групами осадових порід сигнали на частотах ВВ не зареєстровані – у цьому вулкані існують умови для синтезу живої води на межі 46 км та мертвої води – на глибині 48 км. На 7-ми інших локальних ділянках обстеження виявлено вулканічні структури, у яких відгуки на частотах нафти, конденсату, газу та водню жодного разу не реєструвалися [14].

Уздовж сейсмічного профілю 2021 р. на території України [20] обстеження проведено на 18 площах [14]. На 11-ти ділянках виявлено базальтові вулканічні структури з воднем та живою водою! Сигнали на частотах нафти, конденсату і газу зареєстровані на 8 ділянках у вулканічних комплексах, заповнених осадовими породами 1-6 груп, на 2 ділянках – у вулканах вапняків. Відгуки від ВВ отримані також у межах деяких вулканів, заповнених сіллю, гранітами та ультрамафічними породами. У районі профілю виявлено також алмазоносний кімберлітовий вулкан [14].

До наведеного вище доцільно також додати, що на продовженні профіля 2021 р. на території Румунії виявлено чотири базальтові вулканічні структури з воднем та живою водою. Відгуки від нафти, конденсату та газу зареєстровані з вулкана, заповненого 1-6 групами осадових порід, та двох вулканів вапняків. На двох ділянках у районі профілю виявлено алмазоносні кімберлітові вулканічні комплекси [14].

На території України також проведено рекогносцирувальні дослідження площ, де розташовані відомі культові споруди, а також численні локальні ділянки з водоносними горизонтами (цілющою води зокрема) та в межах кількох курортних центрів з мінеральною водою. Обстежені ділянки з культовими спорудами розташовані в контурах базальтових вулканічних комплексів, по яких водень мігрує до верхніх горизонтів розрізу і далі в атмосферу. Майже всі обстежені локальні ділянки з джерелами живої води виявлені в вулканічних структурах, заповнених базальтами, а більшість ділянок з джерелами мертвої води зафіксовано в межах вулканів, заповнених вапняками. Умови для синтезу живої води в базальтових вулканах існують на глибині 68 або 69 км, а для мертвої води у вапняках на глибині 48 км.

Локальні ділянки розміщення джерел із живою (цілющою) водою є перспективними для пошуків природного водню! Курортний центр у Трускавці розташований у межах базальтового вулкану, а поклади мінеральних вод у Миргороді, Сатанові та Моршині розміщені в контурах вулканічних структур, заповнених вапняками. Джерела з мінеральною водою типу «Нарзан» в Ужгородській області виявлені у вулканах з ультрамафічними породами, в яких присутні калійно-магнієві солі. У контурах багатьох обстежених базальтових вулканів, у верхній частині розрізу, в тому числі на невеликій глибині, інструментальними вимірюваннями встановлено наявність резервуарів з живою (цілющою) водою і воднем. Інструментальні вимірювання підтвердили факти міграції водню в атмосферу.

### **Короткі коментарі та висновки**

Ще раз зазначимо у статті, що обробка супутникових знімків і фотографій здійснюється в лабораторних умовах, без організації та проведення польових геолого-геофізичних досліджень. У зв'язку з цією особливістю технології частотно-резонансної обробки супутникових знімків запропоновані проекти рекогносцирувального обстеження всієї території України (включаючи ділянки в межах економічної зони Чорного та Азовського морів) з метою виявлення найбільш перспективних блоків для проведення детальних пошукових робіт на вуглеводні і природний водень можна реалізувати за дуже короткий час. Зрештою, це значно прискорить геологорозвідувальні роботи на нафту, газ, водень в Україні, а також скоротить фінансові витрати на їх проведення.

Для додаткової демонстрації оперативності та ефективності мобільної технології звернемо увагу на наступне. Польові роботи вздовж сейсмічного профілю SHIELD'21

проведено у 2021 р. А перші результати обробки сейсмічних матеріалів опубліковано на початку 2023 р. [20]. Результати обробки супутникових знімків 28 площ вздовж профілю опубліковані в 2021 [14]. Додамо до цього, що матеріали частотно-резонансної обробки супутникових знімків окремих ділянок (площ), розташованих уздовж профілю, можуть бути використані надалі при геолого-геофізичній інтерпретації сейсмічних матеріалів (хвильових полів).

Оперативно проведеними експериментальними дослідженнями рекогносцирувального характеру поповнено базу фактів (свідчень) на користь «вулканічної» моделі формування структурних елементів та зовнішнього вигляду Землі, планет та супутників Сонячної системи, а також родовищ вуглеводнів, рудних корисних копалин та води. На всіх обстежених ділянках у різних регіонах (на території України в тому числі) виявлено вулканічні комплекси (глибинні канали міграції хімічних елементів, флюїдів та мінеральної речовини), заповнені різними групами осадових, метаморфічних та магматичних порід. Акцентуємо також увагу, що корені вулканічних структур різного типу фіксуються на строго визначених глибинах у розрізах Землі.

Доцільно відзначити також у зв'язку з цим, що на користь вулканічної моделі свідчать також опубліковані матеріали про виявлення десятків тисяч вулканічних комплексів (структур) різного типу на Землі [17], Венері [21] та Марсі [19]. Вулканічна модель формування структурних елементів повною мірою укладається в рамки концепції Землі, що розширюється (зростає) [16, 18]. Під час проведення масштабної апробації прямопошукової технології у різних регіонах світу виявлено не одну сотню вулканічних структур, заповнених осадовими, метаморфічними та магматичними породами різного типу. Вулканічні структури закартовані також на деяких планетах та супутниках Сонячної системи [23].

Можливість обстежити в стислі терміни велику кількість локальних ділянок та блоків уздовж профілів, а також у районах розташування родовищ ВВ та пошукових площ надають змогу апробовані процедури інтегральної оцінки значень параметрів розрізу (усереднених значень глибин залягання та товщин комплексів порід різного типу і корисних копалин) у межах досить великих ділянок та площ обстеження. Використання цих процедур під час проведення експериментальних робіт суттєво скорочує витрати часу на проведення досліджень.

У процесі виконання експериментальних робіт з використанням методів обробки супутникових знімків та фотознімків отримано додаткові факти (свідчення) на користь глибинної (абіогенної) теорії генезису нафти, конденсату та газу [11] в процесі водневої дегазації Землі [1, 5]. На даний момент більшість фахівців керуються у своїй практичній діяльності принципами та положеннями біогенної теорії генезису вуглеводнів. З цієї позиції оцінки обсягів метану та вуглекислого газу, які мігрують в атмосферу планети, можуть бути суттєво занижені. Численні факти фіксації сигналів (відгуків) від нафти, конденсату та газу на межах їх синтезу 11 км, 57 км у різних регіонах світу (у тому числі й у межах обстежених ділянок) дозволяють стверджувати про міграцію абіогенного метану в атмосферу Землі у колосальних обсягах!

