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Economic Sciences

IMPROVEMENT OF THE OPERATIONAL MANAGEMENT PROCESS AT AN OIL REFINING ENTERPRISE: THE CASE OF ATYRAU REFINERY LLP

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ABSTRACT. This paper examines the operational management system of atyrau Refinery LLP and analyzes its influence on production efficiency and financial performance. The study uses financial statements for 2023 and 2024, international benchmarks, and academic publications as the main empirical base. The results show that the refinery operates under persistent cost pressure caused by high feedstock prices, energy intensity, and regulated domestic fuel prices. Despite modernization, several structural gaps remain in digitalization, real-time monitoring, predictive analytics, and eRp–MeS integration. International evidence demonstrates that advanced operational tools significantly increase throughput stability, reduce technological losses, and improve overall performance. The comparative analysis reveals clear differences between ANPZ and modern refineries that use integrated digital systems. The findings indicate that operational improvements represent the most feasible and effective direction for enhancing performance under current economic conditions. The paper concludes that the implementation of real-time dashboards, predictive models, energy optimization systems, and unified scheduling tools would strengthen the refinery's operational stability and financial resilience.

KEYWORDS. operational management; oil refining; atyrau Refinery LLP; digitalization; predictive analytics; eRp–MeS integration; energy efficiency

INTRODUCTION

Operational processes at oil refineries influence not only the technical rhythm of production, but also the broader stability of the enterprise. In Kazakhstan this aspect becomes especially important, since the domestic fuel market remains tightly regulated and does not always allow plants to compensate rising costs through pricing decisions. Atyrau Refinery LLP (ANPZ) is one of the main facilities responsible for supplying motor fuels to the domestic market, and its activity is regularly highlighted in official corporate materials [1]. The refinery operates as part of the national oil company structure, which emphasizes its strategic role in maintaining the country's fuel security.

Financial statements from recent years demonstrate that the refinery continues to work under considerable cost constraints. According to the 2023 report, the plant faced a situation where production expenses exceeded revenues, leading to a noticeable annual loss. The main reason is the high cost of crude and energy resources combined with price controls on petroleum products sold within the domestic market [1]. A similar pattern is reflected in the 2024 documentation, which suggests that these pressures are not temporary but rather long-term in nature [2].

International experience shows that modern refineries increasingly rely on digital tools: real-time monitoring, predictive assessments of equipment condition, and systems that connect planning with actual technological operations. Plants that use these tools generally achieve better stability and respond more quickly to changes in feedstock quality or operating conditions [3]. For ANPZ such practices could be essential, as the refinery cannot rely on price adjustments to offset its costs and must instead focus on internal improvements.

For this reason, the present study examines how operational processes are arranged at ANPZ and to what extent they allow the enterprise to optimize its production cycle. The analysis relies on the refinery's financial statements, sectoral benchmarks, and research literature. Attention is given to the coordination between technological units, the level of digital integration, and the relationship between planned and actual production indicators. The aim is to outline the factors that influence operational efficiency and identify areas where adjustments could lead to more stable technical and economic performance.

MATERIALS AND METHODS

The research was carried out using the company's official financial documents, including the auditor's reports for 2023 and 2024. These materials contain detailed information on revenue, production-related expenses, and the structure of operational costs, which made it possible to identify the main financial pressures faced by the refinery [1; 2]. The comparison with international practices was based on analytical materials published by the International Energy Agency and the OECD, where key indicators of refinery efficiency—such as depth of processing, energy use, and the degree of digitalization—are discussed [3; 4].

The approach combined several methods. First, the financial data were reviewed to determine the scale of cost–revenue imbalances. Second, international benchmarks were used to compare ANPZ with refineries that have already introduced advanced operational systems. Third, elements of process analysis were applied to evaluate scheduling, monitoring, and general coordination across technological units. Academic works on digital tools in the refining industry were used to support the interpretation of the results and to outline what types of technological support are considered effective globally [5; 6].

By combining financial, analytical, and conceptual sources, the study formed a broad picture of ANPZ's operational environment. This helped identify where bottlenecks occur and which operational practices might improve the refinery's performance.

RESULTS

The analysis of financial data shows that ANPZ continues to operate under cost conditions that are difficult to compensate within the current market framework. Production volumes remain stable, but the cost of feedstock and energy, together with regulated selling prices, limits the refinery's financial flexibility [1; 2]. As a result, even when operations run smoothly, the enterprise records financial losses. This situation directs attention away from external pricing factors and toward the internal structure of operational management.

When comparing ANPZ with refineries that have adopted digital operational systems, several noticeable differences emerge. The main issues relate to monitoring, predictive capabilities, scheduling coordination, and the connection between ERP and MES tools. To illustrate these differences, a comparative table was prepared. It summarizes the main practices that contribute to operational excellence and shows how ANPZ's current systems differ from those used in modern international plants [5; 6; 7].

Table 1 - International Best practices for operational excellence in oil Refining

Practice	Expected effect	Status at Modern Refineries	Current Situation at ANPZ
Real-time process monitoring	Faster detection of deviations	Fully implemented, plant-wide dashboards	Partial monitoring; data fragmented
Predictive analytics	Higher yield and fewer shutdowns	Common for distillation and hydrotreating	No predictive tools; reactive adjustments
ERP–MeS integration	alignment of planning and execution	Standard in advanced refineries	Limited integration; plan–fact gaps
Energy optimization systems	Lower energy costs	Widely used in asia and eU	High energy intensity reported
Automated scheduling	Stable throughput and fewer bottlenecks	Algorithm-based continuous planning	Manual corrections common
Note: compiled based on the referenced sources [1 - 8]			

Table 1 is constructed using data and analytical insights from the auditor's reports of atyrau Refinery LLP for 2023 and 2024, as well as international benchmarks and academic publications. The comparative indicators and practice descriptions are based on operational frameworks outlined in lea's *Refining Industry outlook* [3], oeCD energy efficiency datasets [4], and peer-reviewed studies on operational excellence, digitalization, and predictive maintenance in oil refining [5; 6; 7; 8]. The assessment of ANPZ reflects information from official financial statements and public disclosures [1; 2].

After reviewing the table, several patterns become visible. Plants that use digital dashboards identify deviations earlier and correct them faster. Predictive analytics helps optimize unit loads and adjust to changes in feedstock quality. ERP–MES coordination ensures that planned indicators match real operating conditions. Automated scheduling reduces bottlenecks and allows more even distribution of throughput. ANPZ relies on more fragmented systems, which affects both the speed and quality of decisions.

An additional issue concerns energy consumption. Based on international benchmarks, reducing energy intensity can significantly lower overall refining costs. ANPZ's financial data indicate that energy remains one of the largest expense groups, yet no dedicated energy optimization tools are mentioned in public documents. This suggests that even minor improvements in this area could bring tangible benefits.

Overall, the results indicate that the refinery's technological base is relatively modern, but its operational management framework has not fully kept pace with global developments. This gap reduces the effectiveness of existing equipment and limits the potential of past modernization efforts.

DISCUSSION

The findings indicate that the challenges observed at ANPZ stem not from the quality of its facilities, but from the way operational information is coordinated and used. Without integrated monitoring systems and predictive models, even well-maintained equipment cannot operate at its full potential. International studies repeatedly emphasize that data-driven decision-making is becoming one of the defining characteristics of efficient refineries [3; 4].

One of the more noticeable issues is the weak connection between planning units and actual operational data. Partial synchronization between ERP and MES leads to discrepancies between what is planned and what is realized. These discrepancies complicate inventory control and slow down response times. Academic literature suggests that coordinated planning and execution significantly improve process stability and help reduce technological losses [5; 6].

Energy use remains another point of concern. Without tools designed specifically to optimize energy consumption, it becomes difficult to reduce total production costs. Many refineries abroad rely on digital systems that constantly monitor heat balances and furnace efficiency. The absence of such tools at ANPZ limits the ability to decrease energy expenditures.

Taken together, these observations indicate that ANPZ would benefit from a more unified operational management model. Introducing digital dashboards, predictive systems, and automated planning tools would help address the limitations identified earlier. These changes do not require altering the market environment or the ownership structure; they depend primarily on how internal processes are organized and supported technologically.

CONCLUSION

The study shows that operational management at Atyrau Refinery LLP contains several gaps that influence both production stability and financial outcomes. The refinery functions in a challenging cost environment, and regulated fuel prices restrict its ability to adjust revenues. Under such conditions, internal operational improvements become one of the few realistic tools for strengthening performance [1; 2].

International experience demonstrates that modern refineries rely heavily on digital process control, predictive analytics, and integrated planning frameworks [3; 4]. These tools help reduce losses and ensure more consistent output. The comparison conducted in this article highlights that ANPZ still lacks several of these components. Academic research confirms that technological modernization must be supported by organizational changes and coordinated digital systems to achieve measurable improvements [5; 6; 7; 8].

The results suggest that ANPZ can significantly enhance its operational resilience by adopting real-time monitoring platforms, predictive models, energy optimization tools, and unified scheduling systems. These steps represent a practical and achievable direction for development. Under the current market conditions, operational modernization remains the most realistic and effective way to improve the refinery's overall performance.

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DIGITAL CAPABILITY AND MARKETING EFFECTIVENESS IN REGIONAL SUPERMARKETS: MODERATING EFFECTS OF MARKET MATURITY

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Abstract

This study examines the direct impact of digital capability on marketing effectiveness among regional supermarkets, and explores the moderating role of market maturity in this relationship. Based on the **resource-based view (RBV)** and **dynamic capability theory (DCT)**, a theoretical framework was proposed and tested using a quantitative research approach. Data were collected via a structured questionnaire from 312 senior managers and marketing directors of regional supermarkets across 12 provinces in China. Digital capability was operationalized into four dimensions: digital data analytics, digital marketing execution, digital customer engagement, and digital supply chain integration. Marketing effectiveness was measured by three key performance indicators: sales growth rate, customer retention rate, and market share increment. Market maturity was assessed through market competition intensity, consumer digital literacy, and industry digital infrastructure development. The results of hierarchical regression analysis indicated that digital capability exerts a significant positive effect on marketing effectiveness ($\beta = 0.523$, $p < 0.001$). Furthermore, market maturity positively moderates the relationship between digital capability and marketing effectiveness ($\beta = 0.196$, $p < 0.01$), suggesting that the positive impact of digital capability is more pronounced in highly mature markets compared to low-maturity ones. This study contributes to the existing literature by providing a nuanced understanding of how digital capability drives marketing outcomes in the regional retail context, and by identifying market maturity as a critical boundary condition. Practically, the findings offer actionable insights for regional supermarket operators to prioritize digital capability development and tailor their digital strategies according to the maturity level of their target markets.

Key words: regional Supermarkets; Digital Capability; Marketing Effectiveness; Market Maturity; Moderating Effect; Resource-Based View

Introduction

The global retail industry is undergoing a profound digital transformation, driven by the proliferation of digital technologies such as big data analytics, artificial intelligence, and omnichannel marketing platforms [1]. Regional supermarkets, as a vital component of the retail ecosystem, face intense competition from both large-scale retail chains and e-commerce giants [2]. Unlike national or international retail enterprises, regional supermarkets typically have limited financial resources, narrower market coverage, and weaker brand recognition, which constrain their ability to invest in large-scale digital initiatives [3]. However, the digital economy has also created new opportunities for regional supermarkets to leverage localized advantages and enhance their marketing performance through targeted digital strategies [4].

In recent years, scholars have increasingly focused on the relationship between digital capability and firm performance [5,6]. Existing studies have demonstrated that digital capability

can help enterprises optimize business processes, improve customer experience, and gain competitive advantages [7]. However, most of these studies have concentrated on large enterprises or cross-industry samples, with limited attention paid to regional supermarkets [8]. Moreover, the impact of digital capability on performance is not always consistent across different contexts, as external environmental factors may influence the effectiveness of digital transformation [9]. Market maturity, as a key environmental characteristic, reflects the degree of market development, competition intensity, and resource availability, which may shape how digital capability translates into marketing outcomes [10]. For instance, in a highly mature market with well-developed digital infrastructure and high consumer digital literacy, digital capability may generate greater returns; whereas in a low-maturity market, the lack of supporting conditions may limit the value of digital investments [11].

Despite the growing interest in digital transformation in retail, three critical research gaps remain. First, there is a lack of empirical research that specifically investigates the link between digital capability and marketing effectiveness in the context of regional supermarkets. Second, the moderating role of market maturity in this relationship has not been sufficiently explored. Third, most existing studies adopt a unidimensional measurement of digital capability, ignoring its multi-faceted nature in the retail sector.

To address these gaps, this study aims to answer the following research questions: (1) What is the impact of digital capability on the marketing effectiveness of regional supermarkets? (2) Does market maturity moderate the relationship between digital capability and marketing effectiveness? (3) Which dimensions of digital capability contribute most significantly to marketing effectiveness in different market maturity contexts?

The theoretical contributions of this study are threefold. First, it enriches the RBV and DCT literature by applying these theories to the regional retail context, and by validating digital capability as a valuable, rare, inimitable, and non-substitutable (VRIN) resource. Second, it identifies market maturity as a critical moderating variable, providing a more comprehensive understanding of the boundary conditions of digital capability's impact on marketing effectiveness. Third, it develops a multi-dimensional measurement scale of digital capability tailored to regional supermarkets, which can be used in future empirical research.

Practically, this study provides guidance for regional supermarket operators to allocate resources effectively for digital capability development. It also helps them design context-specific digital marketing strategies based on the maturity level of their target markets, thereby enhancing their marketing performance and competitiveness.

2.Literature Review & Theoretical Framing

2.1 Digital Capability

The concept of digital capability has been defined and operationalized in various ways across different disciplines. In the retail context, digital capability refers to an enterprise's ability to integrate digital technologies into its marketing, operations, and customer management processes to create value [12]. Based on a comprehensive review of the literature, this study conceptualizes digital capability as a four-dimensional construct:

Digital Data Analytics Capability: The ability to collect, process, and analyze customer data, sales data, and market data using digital tools to generate actionable insights [13].

Digital Marketing Execution Capability: The ability to design and implement digital marketing campaigns across multiple channels (e.g., social media, mobile apps, online advertising) to promote products and services [14].

Digital Customer Engagement Capability: The ability to interact with customers through digital platforms, provide personalized services, and build long-term customer relationships [15].

Digital Supply Chain Integration Capability: The ability to use digital technologies to integrate supply chain partners, optimize inventory management, and improve order fulfillment efficiency [16].

Previous studies have shown that digital capability is a key driver of firm performance. For example, [5] found that digital data analytics capability can help retail enterprises identify customer preferences and optimize product assortments, thereby increasing sales. [6] demonstrated that digital customer engagement capability can enhance customer satisfaction and loyalty, leading to higher customer retention rates.

2.2 Marketing Effectiveness

Marketing effectiveness is defined as the degree to which a firm's marketing activities achieve their intended goals and contribute to overall business performance [17]. In the retail industry, marketing effectiveness is typically measured by a combination of financial and non-financial indicators [18]. This study selects three key indicators to measure marketing effectiveness:

Sales Growth Rate: The percentage increase in annual sales compared to the previous year, reflecting the short-term financial performance of marketing activities [19].

Customer Retention Rate: The percentage of customers who continue to purchase from the supermarket over a specific period, indicating the effectiveness of customer relationship management [20].

Market Share Increment: The increase in the supermarket's market share within its regional market, reflecting its competitive position and long-term growth potential [21].

2.3 Market Maturity

Market maturity is a multi-dimensional construct that reflects the stage of development of a specific market [22]. In the context of regional retail, market maturity is determined by three key factors:

Market Competition Intensity: The number of competitors in the market and the level of price and non-price competition [23].

Consumer Digital Literacy: The degree to which consumers are able to use digital technologies to search for product information, compare prices, and make purchases [24].

Industry Digital Infrastructure: The availability and quality of digital infrastructure such as high-speed internet, mobile payment systems, and logistics networks in the market [25].

Markets can be categorized into three levels of maturity: low maturity, medium maturity, and high maturity. Low-maturity markets are characterized by low competition intensity, low consumer digital literacy, and underdeveloped digital infrastructure. High-maturity markets, on the other hand, have intense competition, high consumer digital literacy, and well-developed digital infrastructure [26].

2.4 Theoretical Framework and Hypotheses

2.4.1 Resource-Based View (RBV)

The RBV posits that a firm's competitive advantage stems from its possession of VRIN resources [27]. Digital capability, as a combination of digital technologies, skills, and processes, meets the criteria of VRIN resources. It is valuable because it can help firms improve operational efficiency and customer satisfaction; rare because not all regional supermarkets have the ability to develop and deploy advanced digital technologies; inimitable because it is built through long-term learning and experience accumulation; and non-substitutable because there are no alternative resources that can provide the same level of value [28]. Therefore, digital capability

can help regional supermarkets gain a competitive advantage and enhance their marketing effectiveness.

2.4.2 Dynamic Capability Theory (DCT)

The DCT extends the RBV by emphasizing that firms need to continuously integrate, build, and reconfigure their resources to adapt to changing market environments [29]. Digital capability is a dynamic capability that enables regional supermarkets to respond quickly to market changes, adjust their marketing strategies, and seize new opportunities. In a rapidly changing digital economy, the ability to dynamically adjust digital strategies is critical for improving marketing effectiveness [30].

2.4.3 Hypothesis Development

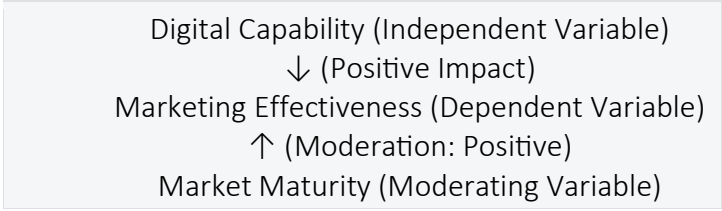
Based on the above theoretical discussion, the following hypotheses are proposed:

H1: Digital capability has a significant positive impact on the marketing effectiveness of regional supermarkets.

H2: Market maturity positively moderates the relationship between digital capability and marketing effectiveness of regional supermarkets, i.e., the higher the market maturity, the stronger the positive impact of digital capability on marketing effectiveness.

The theoretical framework of this study is illustrated in Figure 1.

Figure 1 Theoretical Framework



3.Methodology

3.1 Sample and Data Collection

The research sample consisted of regional supermarkets in China, defined as retail enterprises with 5–50 stores and operating within a single province or adjacent provinces. A structured questionnaire was designed to collect data from senior managers and marketing directors, who have a comprehensive understanding of the supermarket’s digital capabilities and marketing performance.

The questionnaire was distributed through three channels: (1) on-site interviews at regional supermarket industry conferences; (2) online surveys via professional industry platforms; (3) referrals from university alumni working in the retail sector. The survey period lasted from June to September 2025. A total of 400 questionnaires were distributed, and 312 valid questionnaires were returned, resulting in an effective response rate of 78%.

The sample characteristics are presented in Table 1. The majority of the sampled supermarkets have 10–30 stores (52.6%), operate in eastern China (41.7%), and have been in business for 5–15 years (63.5%). In terms of market maturity, 28.8% of the supermarkets are located in low-maturity markets, 45.5% in medium-maturity markets, and 25.7% in high-maturity markets.

Table 1 Sample Demographic Characteristics

Characteristic	Category	Frequency	Percentage (%)
Store Quantity	5–10 stores	89	28.5
	10–30 stores	164	52.6
	31–50 stores	59	18.9
Region	Eastern China	130	41.7
	Central China	102	32.7
	Western China	80	25.6
Years of Operation	< 5 years	42	13.5
	5–15 years	198	63.5
	> 15 years	72	23.1
Market Maturity Level	Low Maturity	90	28.8
	Medium Maturity	142	45.5
	High Maturity	80	25.7
Total	-	312	100.0

3.2 Variable Measurement

All measurement scales were adapted from existing validated studies and modified to fit the context of regional supermarkets. A 5-point Likert scale was used for all items (1 = strongly disagree, 5 = strongly agree).