У зв'язку з зазначеним вище принципово важливими слід вважати зареєстровані інструментальними вимірами факти міграції водню та червоного фосфору в атмосферу в межах виявлених базальтових вулканічних комплексів у ДДЗ, на окремих ділянках вздовж профілю 2021 р. на територіях України та Румунії, а також на ділянках та площах обстеження. Загалом представлені вище результати досліджень підтверджують висновки дослідників про масштабну міграцію глибинного (абіогенного) газу та водню в атмосферу планети Земля!

На багатьох площах та локальних ділянках обстеження проводилося додаткове відпрацювання методичних прийомів виявлення та локалізації за результатами частотно-резонансної обробки супутникових знімків та фотографій зон, у межах яких здійснюється

міграція газу, фосфору, вуглекислого газу та водню у поверхневі горизонти розрізу та атмосферу. Ця методика може використовуватися надалі при проведенні досліджень з метою виявлення та локалізації на родовищах вуглеводнів та пошукових площах локальних зон міграції метану та водню в атмосферу.

Технологія в цілому, а також її окремі методи доцільно використовувати в різних регіонах для попередньої оцінки перспектив нафтогазоносності малорозвіданих і нерозвіданих пошукових блоків і локальних ділянок. Застосування даної технології може дати значний ефект при пошуках промислових скупчень вуглеводнів у нетрадиційних колекторах (зокрема в зонах поширення сланців, вугленосних пластів, кристалічних порід). Своєчасне проведення додаткових досліджень прямопошуковими методами на локальних ділянках буріння пошукових і розвідувальних свердловин сприятиме підвищенню успішності буріння (збільшенню кількості свердловин із промисловими припливами вуглеводнів). Закладка свердловин на ділянках, де розташовані канали вертикальної міграції флюїдів, може призвести до збільшення припливів вуглеводнів. Мобільні технології також можна успішно використовувати під час розвідки маловивчених ділянок і блоків у межах відомих родовищ нафти і газу.

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## PROJECT OF UKRAINE TERRITORY RECONNAISSANCE SURVEYING BY MOBILE DIRECT-PROSPECTING METHODS IN ORDER TO DETECT BLOCKS FOR HYDROCARBONS, HYDROGEN, ORES MINERALS AND WATER PROSPECTING

Mykola Yakymchuk<sup>1</sup>, Ignat Korchagin<sup>2</sup>, Valery Solovyov<sup>2</sup>

<sup>1</sup>*Institute of Applied Problems of Ecology, Geophysics and Geochemistry, Laboratorny Lane, Kyiv, 01133, Ukraine*

<sup>2</sup>*Institute of Geophysics, NAS of Ukraine, 32, Palladin Ave., Kyiv, 03680, Ukraine*

**Purpose.** The project of the Ukraine territory reconnaissance survey with the aim of identifying promising blocks and areas for carrying out detailed prospecting for oil, gas and natural hydrogen is presented. Prepared project can be quickly implemented with using the mobile and low-cost technology, that include modified methods of frequency-resonance processing and decoding of satellite and photo images, vertical electric-resonance sounding of a cross-section, as well as a method of integrated assessment of the prospects of oil and gas potential of large prospecting blocks and license areas.

**Design/methodology/approach.** The developed mobile and low-cost technology include modified methods of frequency-resonance processing and decoding of satellite images and photo images, vertical electric-resonance sounding (scanning) of a cross-section, as well as a method of integrated assessment of the prospects of oil and gas potential of large prospecting blocks and license areas. Separate methods of this direct-prospecting technology are based on the principles of the “substance” paradigm of geophysical research, the essence of which is to search for a specific substance - oil, gas, gas condensate, water, gold, zinc, etc.

**Findings.** For this project practical implementation, the satellite image of the of Ukraine territory is divided into 180 separate blocks (fragments), the frequency-resonance processing of which may be carried out separately. During image fragments processing, the following set of measurement procedures may be performed: a) fixation of responses at the frequencies of oil, condensate and gas; b) registration of signals at the frequencies of methane-oxidizing bacteria; c) establishing the presence of a volcanic structures in which there are conditions for the hydrocarbon’s synthesis at a depth of 57 km; additional fixation of responses of oil, condensate and gas at this depth; d) fixing signals at the frequencies of oil, condensate and gas from the lower part of cross-section at depths of 5 km, 10 km, 15 km in order to assess the prospects of oil and gas discovering in the deep horizons of cross-section. The listed procedures of instrumental measurements have fully demonstrated their effectiveness and informativeness in the process of direct-prospecting methods approbation in the areas (sites) of exploratory wells drilling on land and shelf in various regions of the globe. The developed super-mobile direct-prospecting technology has provided the authors with a unique opportunity to conduct a huge number of experiments in various regions of the globe. In the process of experimental work conducting, numerous evidence was obtained in favor of the deep (abiogenic) genesis of hydrocarbons in the framework of the concept of hydrogen degassing of the Earth.

**The practical significance and conclusions.** The proven technology allows filling the studied cross-section with specific rocks (sedimentary, metamorphic and magmatic), as well as identifying areas on the surface and intervals in the cross-section that are promising for ore and combustible minerals prospecting. The super-mobile methods can be used to assess the prospects for oil and gas (ore) potential of large exploration blocks and local areas (including those put up for auction), to select the optimal locations (sites) for laying exploration and production wells, assessment of the prospects for discovering oil and gas deposits in the deep and super-deep horizons of cross-section, prospecting and localization of zones with deep channels location, through which the chemical elements, fluids and mineral matter migrate into the upper horizons of cross-section. The use of mobile and low-cost technology will significantly speed up the exploration process for oil, condensate, gas, natural hydrogen, as well as reduce the financial costs for its implementation.

**Keywords.** Ukraine, oil, gas, hydrogen, limestones, marls, dolomites, basalts, granites, direct searches, deep structure, carbon dioxide, sounding of the cross-section, remote sensing data processing.

## Psychological Sciences

# BEYOND BRAIN DIFFERENCES: SOCIAL EXPERIENCES, ADAPTATION, AND PSYCHOSOCIAL WELL-BEING AMONG LEFT-HANDED INDIVIDUALS

Telzhan V.S.

Selinus University of Science and Literature, Rome, Italy

### Abstract

Left-handedness has traditionally been examined primarily through neuropsychological, developmental, and cognitive perspectives, whereas its social experience and adaptation to predominantly right-handed environments have received comparatively limited attention. This integrative literature review examines left-handedness through a person–environment perspective, focusing on the relationship between social experience, environmental demands, adaptation, and psychosocial well-being. Literature from psychology, neuroscience, education, ergonomics, sociology, and related fields was synthesised thematically to identify patterns in how left-handed individuals experience and negotiate family, educational, occupational, and everyday environments. Three interconnected themes emerged. First, the practical and psychosocial significance of left-handedness is strongly context-dependent: environmental organisation, cultural expectations, and interpersonal responses influence whether minority hand preference becomes socially consequential. Second, adaptation should not be treated as a unitary process. The synthesis distinguishes functional adaptation, characterised by relatively high individual agency and behavioural flexibility, from socially imposed hand modification aimed at conformity with right-handed norms. It further differentiates individual compensation from environmental accommodation as two pathways for reducing person–environment mismatch. Third, the reviewed evidence does not support a deterministic association between left-handedness and poorer cognitive or psychosocial functioning. Instead, environmental fit, social acceptance, autonomy, normative pressure, and opportunities for adaptation appear to constitute more meaningful explanatory factors. The review proposes an integrative person–environment model in which left-handedness represents an individual characteristic, social and material environments constitute the context of its expression, and adaptation mediates the relationship between environmental demands and psychosocial outcomes. This perspective shifts attention from correcting individual difference toward understanding and, where appropriate, modifying the environments in which that difference becomes consequential.

**Keywords:** left-handedness; handedness; person–environment fit; social experience; adaptation; psychosocial well-being; environmental accommodation; functional adaptation.

### Introduction

Handedness is one of the most visible manifestations of human lateralization, yet its significance extends beyond patterns of motor preference and cerebral organization. Left-handedness represents a relatively stable minority pattern of hand preference: a large-scale meta-analysis estimated its overall prevalence at approximately 10.6%, although estimates vary

according to measurement criteria, sex, ancestry, historical period, and cultural context (Papadatou-Pastou et al., 2020). For much of the scientific history of handedness, research has concentrated on its biological and neuropsychological foundations, including hemispheric specialization, language lateralization, functional asymmetry, motor organization, and developmental mechanisms (Ocklenburg et al., 2014; Papadatou-Pastou et al., 2020; Sun & Walsh, 2006). This body of scholarship has substantially advanced knowledge of lateralization but has also contributed to a predominantly individual-level understanding of left-handedness. The relationship between handedness and brain organization is considerably more complex than the conventional distinction between a “left-brained” and a “right-brained” individual suggests. Although right-handedness is strongly associated with left-hemisphere language dominance, left-handed individuals demonstrate greater variability in patterns of language lateralization. Handedness and language lateralization are related but partly independent characteristics whose development reflects multiple genetic, neurodevelopmental, and environmental influences (Ocklenburg et al., 2014). Accordingly, neuropsychological differences associated with handedness should not be interpreted as evidence of cognitive deficit or superiority. Rather, they provide a biological and developmental context within which individual patterns of motor behaviour emerge. What remains less adequately incorporated into this literature is the social environment in which these patterns are expressed. Human environments are not neutral with respect to handedness. Because right-handed people constitute the substantial majority of the population, everyday objects, educational practices, work arrangements, tools, technologies, and behavioural conventions have historically developed primarily around right-handed use. Research in ergonomics has documented that numerous tools, utensils, office devices, household objects, and public facilities are designed in ways that favour right-handed interaction (Jung & Jung, 2009). From this perspective, some difficulties experienced by left-handed individuals cannot be attributed solely to individual motor or cognitive characteristics. They emerge through an interaction between individual characteristics and an environment structured around majority patterns of behaviour. This distinction is sociologically important. A characteristic that is relatively unproblematic in one environmental context may become consequential when institutions, technologies, cultural expectations, or routine practices are organised according to a different normative pattern. The everyday experience of left-handedness therefore provides an opportunity to examine how majority-based social arrangements shape individual adaptation without assuming that minority status itself constitutes impairment. In this sense, the analytical question shifts from *how left-handed individuals differ from right-handed individuals* to *how left-handed individuals experience and negotiate predominantly right-handed social environments*.

Existing empirical evidence suggests that these experiences encompass both material and social dimensions. In a mixed-method study of 686 left-handed participants, difficulties were reported in a range of everyday activities and in the use of objects and environments organised around right-handed practices. Participants also described social pressure during childhood, particularly expectations surrounding right-handed writing. At the same time, most evaluated their quality of life positively and described adaptation to a predominantly right-handed environment as part of their everyday experience (Dadić et al., 2021). Such findings are important because they caution against a deficit interpretation of left-handedness: environmental inconvenience or social pressure does not necessarily translate into poor psychosocial functioning.

Cultural context further complicates this relationship. Hand preference is biologically grounded, but its social expression is subject to norms concerning appropriate bodily behaviour. Cross-cultural research has demonstrated that attitudes toward left-hand use may influence whether left-handed preferences are accepted, discouraged, or actively modified. For example, Zverev (2006) documented substantial cultural and environmental pressure against left-hand preference among participants in Malawi, including expectations that children should change

habitual left-hand use. More broadly, the meta-analytic evidence indicates that cultural pressure against left-hand use contributes to variation in the observed prevalence and expression of left-handedness across populations (Papadatou-Pastou et al., 2020). These findings illustrate that handedness is simultaneously embodied and socially situated: its neurodevelopmental origins do not eliminate the role of family, education, cultural norms, and the material environment in shaping how it is experienced. This perspective also has implications for psychosocial well-being. Studies examining handedness and psychological outcomes have produced inconsistent findings, and left-handedness should not itself be treated as a psychosocial risk condition. For example, Alhussain et al. (2023), in a large adult sample, found no significant evidence that left-handed participants necessarily experienced poorer psychological well-being or quality of life. Such findings suggest that direct models linking hand preference to psychological outcomes may overlook an important intermediate level of explanation. Rather than asking whether left-handedness *causes* lower or higher well-being, it may be more informative to investigate whether particular social experiences and adaptation processes are associated with psychosocial outcomes among left-handed individuals.

**Research Gap.** Despite substantial research on the neuropsychological foundations of handedness, three limitations remain evident in the existing literature. First, handedness research has been dominated by neurobiological, cognitive, developmental, and motor perspectives. These approaches explain important aspects of lateralization but provide comparatively limited insight into how left-handedness is experienced within family, educational, occupational, and everyday social contexts. Second, studies addressing the everyday lives of left-handed individuals have frequently examined isolated dimensions such as ergonomics, hand-use difficulties, cultural attitudes, quality of life, or childhood pressure. Social experiences, adaptation strategies, and psychosocial well-being have less often been examined within a single analytical framework. Third, there remains an explanatory gap between neuropsychological difference and psychosocial outcome. Existing research does not sufficiently explain the processes through which a neurodevelopmental characteristic becomes socially consequential. The present study argues that this relationship is unlikely to be adequately understood through a simple direct pathway from handedness to well-being. Social experiences and adaptation to predominantly right-handed environments constitute potentially important mechanisms connecting individual characteristics with psychosocial outcomes. Accordingly, the principal research gap addressed in this study lies not in determining whether left-handed individuals are neurologically, cognitively, or psychologically “different” from right-handed individuals, but in understanding how left-handedness is socially experienced, how individuals adapt to environments predominantly structured around right-handed practices, and how these experiences and adaptations are associated with psychosocial well-being.