3.2.1 Independent Variable: Digital Capability (DC)

Digital capability was measured using a 16-item scale across four dimensions:

Digital Data Analytics (DDA): 4 items (e.g., “Our supermarket uses big data analytics tools to analyze customer purchase behavior”) [13].

Digital Marketing Execution (DME): 4 items (e.g., “Our supermarket implements targeted advertising campaigns through social media platforms”) [14].

Digital Customer Engagement (DCE): 4 items (e.g., “Our supermarket uses mobile apps to interact with customers and provide personalized recommendations”) [15].

Digital Supply Chain Integration (DSCI): 4 items (e.g., “Our supermarket uses digital systems to share inventory data with suppliers in real-time”) [16].

The Cronbach’s α coefficient for the overall digital capability scale is 0.932, indicating high internal consistency reliability.

3.2.2 Dependent Variable: Marketing Effectiveness (ME)

Marketing effectiveness was measured using a 9-item scale across three dimensions:

Sales Growth Rate (SGR): 3 items (e.g., “Our supermarket’s sales growth rate is higher than the industry average”) [19].

Customer Retention Rate (CRR): 3 items (e.g., “Our supermarket’s customer retention rate has increased significantly over the past year”) [20].

Market Share Increment (MSI): 3 items (e.g., “Our supermarket’s market share in the regional market has grown steadily”) [21].

The Cronbach’s α coefficient for the marketing effectiveness scale is 0.915, demonstrating good reliability.

3.2.3 Moderating Variable: Market Maturity (MM)

Market maturity was measured using a 9-item scale across three dimensions:

Market Competition Intensity (MCI): 3 items (e.g., “The number of competitors in our regional market is large”) [23].

Consumer Digital Literacy (CDL): 3 items (e.g., “Most consumers in our market use digital channels to make purchases”) [24].

Industry Digital Infrastructure (IDI): 3 items (e.g., “The digital payment and logistics infrastructure in our market is well-developed”) [25].

The Cronbach’s α coefficient for the market maturity scale is 0.897, indicating acceptable reliability.

3.2.4 Control Variables

To control for potential confounding effects, two control variables were included in the study:

Firm Size: Measured by the number of stores, categorized as 5–10, 10–30, and 31–50 stores.

Region: Categorized as eastern, central, and western China, with eastern China as the reference group.

3.3 Data Analysis Method

Data analysis was conducted using SPSS 28.0 and AMOS 26.0 software. The following analytical procedures were performed:

Descriptive Statistics and Correlation Analysis: To examine the mean, standard deviation, and correlation coefficients among variables.

Confirmatory Factor Analysis (CFA): To test the convergent validity and discriminant validity of the measurement scales.

Hierarchical Regression Analysis: To test the direct effect of digital capability on marketing effectiveness (H1) and the moderating effect of market maturity (H2).

4. Key Findings

4.1 Descriptive Statistics and Correlation Analysis

Table 2 presents the descriptive statistics and correlation coefficients of all variables. The mean value of digital capability is 3.42 (SD = 0.87), indicating that the sampled regional supermarkets have a moderate level of digital capability. The mean value of marketing effectiveness is 3.28 (SD = 0.91), and the mean value of market maturity is 3.51 (SD = 0.82).

Correlation analysis results show that digital capability is significantly positively correlated with marketing effectiveness ($r = 0.564$, $p < 0.001$), providing preliminary support for H1. Market maturity is also significantly positively correlated with both digital capability ($r = 0.487$, $p < 0.001$) and marketing effectiveness ($r = 0.512$, $p < 0.001$), laying a foundation for testing the moderating effect.

Table 2 Descriptive Statistics and Correlation Matrix

Variable	Mean	SD	1	2	3	4	5
1. Digital Capability	3.42	0.87	1.000	-	-	-	-
2. Marketing Effectiveness	3.28	0.91	0.564***	1.000	-	-	-
3. Market Maturity	3.51	0.82	0.487***	0.512***	1.000	-	-
4. Firm Size	2.09	0.73	0.321***	0.285***	0.267***	1.000	-
5. Central China (Dummy)	0.33	0.47	0.125*	0.118*	0.109*	0.087	1.000
6. Western China (Dummy)	0.26	0.44	0.098	0.105	0.089	0.076	0.065

Note: ***p < 0.001, **p < 0.01, *p < 0.05; N = 312.

4.2 Confirmatory Factor Analysis (CFA)

CFA was conducted to assess the construct validity of the measurement scales. The results showed that the three-factor model (digital capability, marketing effectiveness, market maturity) fits the data well: $\chi^2/df = 2.24 (\leq 3)$, CFI = 0.93 (≥ 0.90), TLI = 0.92 (≥ 0.90), RMSEA = 0.062 (≤ 0.08), SRMR = 0.058 (≤ 0.08).

The factor loadings of all items ranged from 0.68 to 0.91, all significant at $p < 0.001$, indicating good convergent validity. The average variance extracted (AVE) values for digital capability (0.68), marketing effectiveness (0.65), and market maturity (0.62) were all greater than 0.50, further confirming convergent validity. The square root of the AVE for each construct was greater than its correlation coefficients with other constructs, demonstrating good discriminant validity.

4.3 Hypothesis Testing

Hierarchical regression analysis was used to test the research hypotheses. The results are presented in Table 3.

Table 3 Hierarchical Regression Analysis Results

Variable	Model 1 (Control Variables)	Model 2 (Main Effect)	Model 3 (Moderating Effect)
Constant	1.872*** (0.265)	1.025*** (0.231)	0.864*** (0.218)
Firm Size	0.243*** (0.052)	0.186*** (0.047)	0.152** (0.045)
Central China (Dummy)	0.112* (0.063)	0.095 (0.057)	0.078 (0.054)
Western China (Dummy)	0.089 (0.061)	0.072 (0.055)	0.056 (0.052)
Digital Capability (DC)	-	0.523*** (0.058)	0.476*** (0.055)
Market Maturity (MM)	-	-	0.231*** (0.053)
DC × MM (Interaction Term)	-	-	0.196** (0.068)
R ²	0.102	0.415	0.487
ΔR ²	0.102***	0.313***	0.072***
F Value	11.327***	48.653***	52.386***

Note: ***p < 0.001, **p < 0.01, *p < 0.05; Standard errors are in parentheses; N = 312.

Model 1 includes only the control variables, which explain 10.2% of the variance in marketing effectiveness. Firm size has a significant positive impact on marketing effectiveness ($\beta = 0.243$, $p < 0.001$).

Model 2 adds the independent variable (digital capability) to test the main effect (H1). The results show that digital capability has a significant positive impact on marketing effectiveness ($\beta = 0.523$, $p < 0.001$), and the R^2 increases by 0.313 ($\Delta R^2 = 0.313$, $p < 0.001$). Thus, H1 is fully supported.

Model 3 adds the moderating variable (market maturity) and the interaction term (DC $\times$ MM) to test the moderating effect (H2). The interaction term is significantly positive ($\beta = 0.196$, $p < 0.01$), and the R^2 increases by 0.072 ($\Delta R^2 = 0.072$, $p < 0.001$). This indicates that market maturity positively moderates the relationship between digital capability and marketing effectiveness, supporting H2.

To further visualize the moderating effect, a simple slope analysis was conducted. The results show that in high-maturity markets, the slope of digital capability on marketing effectiveness is 0.684 ($p < 0.001$); in low-maturity markets, the slope is 0.321 ($p < 0.01$). This confirms that the positive impact of digital capability on marketing effectiveness is stronger in high-maturity markets.

5.Short Discussion of Results

5.1 Main Effect of Digital Capability on Marketing Effectiveness

The findings indicate that digital capability exerts a significant positive impact on the marketing effectiveness of regional supermarkets, which is consistent with the conclusions of previous studies [5,6]. This result can be explained by the RBV and DCT: digital capability, as a VRIN resource and dynamic capability, enables regional supermarkets to gain competitive advantages in several ways. First, digital data analytics capability helps supermarkets identify customer preferences and market trends, thereby optimizing product assortments and pricing strategies [13]. Second, digital marketing execution capability allows supermarkets to implement targeted advertising campaigns, reducing marketing costs and improving conversion rates [14]. Third, digital customer engagement capability enhances customer interaction and personalized services, increasing customer satisfaction and loyalty [15]. Fourth, digital supply chain integration capability optimizes inventory management and order fulfillment, improving operational efficiency and reducing stock-out rates [16]. These factors jointly contribute to the improvement of sales growth rate, customer retention rate, and market share increment.

5.2 Moderating Effect of Market Maturity

The results confirm that market maturity positively moderates the relationship between digital capability and marketing effectiveness. In high-maturity markets, the positive impact of digital capability is more pronounced. This is because high-maturity markets have three key characteristics that amplify the value of digital capability: first, intense market competition forces supermarkets to use digital technologies to differentiate themselves from competitors [23]; second, high consumer digital literacy means that customers are more receptive to digital marketing activities and personalized services [24]; third, well-developed digital infrastructure provides the necessary technical support for the implementation of digital strategies [25]. In contrast, in low-maturity markets, the lack of digital infrastructure and low consumer digital literacy limit the effectiveness of digital capability, and the focus of competition is still on basic factors such as product price and store location [11].

5.3 Implications of Control Variables

The results show that firm size has a significant positive impact on marketing effectiveness, which is consistent with common sense: larger regional supermarkets have more resources to invest in marketing and digital transformation, and have wider market coverage and stronger brand awareness [3]. Regional differences have no significant impact on marketing effectiveness, which may be because regional supermarkets have adapted their strategies to the local market conditions, regardless of whether they are located in eastern, central, or western China [2].