**Theoretical Framework.** The study adopts a person–environment perspective, supplemented by an ecological understanding of psychosocial adaptation. Rather than locating adaptation exclusively within the individual, the person–environment approach conceptualises outcomes as emerging from the relationship between individual characteristics and environmental demands, resources, and opportunities. Within this framework, left-handedness is treated as an individual characteristic whose practical and psychosocial significance may vary according to the social and material environment in which it is expressed. This perspective is particularly appropriate for bridging clinical psychology, sociology, and social work. From a psychological perspective, it allows consideration of individual adaptation, coping, self-perception, and well-being. From a sociological perspective, it directs attention toward norms, institutions, social expectations, and majority-oriented everyday practices. From a social-work perspective, it emphasises person–environment fit and the importance of environments that facilitate

participation rather than requiring individuals continually to compensate for avoidable environmental barriers.

The conceptual logic of the study can therefore be represented as follows:

*Left-handedness and neuropsychological background → social experiences in predominantly right-handed environments → adaptation processes → psychosocial well-being*

Social experiences may include acceptance or pressure within the family, experiences at school and work, reactions from other people, and encounters with objects or environments designed primarily for right-handed use. Adaptation refers to the behavioural, cognitive, and social strategies through which individuals negotiate these experiences. Psychosocial well-being constitutes the outcome dimension and reflects the intersection of psychological functioning and perceived social adjustment.

Importantly, this framework does not conceptualise left-handedness as a pathology, disability, or inherent disadvantage. Instead, it distinguishes the individual characteristic from the environmental conditions under which that characteristic may become socially salient.

**The aim of this study** is to examine how social experiences and adaptation to predominantly right-handed environments are associated with psychosocial well-being among left-handed individuals.

#### **Research Objectives**

- the study pursues the following objectives:
  - to examine the social and everyday experiences associated with left-handedness across family, educational, occupational, and routine-life contexts.
  - to identify the environmental and interpersonal situations in which left-handed individuals perceive a need for behavioural or psychosocial adaptation.
  - to examine the adaptation strategies used by left-handed individuals in predominantly right-handed environments.
  - to assess psychosocial well-being among left-handed individuals.
  - to determine whether social experiences are associated with psychosocial well-being.
  - to examine whether adaptation processes contribute to the relationship between social experiences and psychosocial well-being.
  - to identify socio-demographic and experiential differences in patterns of social experience, adaptation, and psychosocial well-being.

The principal **research question** is: *How are social experiences and adaptation to predominantly right-handed environments associated with psychosocial well-being among left-handed individuals?*

#### **Study contribution**

The study contributes to the literature by repositioning left-handedness from an exclusively neuropsychological phenomenon toward a biopsychosocial and person–environment phenomenon. Rather than seeking additional evidence that left- and right-handed individuals differ neurologically, it examines what happens when an established individual characteristic encounters social norms, institutional practices, and material environments predominantly organised around the majority hand preference. This approach provides a bridge between clinical psychology and sociological/social-work perspectives. It also avoids interpreting adaptation as evidence of individual deficiency. Adaptation may instead represent a response to person–environment mismatch and, potentially, a source of behavioural flexibility and resilience. By integrating social experience, adaptation, and psychosocial well-being within one analytical framework, the study seeks to clarify why the consequences of left-handedness may vary substantially across individuals and social contexts.

## Methods

This study employed an **integrative literature review** to examine the social experiences, adaptation, and psychosocial well-being of left-handed individuals. The literature search and analysis were conducted between **March and May 2026**. The integrative approach was selected because research on left-handedness spans multiple disciplines, including neuroscience, psychology, education, ergonomics, sociology, and health and social sciences, allowing evidence from different methodological traditions to be synthesised within a common analytical framework.

Relevant publications were identified through searches of **Scopus, Web of Science, PubMed, and** using combinations of the keywords *left-handedness, left-handed individuals, handedness, social experience, social adaptation, psychosocial well-being, quality of life, social attitudes, stigma, socialization, cultural pressure, education, workplace, retraining, and right-handed environment*. Boolean operators **AND** and **OR** were used to combine search terms. Additional searches in Russian and Kazakh were conducted to identify studies relevant to Kazakhstan and the broader post-Soviet context. Studies were included if they: (1) examined left-handedness as a substantive phenomenon; (2) addressed social, cultural, educational, occupational, environmental, psychological, or psychosocial dimensions; (3) presented empirical findings or theoretically relevant evidence; and (4) were published in peer-reviewed academic sources in English, Russian, or Kazakh. Neuropsychological studies were included selectively when they provided essential background for understanding handedness. Publications were excluded if handedness was used only as a control variable, if they focused exclusively on neurological or clinical conditions without relevance to social experience or adaptation, if they were duplicates, or if insufficient information was available for assessment. Study selection proceeded through sequential screening of identified records, removal of duplicates, assessment of titles and abstracts, and full-text evaluation against the eligibility criteria. The selection process was documented as *records identified → duplicates removed → full texts assessed → studies included in the final synthesis*.

The included studies were analysed using thematic synthesis. Findings were coded and organised into four interconnected domains: (1) *neuropsychological foundations of left-handedness*, (2) *social and cultural experiences*, (3) *adaptation to predominantly right-handed educational, occupational, and everyday environments*, and (4) *psychosocial well-being*. A person–environment perspective guided interpretation, allowing reported difficulties to be considered in relation to the interaction between individual characteristics and social or environmental conditions rather than as inherent consequences of left-handedness. International evidence was subsequently compared with available literature from Kazakhstan and relevant post-Soviet contexts to identify common patterns, contextual differences, and remaining research gaps.

## Results

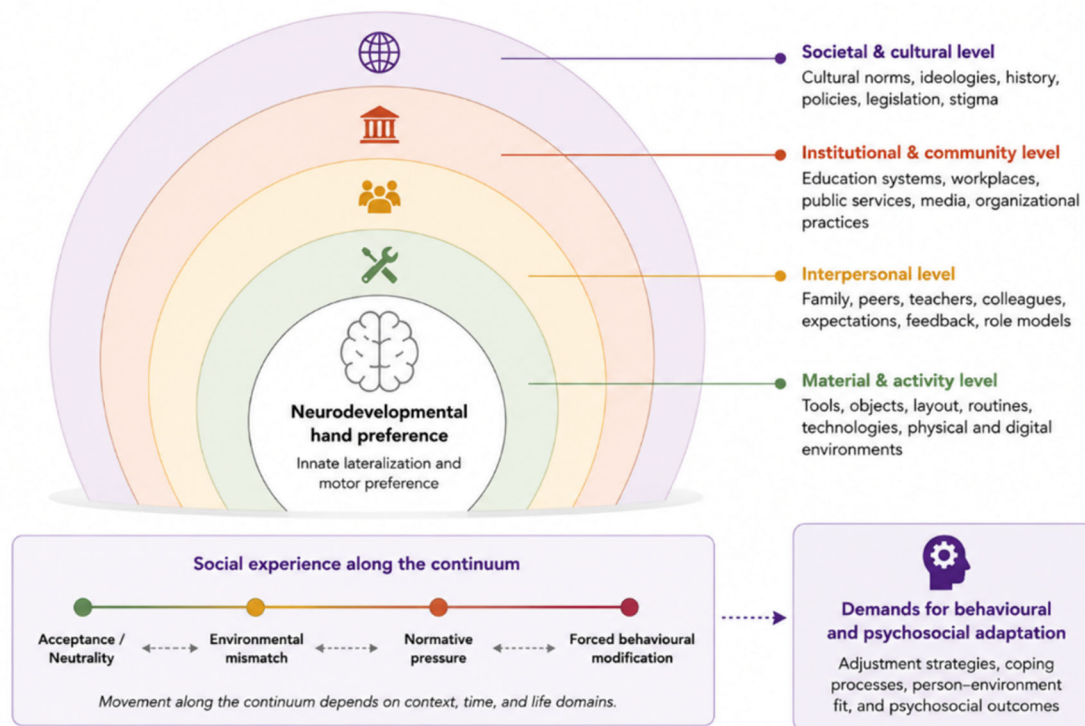
The thematic synthesis revealed three closely interconnected domains through which the psychosocial significance of left-handedness can be understood:

1. Social experiences within predominantly right-handed environments;
2. Behavioural and psychosocial adaptation to environmental demands;
3. Psychosocial well-being in relation to social experience and adaptation.

Across the reviewed literature, an important distinction emerged between left-handedness as an individual characteristic and the conditions under which left-handedness is expressed. Neuropsychological research establishes handedness as a multidimensional phenomenon associated with cerebral lateralisation and developmental processes (Ocklenburg et al., 2014; Papadatou-Pastou et al., 2020; Sun & Walsh, 2006). However, the social and psychosocial literature indicates that the practical consequences of left-handedness cannot be inferred directly from these neurobiological differences. Instead, the evidence suggests that

environmental organisation, cultural expectations, interpersonal responses, and opportunities for adaptation influence whether left-handedness becomes consequential in everyday life.

*From neuropsychological difference to social experience.* The first theme concerned the conditions under which an individual hand preference becomes socially salient. The reviewed evidence indicates that left-handedness is not experienced in a social vacuum. Because right-handedness represents the population majority, many routine practices and material environments have historically been organised around right-handed patterns of action. The large-scale meta-analysis by Papadatou-Pastou et al. (2020) estimated the overall prevalence of left-handedness at approximately 10.6%, while also demonstrating substantial variation associated with sex, geographical region, ancestry, historical period, and methods of handedness classification. Such variation is important for the present synthesis because it indicates that the observable expression of hand preference cannot be interpreted exclusively in biological terms. Cultural tolerance and historical practices may influence whether an underlying left-hand preference is openly expressed, discouraged, or modified. The distinction between biological characteristic and social expression became particularly evident when studies from culturally different environments were compared. In relatively permissive contexts, left-handedness was more commonly described in terms of practical inconvenience and adaptation. Dadić et al. (2021), for example, identified difficulties across multiple everyday activities among left-handed participants while simultaneously finding generally positive evaluations of quality of life. In contrast, research conducted in more culturally restrictive environments demonstrated that left-hand preference may become an explicit object of social regulation. Zverev (2006) provides a particularly clear example. In an urban and semi-urban Malawian sample involving pupils, teachers, and guardians, 75% of respondents indicated that the left hand should not be preferred for at least some habitual activities, while 87.6% supported forcing left-handed individuals to change their preferred hand. Writing, drawing, and greeting were among the activities most strongly subjected to normative expectations. Parents and close relatives were identified as major sources of pressure. Evidence from children in another cultural context similarly demonstrates that modification of handedness can occur at substantial rates. In a study of innately left-handed children, 59.3% were reported to have experienced attempts to convert them to right-handedness. Parental educational level and children's grade level were among the factors associated with conversion practices. These findings suggest that the social experience of left-handedness varies along a continuum from environmental inconvenience to active normative regulation (Figure 1).



**Figure 1. Contextual continuum of social experience of left-handedness**

Family and educational settings emerged as particularly important because they represent contexts in which hand preference becomes visible relatively early in development. Writing, drawing, eating, object manipulation, and socially regulated gestures provide repeated opportunities for adults to respond to a child's preferred hand. The cross-cultural findings are particularly informative in this respect. Zverev (2006) demonstrated that negative attitudes toward left-hand use were not restricted to isolated practical activities but reflected broader assumptions concerning the appropriateness and competence of the left hand. The finding that parents and close relatives represented prominent sources of discouragement suggests that family socialisation can mediate the relationship between cultural norms and individual behaviour. Educational settings can reinforce this process because handwriting and manual performance are repeatedly observed and evaluated. The clinical significance of these findings should nevertheless be interpreted cautiously. Evidence of correction or hand conversion does not by itself establish subsequent psychopathology. What the available literature demonstrates more clearly is exposure to an externally imposed demand to modify naturally preferred behaviour. This distinction is essential. The psychological meaning of learning to operate a right-handed tool voluntarily is not necessarily equivalent to being instructed that one's preferred hand is socially inappropriate. The former represents practical adaptation; the latter introduces an interpersonal and normative component involving conformity. Comparison across studies therefore revealed that cultural context modifies the social visibility of handedness more consistently than it establishes any uniform psychological consequence of handedness itself. In more permissive environments, the dominant challenge appears to concern person-environment fit: left-handed individuals encounter objects or routines that may be less convenient but develop strategies for managing them. In restrictive contexts, environmental mismatch can be accompanied by explicit social pressure. Thus, the same neurodevelopmental characteristic can generate substantially different lived experiences depending on the surrounding normative environment. This finding supports the central person-environment assumption of the present review: the psychosocial significance of an individual characteristic cannot be understood independently of the environment within which it is expressed.

*Adaptation to Predominantly Right-Handed Environments.* The second major theme concerned adaptation to environments in which tools, routines, educational practices, and occupational expectations are predominantly organised around right-handed performance. Rather than representing an intrinsic limitation associated with left-handedness, adaptation can be conceptualised as a response to the degree of fit between an individual's preferred pattern of hand use and the demands imposed by the surrounding environment. This distinction is important because the practical consequences of handedness are not determined by hand preference alone. They also depend on whether environments permit preferred-hand use, provide appropriate equipment, or require individuals to modify established motor strategies. Recent occupational evidence illustrates this interaction particularly clearly. In a study of left-handed surgeons and surgical trainees, Tomar et al. (2026) found that 85.7% of participants experienced practical difficulties during surgical training, while 57.1% reported pressure to become ambidextrous. Such findings demonstrate that adaptation may arise not because left-handed individuals have lower functional capacity, but because training systems, instruments, and established professional practices are organised predominantly around right-handed performance. In this context, the demand for adaptation originates partly in the environment rather than exclusively within the individual. Adaptation may consequently occur at several interconnected levels. At the behavioural level, individuals may alter movement trajectories, reposition tools, change body or hand position, develop alternative techniques, or selectively use the non-preferred hand for tasks that are difficult to perform within a right-hand-oriented configuration. At the cognitive level, repeated exposure to asymmetric environmental demands may encourage anticipatory planning and the development of alternative task strategies. At the interpersonal and institutional levels, adaptation may involve negotiating established expectations concerning how particular activities are conventionally performed. The resulting behaviour can therefore reflect functional flexibility rather than correction of an underlying deficit. A critical distinction must nevertheless be made between functional adaptation and socially imposed hand modification. Functional adaptation is primarily directed toward accomplishing a task effectively while retaining substantial individual agency. Socially imposed modification, by contrast, occurs when behavioural change is expected because left-hand use conflicts with educational, interpersonal, or cultural expectations. Neuroimaging research on individuals who were forced during childhood to switch from left- to right-handed writing demonstrates why these processes should not be treated as equivalent. Klöppel et al. (2007) showed that converted left-handers retained distinctive patterns of cortical motor organisation despite long-term right-hand writing. Earlier work by Siebner et al. (2002) similarly demonstrated persistent differences in the functional neuroanatomy of handwriting among converted left-handers. These findings indicate that externally induced behavioural change does not simply transform an innately left-handed individual into the functional equivalent of a natural right-hander.

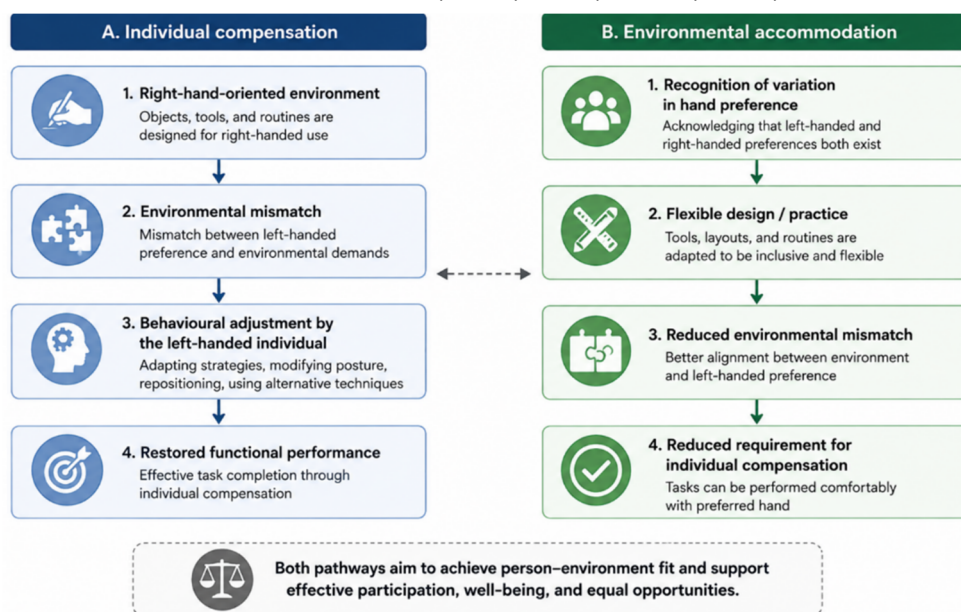
**Table 1. - Comparative characteristics of adaptation and imposed hand modification**

| Dimension                                       | Functional adaptation                              | Socially imposed modification                          |
|-------------------------------------------------|----------------------------------------------------|--------------------------------------------------------|
| Primary source                                  | Environmental/task demands                         | Interpersonal or cultural expectations                 |
| Individual agency                               | Relatively high                                    | Reduced                                                |
| Main purpose                                    | Effective task performance                         | Conformity with right-handed norm                      |
| Preferred hand                                  | Usually retained                                   | May be discouraged or suppressed                       |
| Typical context                                 | Tools, equipment, workstations, routine activities | Family, schooling, culturally regulated activities     |
| Psychological interpretation                    | Behavioural flexibility/compensation               | Normative pressure or externally imposed adjustment    |
| Expected person–environment relationship        | Individual adapts to task                          | Individual is expected to conform to majority practice |
| Evidence represented in the reviewed literature | Everyday adaptation and ergonomic challenges       | Cultural pressure and handedness conversion            |

This distinction has important clinical and psychosocial implications. Behavioural modification cannot be interpreted independently of the circumstances under which it occurs. Voluntarily learning to operate equipment designed for right-handed use is conceptually different from being required to suppress a preferred hand because that preference is considered inappropriate. The first preserves a comparatively high degree of agency and may increase an individual's functional repertoire; the second introduces an element of externally imposed conformity. Evidence from converted left-handers further suggests that extensive practice with the non-preferred hand can modify sensorimotor organisation without completely eliminating neural characteristics associated with the original hand preference (Klöppel et al., 2007; Siebner et al., 2002). The evidence therefore supports a model in which adaptation should be interpreted along at least two dimensions: the magnitude of environmental mismatch and the degree of individual autonomy in responding to it. A person who voluntarily develops alternative strategies in response to an inconvenient tool encounters a different psychosocial situation from an individual whose natural hand preference is explicitly discouraged. This distinction prevents functional compensation, behavioural flexibility, coercive conversion, and social conformity from being collapsed into a single category of “adaptation.”

*Individual compensation and environmental accommodation.* A further distinction concerns the locus of adaptation. Conventional accounts often implicitly assume that adjustment should occur within the left-handed individual: the environment remains unchanged, while the individual learns to operate successfully within it. A person–environment interpretation permits a broader conceptualisation. Mismatch can be reduced either through individual compensation or through environmental accommodation. In the first pathway, environmental conditions remain predominantly unchanged and the individual develops compensatory strategies. These may include alternative movement patterns, selective use of the non-preferred hand, ambidextrous task performance, repositioning of equipment, or task-specific behavioural modifications. The occupational experiences reported by Tomar et al. (2026) provide a contemporary illustration of this pathway: left-handed surgical trainees frequently encounter practical difficulties in training environments structured around conventional right-handed techniques and instruments. In the second pathway, the environment itself is modified to reduce the need for compensation. Appropriate equipment, flexible workstation organisation, alternative teaching techniques, and

acceptance of different patterns of hand use can reduce the discrepancy between individual preference and environmental demand. Conceptually, this pathway is important because it shifts



**Figure 2. Individual compensation and environmental accommodation: two pathways to person-environment fit in left-handedness**

the analytical question from *How successfully can the left-handed person adapt?* to *what extent does the environment unnecessarily require adaptation?* (Figure 2.)