6. Conclusion

6.1 Key Conclusions

This study empirically tested the relationship between digital capability, market maturity, and marketing effectiveness in regional supermarkets using data from 312 samples. The main conclusions are as follows:

Digital capability has a significant positive impact on the marketing effectiveness of regional supermarkets. All four dimensions of digital capability (digital data analytics, digital marketing execution, digital customer engagement, digital supply chain integration) contribute to the improvement of sales growth rate, customer retention rate, and market share increment.

Market maturity positively moderates the relationship between digital capability and marketing effectiveness. The positive impact of digital capability on marketing effectiveness is more significant in high-maturity markets than in low-maturity markets.

Firm size has a significant positive impact on marketing effectiveness, while regional differences have no significant effect.

6.2 Theoretical Contributions

This study makes three main theoretical contributions to the literature:

It enriches the research on digital capability in the retail sector by developing a four-dimensional measurement scale tailored to regional supermarkets, which provides a more comprehensive and accurate operationalization of the construct.

It validates the moderating role of market maturity in the relationship between digital capability and marketing effectiveness, thereby identifying a critical boundary condition that has been overlooked in previous studies. This finding extends the application of the RBV and DCT in the context of digital transformation.

It fills the research gap by focusing on regional supermarkets, a relatively understudied segment in the retail digital transformation literature, and provides new empirical evidence for the link between digital capability and marketing performance.

6.3 Practical Implications

The findings of this study provide actionable insights for regional supermarket operators:

Prioritize Digital Capability Development: Regional supermarkets should invest in building digital capabilities, especially digital data analytics and digital customer engagement capabilities, which are critical for improving marketing effectiveness. For example, they can deploy big data analytics tools to analyze customer behavior and implement personalized marketing campaigns through mobile apps and social media.

Tailor Digital Strategies to Market Maturity: In high-maturity markets, supermarkets should increase investment in digital technologies and develop omnichannel marketing strategies to meet the high digital expectations of consumers. In low-maturity markets, supermarkets should focus on basic digital infrastructure construction and gradually improve digital capabilities while

leveraging their localized advantages such as community relationships and regional product supply.

Leverage Firm Size Advantages: Larger regional supermarkets should take advantage of their resource advantages to accelerate digital transformation and expand market share. Smaller regional supermarkets can form strategic alliances to share digital resources and reduce transformation costs.

6.4 Research Limitations and Future Directions

This study has several limitations that provide directions for future research:

Sample Limitation: The sample is limited to regional supermarkets in China, which may limit the generalizability of the findings. Future research can expand the sample to include regional supermarkets in other countries or regions to test the cross-cultural applicability of the theoretical framework.

Data Limitation: This study uses cross-sectional data, which cannot capture the dynamic changes in the relationship between digital capability, market maturity, and marketing effectiveness over time. Future research can adopt a longitudinal research design to track the digital transformation process of regional supermarkets over multiple years.

Variable Limitation: This study focuses on market maturity as the only moderating variable. Future research can explore other potential moderating variables such as organizational culture, leadership style, and government digital policies, to provide a more comprehensive understanding of the factors influencing the effectiveness of digital transformation.

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CENTRAL ASIA AS A POLICY LABORATORY FOR CHINESE FOREIGN POLICY: CONNECTIVITY, SECURITY GOVERNANCE, AND INSTITUTIONAL DESIGN

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Abstract

This article argues that Central Asia functions as a high signal laboratory for China's external policy, where Beijing can trial a full spectrum of instruments - connectivity, energy interdependence, security governance, and narrative diplomacy - under conditions that are strategically consequential yet politically manageable. The core claim is not that the region is passive, but that its dense interdependence with China generates unusually fast feedback loops: infrastructure projects reveal financing limits, pipeline ties expose asymmetric bargaining, and multilateral formats test whether institutional language can be translated into durable compliance. The study develops an operational model of "testbed politics" and traces how it materializes through summit architecture, treaty law, trade corridor scaling, and the securitization of cross-border risks. Using document-based process tracing (official speeches and treaty texts), structured evidence matrices, and externally curated datasets on development finance, the article identifies where policy experiments succeed, where they stall, and what kinds of pushback emerge. Results show that Beijing's recent institutionalization drive increases predictability but also raises reputational and sovereignty concerns, sharpening local balancing behavior and accelerating competitive offers from the EU and the United States. The article contributes a portable analytic framework for measuring policy experimentation in regional orders and provides concrete recommendations for risk-aware engagement by Central Asian governments and external partners.

Keywords: China-Central Asia relations, policy experimentation, regional order, Belt and Road, asymmetric interdependence, institutionalization, soft power, risk governance, connectivity corridors.

Introduction

To call Central Asia a "testbed" for Chinese external policy is not to strip the region of agency. It is, rather, to recognize a structural feature of contemporary Eurasia: Central Asia offers Beijing an arena where strategic priorities converge - Xinjiang-adjacent security, overland connectivity, energy supply, and diplomatic architecture - and where the consequences of policy design are legible quickly because interdependence is thick and geographically concentrated. The region sits at the hinge of China's westward projection, yet it is not an arena of direct military contestation in the way the Western Pacific can be. That combination - high stakes, lower direct escalation risk - makes the region unusually suited for policy rehearsal and instrument calibration.

A useful starting point is the moment when China's leadership publicly framed overland Eurasian connectivity in explicitly regional terms. In a 2013 speech delivered at Nazarbayev University in Astana, Xi Jinping advanced the notion of jointly building a "Silk Road Economic Belt," presenting connectivity as an integrative, development-centered project rather than a narrow

transport plan. That speech matters analytically not because it “created” geography, but because it marked an attempt to convert geography into policy language, and policy language into a portfolio of instruments that could be replicated, adjusted, and scaled.

What turns a region into a testbed is not rhetoric alone. A testbed is defined by three properties: (1) policy instruments can be deployed across multiple sectors simultaneously; (2) feedback arrives quickly enough to recalibrate; (3) outcomes can be packaged into templates for other theaters. Central Asia exhibits all three. When logistics corridors expand or choke, the signal is immediate. When credit terms become politically contested, the reputational cost is visible. When security cooperation intensifies, domestic legitimacy constraints surface. In that sense, Central Asia is not simply “where China is active,” but where China can trial a modular approach to regional order-building.

Literature review

The most productive scholarship on China-Central Asia relations has moved beyond single-factor explanations. One stream highlight how narrative diplomacy and attraction compete with suspicion, emphasizing that “soft power” cannot be assumed to flow automatically from infrastructure and trade. In a 2025 *International Affairs* study, Vanderhill J., Joireman S. F., and Tulepbayeva R. show that the translation of Chinese presence into public legitimacy is uneven, mediated by local identities, media ecosystems, and historical memory [2]. The implication for a testbed argument is sharp: if legitimacy is not a byproduct of material engagement, then Beijing must treat perception management as an instrument, not a decorative afterthought.

A mature discussion of China’s external policy in Central Asia begins by refusing two lazy shortcuts: the romantic “New Great Game” metaphor and the equally simplistic idea that infrastructure automatically translates into durable authority. What the strongest scholarship has done in the last decade is to re-specify the dependent variable. Instead of asking whether China “gains influence” (a phrase so elastic it risks becoming unfalsifiable), it asks how influence is operationalized through repeatable instruments and how these instruments perform when they encounter domestic politics, sovereignty sensitivities, and rival external offers. This turn is visible in work that treats Central Asia not merely as a recipient of projects, but as a structured environment in which policy choices generate fast feedback. In that sense, the region becomes a living laboratory: outcomes are observed quickly (through protests, procurement renegotiations, corridor bottlenecks, elite repositioning), and Beijing can revise templates in near real time.

The key conceptual move for a “testbed” framing is to treat experimentation as a governance phenomenon. A testbed is not simply a place where activity is concentrated. It is a place where an actor can trial modular packages (connectivity plus finance plus security cooperation plus narrative framing), observe second-order effects, and then standardize the design into exportable formats. Much of the literature already gestures toward this, but often without naming it explicitly, which leaves the argument implicit. The analytical opportunity is to make the mechanism explicit: instrument portfolio - observable outputs - feedback - adaptation - template diffusion. Once this chain is specified, Central Asia becomes a comparative case for studying how an ascending power learns to govern interdependence abroad.

The most empirically persuasive work on China’s soft power in Central Asia treats legitimacy as neither automatic nor linear. A 2025 *International Affairs* article by Vanderhill R., Joireman S. F., and Tulepbayeva R. demonstrates that even substantial economic engagement can fail to produce commensurate soft power, and that responses vary markedly across Central Asian states because local identity narratives, media environments, and historical memory filter how “China” is interpreted at the societal level [1].

This finding is devastating for any purely economistic model. It implies that perception management is not an ornamental layer. It is a policy instrument with its own constraints and

failure modes. In testbed terms, legitimacy functions like a stress gauge: when project delivery is fast but trust is brittle, the model predicts backlash risk, reputational drag, and greater bargaining leverage for local elites seeking renegotiation or diversification.

Crucially, the best studies do not reduce public attitudes to a single variable such as “Sinophobia.” They treat perception as a structured outcome of social identity, elite discourse, and lived experience with migration, labor relations, and distributional effects. This matters because policy learning depends on diagnosing why resistance occurs. If skepticism is driven by opacity and elite capture narratives, then transparency and local value capture become repair strategies. If it is driven by deeper identity anxieties, then even perfect contract design may not stabilize legitimacy. The literature therefore pushes analysts to distinguish between technocratic fixes and structural limits.

A complementary empirical window comes from survey-based work. Primiano C. B. and Kudebayeva A. examine attitudes toward the Belt and Road in Kazakhstan through a university survey and find polarization tied to political orientation and social identity processes, reminding us that “public opinion” is internally stratified and politically interpretable [2].

For a testbed framework, this is valuable because it highlights an underappreciated channel of feedback: domestic contestation can become a constraint on corridor diplomacy even when elite-to-elite relations remain smooth.