*Psychosocial well-being and the integrative person-environment model.* The third theme concerned the relationship between handedness and psychosocial functioning. The available evidence does not justify a deterministic model in which left-handedness itself is assumed to produce poorer psychological or cognitive outcomes. Instead, the literature increasingly indicates that direction of hand preference is an insufficient explanatory variable when considered independently of environmental and developmental context. Meta-analytic evidence is particularly important in challenging deficit-based interpretations. Ntolka and Papadatou-Pastou (2018), synthesising evidence from 36 studies involving more than 66,000 participants, found that the overall difference in intelligence between left- and right-handed individuals was negligible. Although a very small statistical advantage for right-handers appeared in part of the analysis, the effect was marginal and disappeared when the largest individual study was excluded. Papadatou-Pastou (2018) similarly concluded that when handedness is operationalised as the direction of hand preference, the evidence does not support a meaningful general cognitive difference between left- and right-handed groups. Evidence from educational research points in the same direction. Ferrero et al. (2017), in a systematic review and meta-analysis involving 26 studies and 3,578 children, found no reliable overall association between crossed laterality and either academic achievement or intelligence. Although crossed laterality is conceptually distinct from left-handedness, these findings are relevant because they demonstrate the risks of interpreting atypical patterns of lateral preference as inherently dysfunctional. Taken together, these findings suggest that neurodevelopmental variation should not be conflated with psychological dysfunction or reduced adaptive capacity. The more theoretically informative variables may instead lie in the relationship between the individual and the surrounding environment. Environmental compatibility, opportunities for autonomous adaptation, social acceptance, exposure to normative pressure, and the availability of accommodation may determine whether handedness remains a relatively neutral individual characteristic or becomes a recurrent source of adjustment. The resulting integrative model therefore proposes that psychosocial consequences emerge not directly from left-handedness but through the contexts in which left-

handedness is expressed. A predominantly right-handed environment may generate functional demands; individuals respond through varying forms of compensation; institutions may either intensify or reduce those demands; and the degree of autonomy involved in this process may influence its psychosocial meaning. From this perspective, left-handedness is best understood not as a deficit requiring correction but as an individual characteristic whose practical significance is partly produced by person–environment fit.

### Discussion

The present integrative review sought to move the study of left-handedness beyond a predominantly neuropsychological interpretation by examining how hand preference is experienced within social and material environments, how left-handed individuals adapt to predominantly right-handed contexts, and how these processes may relate to psychosocial well-being. Three interconnected findings emerged from the synthesis. First, the practical and social significance of left-handedness appears to depend substantially on the environment in which it is expressed. Second, adaptation is heterogeneous and should be differentiated according to both the source of environmental demands and the degree of individual autonomy involved. Third, the available evidence does not support a deterministic pathway from left-handedness to poorer psychosocial functioning. Taken together, these findings support a person–environment interpretation in which the consequences associated with minority hand preference arise partly from the relationship between individual characteristics and environmental organisation rather than from handedness itself. One of the central implications of the present synthesis is that left-handedness should not be interpreted exclusively as an individual neurodevelopmental characteristic. Hand preference is expressed through interaction with objects, educational practices, occupational arrangements, interpersonal expectations, and cultural conventions. Consequently, its practical significance changes according to context. A left-handed preference may be almost inconsequential in an environment that permits flexible hand use while becoming highly salient when tools, procedures, or behavioural expectations prescribe a particular pattern of action. This interpretation extends the conventional neuropsychological literature without contradicting it. Research demonstrating differences in cerebral lateralisation and motor organisation provides an important explanation of how hand preference develops, but it does not by itself explain why individuals with similar patterns of hand preference may report markedly different social experiences. The present synthesis suggests that an intermediate explanatory level is required. The social and material environment can either amplify or minimise the practical consequences of neurodevelopmental variation. This argument is consistent with evidence showing that handedness should not be treated as a straightforward indicator of cognitive capacity. Ntolka and Papadatou-Pastou (2018), in their systematic review and meta-analysis, found only negligible differences in intelligence between left- and right-handed individuals. Papadatou-Pastou (2018) similarly demonstrated that relationships between handedness and cognitive ability are considerably more complex than categorical assumptions concerning cognitive superiority or inferiority. Such findings reinforce an important distinction: difference in lateralisation does not imply deficit in functioning. The present review extends this reasoning into the psychosocial domain. If left-handedness does not inherently imply cognitive disadvantage, environmental difficulties experienced by left-handed individuals should not automatically be interpreted as manifestations of individual inadequacy. Instead, some difficulties may reflect a mismatch between individual motor preference and environments structured around majority patterns of hand use.

A second important contribution concerns the conceptualisation of adaptation. The synthesis indicates that adaptation among left-handed individuals cannot adequately be represented as a single behavioural process. At least two analytically distinct forms should be recognised: functional adaptation to environmental demands and socially imposed modification

of preferred-hand behaviour. Functional adaptation can involve repositioning objects, modifying movement patterns, learning alternative techniques, selectively using the non-preferred hand, or developing task-specific forms of ambidexterity. Such strategies may represent behavioural flexibility rather than evidence of impairment. Contemporary occupational evidence provides a particularly clear illustration. Tomar et al. (2026) found that 85.7% of surveyed left-handed surgeons and surgical trainees reported practical difficulties during training, while 57.1% experienced pressure to become ambidextrous. These findings are important because they demonstrate that even in highly skilled professional populations, left-handed individuals may encounter environmental demands generated by established equipment, training procedures, and professional conventions. The distinction between adaptation and imposed modification becomes particularly important when individual agency is considered. Learning voluntarily to use an alternative technique because a particular instrument is inconvenient is psychologically different from being instructed to suppress a naturally preferred hand. Neuroimaging studies of converted left-handers support this distinction. Long-term switching of handwriting from the left to the right hand does not simply reproduce the neural organisation characteristic of natural right-handers. Instead, altered patterns of motor organisation remain detectable among individuals who experienced early conversion (Klöppel et al., 2007; Siebner et al., 2002). These findings have broader theoretical implications. They suggest that behavioural conformity should not be interpreted as evidence that the original person–environment mismatch has disappeared. An individual may become highly competent at performing a task using the non-preferred hand while the behavioural adaptation continues to reflect an environment originally organised around another pattern of motor behaviour. Successful performance therefore does not necessarily indicate optimal environmental fit. This distinction also challenges the assumption that adaptation should occur exclusively within the individual. From a person–environment perspective, mismatch can be reduced through two complementary pathways: individual compensation and environmental accommodation. Individual compensation requires the person to modify behaviour in response to existing environmental demands. Environmental accommodation instead modifies tools, procedures, teaching practices, or work arrangements so that individuals can perform tasks without unnecessary suppression of preferred patterns of behaviour. The distinction is particularly relevant to education, occupational psychology, ergonomics, and social work. When environmental modification is feasible, repeatedly requiring individual compensation may represent an inefficient distribution of adaptive burden. Providing appropriate equipment, flexible seating or workstation arrangements, alternative instructional techniques, and acceptance of different hand-use strategies may reduce unnecessary mismatch without categorising left-handedness as a special clinical condition.