A second major stream foregrounds security as the structural backbone beneath economic engagement. Tukmadiyeva M. shows how Xinjiang-linked concerns shape China’s approach to Central Asia and how security logic can seep into economic policy, particularly when border management and regime stability are treated as prerequisites for connectivity [3].

This matters for two reasons. First, it clarifies why some cooperation packages carry a security subtext even when presented as development. Second, it explains why “stability” rhetoric often functions as a justificatory bridge between domestic governance priorities and external partnerships. In other words, security is not a separate pillar. It is a meta-condition that can justify, accelerate, or constrain other instruments.

The literature also warns against imagining security cooperation as frictionless. Security collaboration can be institutionally routinized, but it can also trigger sovereignty sensitivities or legitimacy concerns if publics interpret it as external intrusion or as a mechanism for constraining domestic space. For a testbed argument, this is a classic feedback dilemma: securitization may protect corridors and reduce short-term risk, yet it can increase long-term reputational and political risk.

A third stream emphasizes that China’s engagement is institutionally layered rather than purely bilateral, and that institutional form changes the rules of the game. The most cited analytical account of the region’s multilateral security architecture remains Aris S., who argues that the SCO’s organizational design and its focus on the “three evils” helped it become a primary security platform in Central Asia, in part because it matched the preferences of prevailing leaderships and offered an appropriate regional framework [4].

This contribution is central for a testbed framing because institutions convert episodic cooperation into routinized governance. They standardize vocabulary, create procedural expectations, and stabilize cooperation even when bilateral relations fluctuate.

Yet institutionalization is not a monotonic good. The literature increasingly treats institutions as dual-use: they can reduce transaction costs and uncertainty, but they can also amplify backlash if institutional density is read domestically as constraint. The interpretive challenge is to assess when institutionalization serves as credible commitment and when it becomes a symbolic shell. That is why scholarship that examines how Central Asian states themselves interpret these institutions is particularly valuable. Dadabaev T. analyzes how regional identity formation within the SCO looks from Central Asian perspectives, emphasizing motivations,

concerns, and the pragmatic calculus that shapes engagement with China through multilateral formats [5]. For testbed logic, this is a critical corrective: the region is not merely a site of Beijing's design. It is a site where partners interpret, bargain, and sometimes dilute or redirect institutional agendas. A sophisticated literature review cannot treat Central Asia as an inert surface on which great powers inscribe preferences. The concept of multivectorism is analytically useful precisely because it captures how states translate structural constraint into strategy. Vanderhill R., Joireman S. F., and Tulepbayeva R. argue that Kazakhstan's multivectorism offers a model strategy for secondary powers navigating between major actors, especially after 2014 when sovereignty anxieties intensified [6].

This is directly relevant to the "testbed" thesis: policy experiments do not run in a vacuum. They run in an environment populated by strategic actors who learn too. Multivectorism is, in effect, the region's own adaptive algorithm. It converts external competition into bargaining leverage, route diversification, and selective institutional uptake.

The implication is methodological and theoretical. If Central Asian states are active co-producers of outcomes, then China's "tests" are partly tests of partner management: how much autonomy can be accommodated without losing strategic coherence, and what kinds of concessions are efficient versus reputation-damaging? This moves the debate away from moralizing and toward institutional analysis. Perhaps the most contested dimension of China's external policy is infrastructure finance. Here, high-quality scholarship has improved the debate by replacing slogans with analytic frameworks and measurable data. Bandiera L. and Tsiropoulos V. propose a framework to assess debt sustainability impacts under the Belt and Road, explicitly addressing the problem that comprehensive and consistent information on financing terms is often unavailable [7].

This is important not because it gives a single verdict on "risk," but because it specifies what must be measured: debt vulnerabilities, fiscal risks, corridor exposure, and the interaction between macro constraints and project pipelines. A testbed argument gains rigor here: if China revises lending practices, restructures terms, or shifts toward co-financing under partner or reputational pressure, those are observable adaptations consistent with policy learning. Data infrastructure has also advanced. The AidData team's *Scientific Data* publication introduces a geospatial methodology for identifying features of Chinese development finance projects, linked to a global dataset covering thousands of projects and a long-time horizon [8]. For Central Asia research, the significance is methodological: claims about "scale" and "pattern" can be anchored to structured, external datasets rather than anecdote. This reduces the temptation to invent precision and improves replicability, which is especially crucial in politically charged debates.

The literature has increasingly used micro-level evidence to discipline macro-level narratives. A notable contribution is Chen J. Y.-W. and Jimenez-Tovar S., who compare small-scale survey evidence among university students in Kazakhstan and Kyrgyzstan to infer how future elites perceive Chinese influence, highlighting variation across national contexts and the persistence of Russia as a reference point in regional status hierarchies [9].

This line of work is valuable because it prevents the analyst from treating "Central Asia" as a single public sphere. For a testbed model, it suggests that Beijing's instruments may be stable, but their social reception is not. That reception itself becomes feedback, shaping the sustainability of projects and the credibility of narratives.

Taken together, the scholarship supports four propositions that a "testbed" framework can formalize. Legitimacy is not purchased by infrastructure - societal reception is filtered through identity politics, media ecosystems, and distributional perceptions, and this reception can constrain policy even when elites cooperate [1], [2]. Security logic is structurally embedded - Xinjiang-adjacent risk and regime stability concerns leak into economic instruments and justify institutional choices, producing both governance capacity and legitimacy costs [3].

Institutionalization is a double-edged instrument - multilateral formats reduce uncertainty but can be read as constraint, making partner interpretation and agenda control central variables. Finance is a credibility battlefield - debt sustainability and fiscal risk are not rhetorical side themes but mechanisms through which external policy is judged and contested, and they can induce visible adaptation in lending and contracting practices.

What remains comparatively under-specified is the learning mechanism that links these propositions. Many studies describe outcomes, but fewer theorize how China revises tools in response to feedback and how revised templates travel to other regions. The “testbed” concept is a way to integrate the literature into a single causal architecture: it treats Central Asia as a place where instrument performance is evaluated under tight interdependence and visible competition, and where policy design is iterated rather than simply asserted. This article’s novelty, therefore, is not to add another descriptive layer, but to convert a set of empirical insights into a coherent framework for identifying experimentation, adaptation, and template diffusion - while keeping Central Asian agency analytically central rather than rhetorically acknowledged.

Materials and methods

The study uses documentary process tracing with triangulation across three evidence types: (1) official Chinese speeches and summit (2) trade statistics attributed to China’s General Administration of Customs and reported by national agencies, and (3) corporate technical descriptions of cross-border energy infrastructure. This design is chosen because Central Asia policy operates through public commitments, measurable flows, and physical assets with stable parameters.

Results

If Central Asia is a testbed, we need to specify what exactly is being tested. The temptation is to treat the concept metaphorically, but a serious analysis demands operational clarity. In policy science, a test environment is defined by instruments, outputs, feedback, and revision. External policy behaves similarly when the actor can deploy multiple instruments and observe which combinations produce stable gains under real constraints. In Central Asia, China has an unusually broad instrument set: transit infrastructure, energy interdependence, development finance, multilateral security platforms, elite diplomacy, and a dense narrative architecture around “shared future” and regional community.

Yet instrument breadth alone does not create a testbed. What matters is the feedback loop. Central Asia compresses time. A rail corridor that saves days on transit also concentrates rents, bottlenecks, and political contestation. A loan that unlocks infrastructure also becomes a domestic political object, especially when fiscal space tightens. A pipeline that stabilizes supply also intensifies asymmetric dependence, creating leverage and resentment simultaneously. These are not abstract dynamics; they are the standard dilemmas of interdependence, but here they appear in a concentrated geopolitical corridor where multiple external actors compete.

The central analytic move in this article is to treat “testbed politics” as a measurable set of mechanisms. Mechanisms are the bridge between intentions and outcomes. They are what allow us to say not merely that “China is influential,” but *how* influence is attempted, *where* it is resisted, and *why* some tools travel better than others to new contexts. Table 1 therefore formalizes the concept into domains, instruments, observable outputs, local agency levers, and risk channels. This is also where Central Asian agency becomes visible: the same instrument can produce different outcomes depending on procurement regimes, transit pricing, and the strategic use of partner competition.

Table 1. Operationalization of “Central Asia as a Testbed” for China’s External Policy

Domain	Policy instrument (what Beijing uses)	Observable output (what can be counted/seen)	Local agency lever (what Central Asian states can do)	Main risk channel (what can go wrong)
Connectivity and transit	Transport corridors, customs coordination, multimodal nodes	Trade value growth, corridor agreements, freight routings	Route diversification, tender rules, transit pricing	Bottlenecks, corridor rivalry, backlash narratives
Energy interdependence	Pipeline infrastructure, long-term purchase contracts	Annual volumes, cumulative deliveries, expansion plans	Pricing, diversification, domestic regulation	Asymmetric dependence, infrastructure security
Security governance	Multilateral security platforms, counterterrorism cooperation	Treaty texts, institutional bodies, joint statements	Agenda-setting, legal framing, transparency constraints	Securitization spillovers, legitimacy costs
Narrative and elite diplomacy	Summits, treaty language, “community” framing	Communiqués, grants, institutional formats	Balancing narratives, signaling autonomy	Narrative inflation, elite capture allegations
Finance and debt governance	Policy-bank lending, project finance, settlement pilots	Disclosure patterns, refinancing episodes	Competitive co-financing, debt disclosure	Debt distress, contingent liabilities

Table 1 makes two points that are easy to miss in purely descriptive writing. First, the testbed is multi-domain by design. Beijing’s approach does not rely on a single lever; it relies on portfolio effects. Connectivity projects can increase trade and also reshape security narratives. Security platforms can reduce cross-border risk and also discipline domestic politics. Elite diplomacy can speed decision-making and also deepen public suspicion. A portfolio strategy is rational when an actor aims to construct a regional order, because order is rarely produced by one instrument alone.

Second, the table clarifies the distinction between “presence” and “governance.” Presence is measurable by projects and visits. Governance is measurable by institutional language, treaty form, routinized summit mechanisms, and the production of standardized cooperation templates. This difference is crucial for understanding why Beijing has pushed beyond bilateral ties toward regional architecture. Once governance becomes the object, the region becomes a proving ground for institutional technologies: Can summit formats be routinized? Can legal language be stabilized? Can infrastructure finance be normalized across multiple jurisdictions? These are experiments in regional order, not merely commerce.

A third insight concerns local agency. Central Asian governments are not “objects” of policy; they are selective amplifiers or dampeners. Procurement rules, debt disclosure practices, corridor pricing, and the deliberate engagement of alternative partners can all reshape outcomes. The “testbed” concept therefore does not imply unilateral control; it implies that China treats the region as an environment where instrument performance can be evaluated and improved under competitive conditions.

Finally, the risk channels listed in Table 1 are not side notes. In practice, policy failure often arrives through risk, not through immediate opposition. Debt risk becomes political risk. Infrastructure security becomes reputational risk. Narrative inflation becomes legitimacy loss. In this sense, Central Asia is also a testbed for China's risk governance abroad: whether Beijing can manage second-order effects that emerge not from hostile intent, but from the friction of real societies.

A model is necessary because "influence" is otherwise too elastic. If every project counts as influence, the concept becomes indistinguishable from activity. The testbed thesis instead proposes a causal chain: instruments produce outputs, outputs generate feedback, feedback triggers adaptation, and adapted templates travel outward to other regions. This is precisely how policy learning operates in complex systems. The question becomes empirical: do we observe learning and template diffusion?

We do observe signs of institutional learning. One marker is the rapid institutionalization of the China-Central Asia format into a recurring summit architecture and treaty language. Reuters reported that in June 2025 China signed a treaty of "permanent good-neighbourliness and friendly cooperation" with the leaders of the five Central Asian states during a summit in Astana, accompanied by a grant pledge and emphasis on sectors such as natural gas, minerals, railways, and agriculture [7]. Whether one reads this as reassurance or as institutional capture, it is clearly a move from episodic diplomacy to rule-shaped diplomacy, which is exactly what a testbed would produce when early iterations are deemed successful.

Another marker is measurable scaling in economic ties. Xinhua, citing China's customs authority, reported that trade between China and the five Central Asian countries expanded from 312.04 billion yuan in 2013 to 674.15 billion yuan in 2024, and that the first five months of 2025 reached 286.42 billion yuan, a record for that period [8]. These numbers do not "prove influence," but they establish that the arena is large enough for policy experiments to have real economic mass. Large arenas generate data. Data, in turn, supports learning.

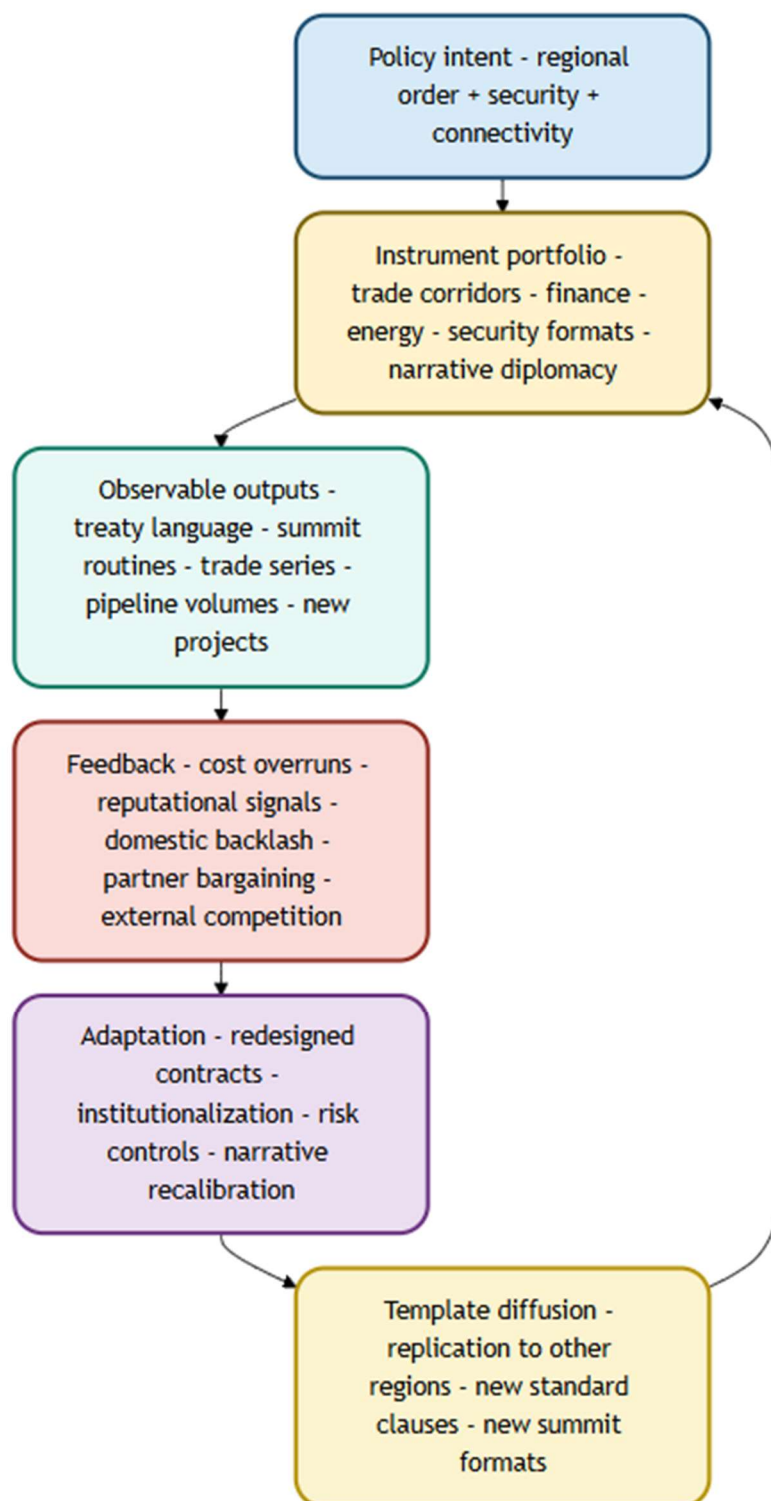


Figure 1. "Testbed politics" mechanism

Figure 1 reframes the analytic task. It discourages simplistic binaries like "China dominates" versus "Central Asia resists." Instead, it foregrounds iteration. A testbed produces revisions: contract models change, rhetoric adjusts, summit formats stabilize, and risk controls become more explicit. That is precisely what we should look for in the record - not a single moment of "success," but repeated cycles of deployment, backlash, and adjustment.

The model also illuminates why treaty language is not merely symbolic. In external policy, treaties often serve as commitment devices and as narrative tools simultaneously. They speak to external audiences (partners and rivals) and to internal ones (bureaucracies and publics). If the

treaty is paired with material incentives, it becomes an instrument of institutionalization, not only diplomacy. Reuters' description of the 2025 treaty language and accompanying grant pledge fits neatly into this logic: a legal frame plus resource signaling, designed to reduce uncertainty and anchor cooperation [7].

Equally important, the model explains why competition intensifies precisely when institutionalization deepens. External actors watch for templates. When a template appears scalable, rivals react by offering alternatives. That is why an EU or US turn toward Central Asia often follows visible institutional moves by China: it is not only about today's projects, but about tomorrow's rules.

Finally, the mechanism clarifies what counts as empirical falsification. If we do not observe adaptation - if the same contract pathologies recur without revision, if institutional formats remain hollow, if feedback does not alter design - then Central Asia is not a testbed, merely a theater. The evidence reviewed here points toward iterative design, which supports the testbed interpretation.

A second challenge is to avoid circular reasoning. If we label every development "testing," we learn nothing. Table 2 therefore asks a stricter question: what specific mechanisms are being tested, what would count as success, what would count as failure or pushback, and why does it matter theoretically? The goal is to discipline interpretation by defining outcomes before we narrate them.

Consider institutionalization again. A treaty that commits parties to durable principles can reduce uncertainty, but only if it is linked to implementable mechanisms and repeated summit routines. A purely rhetorical treaty can still have value as signaling, but it is not robust governance. The evidence matrix separates these pathways. It also makes room for local agency: pushback does not always appear as overt rejection. It can appear as renegotiation, slow implementation, selective compliance, or accelerated diversification toward other partners.

The same logic applies to trade corridors. A rapid increase in trade volume can reflect structural complementarities, but it can also reflect political rerouting. What matters for a testbed is whether corridor scaling produces governance innovations - new customs arrangements, risk-sharing models, or standardized logistics protocols - and whether these innovations then travel beyond the region.

Finance and debt governance are even more sensitive. Here the literature has been polarized. Table 2 therefore anchors evaluation in peer-reviewed frameworks and curated datasets. The AidData geocoded dataset in *Scientific Data* provides a cross-national evidence base for Chinese development finance commitments and their characteristics [5]. Meanwhile, Bandiera and Tsiropoulos develop an analytic framework in the *Journal of Development Economics* for assessing debt sustainability challenges associated with BRI-type lending, offering tools to separate genuine distress risk from political rhetoric [6]. Together, these sources allow analysis without sensationalism and without invented precision.