The third major implication concerns psychosocial well-being. The reviewed evidence does not support the assumption that left-handedness itself constitutes a psychosocial risk factor. Instead, the findings point toward a more conditional relationship in which the psychosocial meaning of handedness depends on the social circumstances surrounding its expression. This distinction is theoretically significant. A direct model would assume: *Left-handedness* → *poorer psychosocial well-being*

The present synthesis instead supports a more differentiated pathway: *Left-handedness* → *person–environment interaction* → *social experience and environmental mismatch* → *adaptation processes* → *psychosocial outcomes*

Within this framework, the potential psychosocial consequences of left-handedness are mediated by experiences such as acceptance, environmental compatibility, autonomy, repeated pressure to conform, and opportunities for successful adaptation. Hand preference therefore represents a starting characteristic rather than a sufficient explanation of psychosocial outcome. This interpretation is compatible with broader evidence questioning deterministic associations

between atypical laterality and functional disadvantage. For example, Ferrero et al. (2017) found no reliable overall relationship between crossed laterality and either intelligence or academic achievement. Although crossed laterality should not be equated with left-handedness, these findings demonstrate the methodological risks associated with interpreting patterns of lateral preference as inherently dysfunctional. The concept of agency may be particularly important for understanding variation in psychosocial consequences. Two individuals may exhibit apparently similar behavioural modification while experiencing it very differently. When adjustment is voluntary and enables effective performance, it may be experienced as competence, flexibility, or problem solving. When the same behavioural change results from repeated criticism, correction, or cultural pressure, it may carry a substantially different psychosocial meaning. Thus, the form of adaptation alone is insufficient; the conditions under which adaptation occurs must also be considered. This distinction helps reconcile an apparent contradiction within the literature: environmental inconvenience can coexist with successful functioning. Experiencing difficulties with tools, handwriting arrangements, occupational equipment, or other right-oriented environments does not necessarily produce reduced well-being. Individuals may develop effective compensatory strategies, environments may become more accommodating, and left-handedness may become progressively less socially salient. Conversely, relatively minor functional differences may acquire greater psychological significance when accompanied by interpersonal criticism or pressure to conform.

The findings have several implications for professional practice. From a clinical psychological perspective, left-handedness should not itself be pathologised or treated as an explanatory diagnosis for psychological difficulties. Where left-handed individuals report negative experiences, assessment should distinguish between hand preference itself and the interpersonal or environmental circumstances surrounding it. Questions concerning childhood correction, pressure to switch hands, repeated environmental inconvenience, autonomy in adaptation, and current person–environment fit may be more informative than hand preference alone. Educational practice represents a particularly important context because handwriting and manual activities make hand preference highly visible during childhood. The findings suggest that educational responses should prioritise functional support rather than behavioural normalisation. A child who writes effectively with the left hand does not require correction simply because the majority of classmates use the right hand. Where difficulties occur, modifying paper position, seating arrangements, teaching techniques, or equipment may provide a more appropriate response than changing hand preference. Occupational settings raise similar considerations. The findings reported by Tomar et al. (2026) demonstrate that environmental asymmetry remains relevant even in contemporary professional contexts. Occupational adaptation should therefore not automatically be treated as an individual responsibility. Ergonomic design and professional training can incorporate greater flexibility in order to accommodate natural variation in hand preference.

*Limitations and directions for future research.* Several limitations of the available evidence should be acknowledged. First, the literature addressing the social and psychosocial dimensions of left-handedness remains substantially smaller than the neuropsychological literature. Consequently, some components of the proposed person–environment model are theoretically well supported but have not yet been tested within a single empirical design. Second, substantial heterogeneity exists in the conceptualisation and measurement of handedness. Studies variously classify participants according to writing hand, self-reported preference, multidimensional handedness inventories, or degree of lateral preference. These methodological differences complicate direct comparisons between studies. Third, evidence concerning adaptation is frequently derived from particular contexts, including handwriting, education, everyday object use, or specialised occupations. Findings from these settings should not automatically be

generalised to all left-handed individuals. Occupational environments characterised by highly standardised instruments, for example, may generate substantially greater adaptive demands than ordinary everyday contexts. Fourth, causal relationships between environmental mismatch, adaptation, and psychosocial well-being remain insufficiently established. Much of the available evidence is cross-sectional or retrospective. Longitudinal studies are needed to determine whether repeated environmental mismatch predicts later psychosocial outcomes and whether autonomous adaptation or environmental accommodation moderates this relationship. Future research should therefore move beyond simple comparisons between left- and right-handed groups. Studies focusing specifically on left-handed populations could examine variability in social experiences, childhood hand correction, perceived environmental fit, adaptation strategies, autonomy, and psychosocial well-being. Such designs would permit direct testing of whether adaptation mediates or moderates associations between environmental experiences and psychosocial outcomes. Cross-cultural research is particularly important because the social meaning of left-hand use varies across cultural and historical contexts. Experimental and ergonomic research could additionally compare individual compensation with environmental accommodation. Such research would help determine whether redesigning tasks or equipment reduces cognitive, behavioural, or psychological demands more effectively than requiring individuals to develop compensatory strategies.

### **Conclusion**

Left-handedness is a neurodevelopmentally grounded characteristic, but its everyday significance cannot be understood from neuropsychology alone. The present integrative review indicates that the social and psychosocial consequences associated with left-handedness emerge through interaction with environments predominantly organised around right-handed behaviour. Three conclusions follow from the synthesis. First, environmental and social context determines whether left-handedness remains a relatively neutral individual characteristic or becomes a source of recurrent practical or interpersonal adjustment. Second, adaptation should not be conceptualised as a unitary process. Functional compensation undertaken with substantial individual agency differs fundamentally from socially imposed modification intended to produce conformity with right-handed norms. Third, the available evidence does not support a deterministic relationship between left-handedness and poorer cognitive or psychosocial functioning. The more informative explanatory variables appear to include environmental fit, social acceptance, autonomy, normative pressure, and opportunities for adaptation or accommodation. These findings support an integrative person–environment model in which left-handedness constitutes the individual characteristic, social and material environments provide the context, adaptation represents a mediating process, and psychosocial well-being represents a potential outcome. Importantly, successful adaptation should not automatically be interpreted as evidence that environmental arrangements are appropriate. Individuals may achieve high levels of functioning precisely because they have developed effective strategies for compensating for environments designed around majority behaviour. The conceptual distinction between individual compensation and environmental accommodation therefore has particular importance. Improving person–environment fit does not always require individuals to modify their behaviour. In many educational, occupational, and everyday settings, relatively modest changes in equipment, practices, or expectations may reduce unnecessary adaptive demands while preserving individual autonomy. Accordingly, left-handedness should be approached neither as pathology nor simply as an inconsequential biological variation. It provides a useful model for understanding how neurodevelopmental characteristics acquire different meanings and consequences depending on the environments in which they are expressed. By shifting attention from individual difference alone toward the interaction between individual characteristics, social

experience, environmental demands, agency, and adaptation, the present review offers a framework for future psychological, educational, ergonomic, and social research on handedness.

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<https://publisher.agency>

Paris University

88 Avenue des Ternes

Paris, France

75017