Table 2. Evidence matrix: how the testbed works in practice (selected verifiable markers)

Mechanism in the testbed model	What is being tested	What counts as success for Beijing	What counts as failure or pushback	Why this matters analytically	Primary verification anchor
Institutionalization	Can ad hoc ties become durable regional architecture	Treaty language + routinized summit mechanisms	Hollow documents, uneven implementation	Order-building depends on durable rules	2025 treaty reporting [7]
Trade corridor scaling	Can overland Eurasian routes be expanded reliably	Sustained trade growth + corridor throughput	Bottlenecks, politicized rerouting	Connectivity reshapes dependencies	Customs series trend [8]
Energy leverage calibration	Can energy ties translate into predictable influence	Stable deliveries + incremental upgrades	Pricing disputes, diversification, delays	Asymmetric interdependence becomes leverage	Pipeline volumes reporting [9]
Security governance	Can security cooperation be normalized multilaterally	Legal-institutional embedding	Legitimacy backlash, securitization anxiety	Security norms shape regional order	SCO Charter (UN) [10]
Narrative conversion	Can material presence become legitimacy	Positive reception + reduced suspicion	High presence, low trust	Soft power is not automatic	Soft power scholarship [2]

Table 2 forces precision about “success” and “failure.” In many discussions of China’s external policy, success is assumed: if a project is built, the influence is presumed. The evidence matrix rejects that shortcut. A project can exist and still produce political backlash. A treaty can be signed and still remain thin. A summit can be held and still fail to routinize compliance.

The table also clarifies that pushback is often quiet. Central Asian states may not loudly reject cooperation; they may instead diversify. They may accept certain instruments (trade, transit) while hedging others (security, finance). The testbed framework predicts such selective uptake, because partners are rational actors managing asymmetric dependence. The testbed is therefore interactive: Beijing tests instruments, and partners test Beijing’s tolerance for bargaining, revision, and autonomy.

A further implication is methodological. Table 2 provides a template that can be reused for other regions. If Central Asia is genuinely a testbed, then the same mechanism categories should appear elsewhere in similar form: institutionalization drives, corridor scaling, debt-risk

management, narrative conversion. What changes is the local ecology: domestic politics, rival presence, and the intensity of securitization. That is exactly why Central Asia is useful analytically - it is “compact enough” to study deeply, yet structurally connected to broader Eurasian order-making.

Security cooperation in Central Asia cannot be analyzed as an add-on. It functions as an institutional technology that stabilizes cross-border governance under a shared vocabulary: terrorism, separatism, extremism, and the promise of stability. This vocabulary has legal form. The Shanghai Cooperation Organization’s Charter is registered in the UN treaty system, which gives it a formal international-law footprint and makes its institutional design publicly verifiable [10]. The Charter’s significance here is not moral evaluation; it is analytic: it institutionalizes a security logic that can be linked to other policy sectors.

The region’s security architecture also acts as a reputational hedge. When Beijing presents connectivity projects, it can simultaneously point to multilateral security formats as evidence that cooperation is “rules-based” and regionally supported. This is an important difference between purely bilateral security ties and multilateral ones: multilateralism can diffuse responsibility and cloak bilateral asymmetries.

However, securitization carries a predictable risk: it can trigger sovereignty concerns and public suspicion, especially when security language appears to justify constraints on domestic space. The testbed interpretation predicts that Beijing will calibrate securitization intensity: enough to manage Xinjiang-adjacent risk and protect corridors, but not so much as to provoke sustained public resistance that could undermine long-term cooperation.

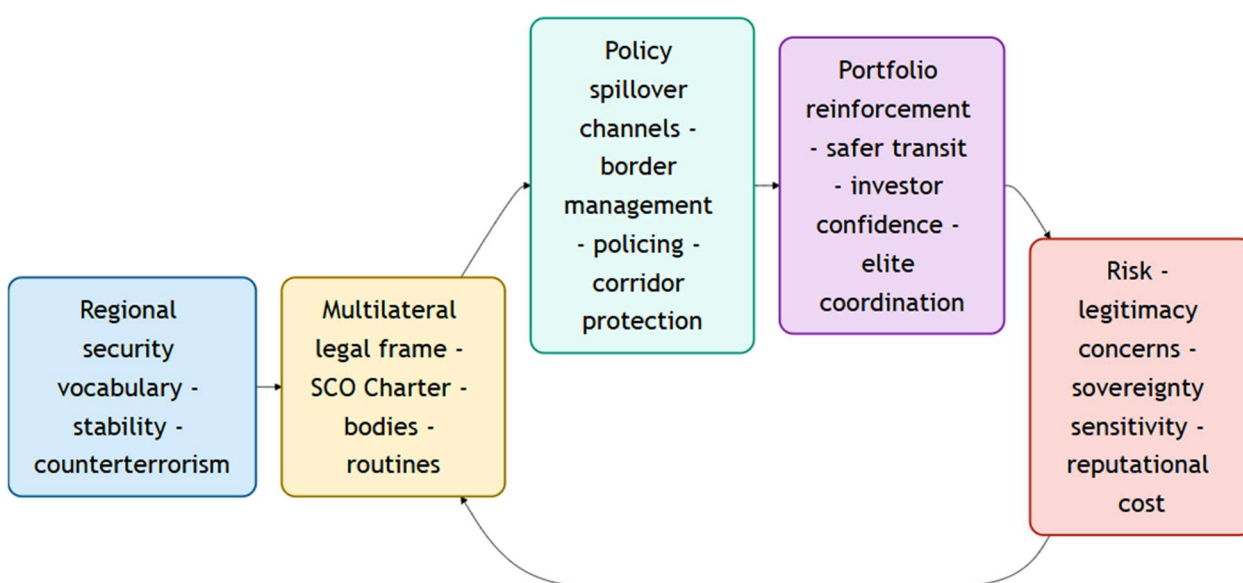


Figure 2. Institutional pipeline from security language to policy portfolio

Figure 2 explains why debates about “economics versus security” often miss the structure of contemporary regionalism. In practice, the economic and the security are braided. A corridor is a logistics object, but it is also a governance object. Protecting it invites securitization. Securitization invites legitimacy scrutiny. That scrutiny then feeds back into how projects are framed and implemented. This is a classic feedback loop, and it is exactly what makes a region a testbed.

The UN-registered status of the SCO Charter matters because it locks the security vocabulary into an institutional format that is hard to dismiss as ad hoc. It provides continuity across leadership changes and reduces uncertainty for bureaucracies that implement cooperation. Yet continuity can also harden perceptions of constraint. The testbed framework therefore

predicts a recurring pattern: institutional stability rises, and simultaneously balancing behavior intensifies. States can welcome stability and still fear over-embedding.

This also clarifies why external competition increases. When security and connectivity are institutionalized, rival actors interpret the region as a site of rule-making, not only market-making. That perception triggers alternative offers: governance assistance, investment packages, security dialogues. The next figure takes that competitive dimension seriously.

Central Asia is not only a site of China's experimentation; it is a site of competitive regionalism. When external actors treat the region as strategically pivotal, they attempt to shape the menu of options available to Central Asian states. The EU's 2019 Joint Communication on Central Asia explicitly frames the relationship around resilience, prosperity, and regional cooperation, signaling a governance-centered approach rather than a narrow trade agenda [11]. Meanwhile, the United States has institutionalized the C5+1 platform as a regional diplomatic format, aimed at cooperation with the five Central Asian states on issues ranging from security to economic connectivity [12]. These moves do not erase China's role, but they raise the strategic price of policy missteps. In a competitive environment, reputational shocks travel faster, and partner states gain leverage by signaling alternative alignments.

Beijing itself has responded by intensifying narrative and institutional framing. In the 2022 virtual summit remarks, China explicitly elevated "community with a shared future" language and emphasized principles such as mutual respect and good-neighborliness [13]. In 2023, the China-Central Asia summit keynote speech reinforced this community framing and positioned the region as the cradle of the Silk Road Economic Belt idea [14]. What matters here is not whether one accepts the rhetoric, but how rhetoric functions as policy glue in a competitive environment: it tries to stabilize expectations and reduce partner incentives to defect.

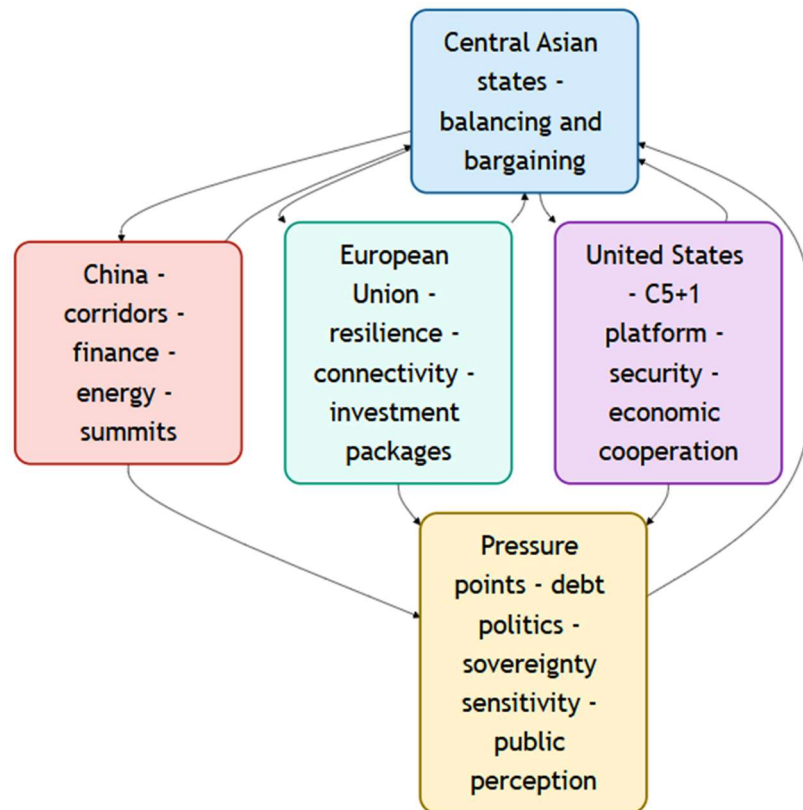


Figure 3. Competitive regionalism map

Figure 3 makes the competitive structure explicit. A testbed is most informative when multiple actors observe the outcomes. Central Asia is precisely such a space. If China's institutionalization succeeds, rivals learn and counter-offer. If it fails, rivals exploit the reputational opening. This dynamic accelerates learning cycles and forces Beijing to refine instruments.

Competition also empowers local agency. Central Asian states can use external rivalry to negotiate better terms, diversify routes, and avoid overdependence. In the testbed framework, this is not noise; it is the mechanism that generates feedback and forces adaptation. When partners have alternatives, Beijing must compete not only with money, but with contract quality, transparency, and respect for sovereignty optics.

This competitive lens also helps interpret why Beijing invests in legal and narrative architecture. Infrastructure alone is not enough in a crowded field. Treaties, summit routines, and shared vocabulary aim to bind partners through predictability and expectation. Yet binding can be interpreted as constraint, so the strategy is inherently delicate. That delicacy - the constant need to calibrate - is exactly what a testbed environment produces.

Discussion

The results support a disciplined version of the testbed claim. Central Asia is not a passive stage for Chinese ambition; it is an arena where multiple policy instruments are tested under real constraints and observed by rivals. Three points deserve emphasis.

First, institutionalization has accelerated. The 2025 treaty reported by Reuters indicates a move toward legally framed, routinized partnership language, reinforced by material incentives [7]. Institutionalization reduces uncertainty but raises sovereignty sensitivity, especially when paired with security vocabulary. Thus, institutionalization is a capability with built-in backlash risk.

Second, economic scaling creates both opportunity and vulnerability. The customs-based trade series reported by Xinhua and State Council channels shows a clear expansion from 2013 to 2024, with record levels for early 2025 [8]. Growth strengthens interdependence and makes the region more central to China's westward economic strategy. But it also makes China more exposed to regional political disruptions, forcing greater risk governance sophistication.

Third, finance and legitimacy remain the most fragile dimensions. The AidData dataset offers a rigorous external base for tracking Chinese development finance globally and regionally [5]. The debt sustainability framework in the *Journal of Development Economics* provides analytic tools for diagnosing distress risk without propaganda [6]. Together, they imply a sober conclusion: the success of Chinese external policy in Central Asia depends less on how much is built and more on how risk is distributed, disclosed, and politically managed.

Finally, competitive regionalism means China's policy errors are amplified. EU and US regional formats give Central Asian states additional bargaining power [11], [12]. This does not diminish Beijing's role; it changes the equilibrium. A testbed is not only where policies are tested; it is where they are stress-tested by competition.

Conclusion

Central Asia has become an unusually information-rich arena for evaluating how China practices external policy under real constraints. The region concentrates several of Beijing's strategic imperatives in one geopolitical corridor: western border security considerations, overland connectivity toward Europe and the Middle East, energy supply reliability, and the long-term ambition to embed cooperation in durable institutions rather than episodic diplomacy. In 2013, when Xi Jinping delivered his speech at Nazarbayev University and publicly advanced the Silk Road Economic Belt idea, the significance was not only rhetorical. It announced an intent to treat Central Asia as a place where economic integration, political reassurance, and institutional design could be assembled into a repeatable portfolio and then scaled.

What makes the region testbed-like is the speed and clarity of feedback. Connectivity plans do not remain abstract in Central Asia: corridor performance is quickly translated into trade statistics, logistics bottlenecks, border procedures, and domestic narratives about “who benefits.” In mid-2025, the trade figures released via Xinhua and attributed to China’s customs authority indicated that China’s trade with the five Central Asian states reached 286.42 billion yuan in the first five months of 2025, a record for that period. This kind of measurable scaling matters in a scientific sense because it provides a hard empirical backdrop for interpreting political moves: institutionalization and rhetoric do not float in a vacuum; they are attached to a growing material relationship whose distributional consequences are debated domestically.

Institutional design, in turn, has visibly thickened. The 2025 Astana summit produced a treaty framed as “permanent good-neighbourliness and friendly cooperation,” reported by Reuters, alongside a pledge of 1.5 billion yuan in grants. From a governance perspective, this is not merely ceremonial. Treaties and summit routines function as commitment devices: they reduce uncertainty for bureaucracies, investors, and security services by stabilizing expectations, and they attempt to transform bilateral bargaining into predictable regional architecture. Yet the same institutional density can also generate counter-effects. The more durable the architecture becomes, the more it can be interpreted by local publics as constraint, and by elites as a domain where sovereignty optics must be actively managed. This is precisely why the “testbed” metaphor must be treated analytically rather than triumphantly: policy learning occurs not only from success, but from friction.

Security governance is a central part of that friction. Central Asia is one of the few regions where China’s security vocabulary, multilateral institutional forms, and economic portfolio are tightly braided. The Shanghai Cooperation Organization is critical here because its Charter is registered in the UN system, giving the institutional design a formal international-law footprint rather than an opaque arrangement. In practice, such institutional frameworks can facilitate coordination on cross-border risks and protect the political conditions under which large-scale connectivity is possible. At the same time, they can amplify legitimacy concerns if securitization is perceived as spilling into domestic governance. The testbed logic predicts continuous calibration: too little security framing risks corridor vulnerability, too much risks reputational costs and domestic backlash that can slow implementation or strengthen balancing behavior.

Political economy is the other axis where learning is most visible, and also most politically charged. Infrastructure finance is not neutral capital. It is a governance relationship that distributes risk across state budgets, state-owned enterprises, and societies, often under conditions of incomplete information. This is exactly why debt sustainability frameworks matter more than slogans. Bandiera and Tsiropoulos propose an approach for assessing how Belt and Road corridor investments can affect debt vulnerabilities even when comprehensive information on terms is limited, which is a realistic description of the empirical environment researchers face. The point is not to label outcomes in advance, but to insist on measurable mechanisms: contingent liabilities, refinancing pressure, foreign-exchange exposure, and the domestic politics of transparency. If China adjusts contract design, increases co-financing, or shifts toward more reputationally resilient forms of engagement in response to these pressures, that is direct evidence of policy adaptation.

Methodologically, the research landscape has also improved, which strengthens what can be claimed without invention. The AidData team’s peer-reviewed dataset work in *Scientific Data* provides a structured, geocoded basis for analyzing patterns of Chinese development finance and project characteristics across countries and over time. For Central Asia, these matters because it allows a discipline of argument: rather than relying on anecdotes, scholars can cross-check claims about scale, sectoral concentration, and the geography of projects. The existence of such datasets

does not settle political debates, but it sharply raises the standard for empirical seriousness, which is exactly what high-quality scholarship requires.

Competitive regionalism now intensifies the testbed dynamic. Central Asia is no longer a quiet arena of “mostly bilateral” engagement. It is increasingly a site where multiple external actors watch each other’s templates and counter-offer. In such an environment, the penalty for reputational shocks rises: procurement controversies, debt anxieties, and public protests do not remain local stories, they become strategic signals interpreted by rivals and leveraged by domestic actors. That context helps explain why Beijing has invested heavily in narrative and institutional framing in official summit speeches, including the 2022 virtual summit remarks and the 2023 China-Central Asia summit keynote that explicitly articulate a “shared future” community language and emphasize good-neighborliness principles. Even if one reads this language skeptically, it performs an observable function: it attempts to stabilize expectations and lower the perceived political cost of cooperation for partner elites.

The core conclusion, therefore, is double-edged but analytically clean. Central Asia functions as a testbed not because it is weak or passive, but because it is structurally positioned to generate rapid feedback across multiple policy domains at once. Beijing can deploy a portfolio, observe results, absorb friction, and revise templates. Yet the same structure gives Central Asian states agency and leverage: they bargain, diversify partners, and convert external competition into improved terms or symbolic autonomy. In other words, the testbed is interactive. China tests instruments, while Central Asian governments test China’s tolerance for revision, transparency demands, and sovereignty-sensitive framing.

This conclusion has practical implications. For Central Asian governments, the priority is not to “choose a side,” but to professionalize bargaining capacity and reduce politicized volatility by improving disclosure, procurement standards, and risk-sharing norms in major projects. For China, the strategic challenge is to treat reputational resilience as an asset class: project delivery metrics are no longer sufficient if legitimacy and fiscal risk determine long-term sustainability. For external partners beyond China, credibility depends on delivery and respect for local constraints, not only on rhetoric about “alternatives.” A region becomes a testbed precisely when actors can learn. Central Asia is now one of the clearest places where that learning is visible in real time, through measurable trade expansion, treaty institutionalization, and the continuing negotiation between connectivity ambition and sovereignty politics.

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Pedagogical Sciences

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ИНТЕРАКТИВТІ ЖӘНЕ ВЕБ-ТЕХНОЛОГИЯЛАРДЫ ҚОЛДАНУ АРҚЫЛЫ БАСТАУЫШ СЫНЫП ОҚУШЫЛАРЫНЫҢ БІЛІМ САПАСЫН ЖЕТІЛДІРУ

ЖАНТАСОВА ЖАДЫРА НУРМАХАНБЕТОВНА

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АМАНЖОЛОВА ЖҰЛДЫЗАЙ ОРЫНБАСАРҚЫЗЫ

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Аңдатпа. Мақалада бастауыш сынып оқушыларының білім сапасын арттыруда интерактивті және веб-технологияларды қолдану жолдары қарастырылған. Зерттеу барысында веб-ресурстар мен интерактивті тапсырмалардың оқушылардың танымдық белсенділігін, пәндік дағдыларын және коммуникативтік қабілеттерін дамытудағы рөлі талданды. Интерактивті әдістер мен веб-платформаларды қолданудың сабаққа қатысу белсенділігін, оқу мотивациясын және білімді меңгеру деңгейін арттырудағы тиімділігі көрсетілген. Мақала практикалық мысалдар мен әдістемелік ұсынымдарды қамтиды, бұл бастауыш сынып мұғалімдері үшін сабақ жоспарын жетілдіру және цифрлық технологияларды тиімді қолдануға негіз бола алады.

Түйін сөздер: интерактивті технологиялар, веб-технологиялар, бастауыш сынып, білім сапасы, оқушылардың дағдылары, электронды ресурстар, онлайн тест

Кіріспе

Қазіргі білім беру жүйесі жылдам цифрлануда, бұл оқу процесін жаңартуды және заманауи технологияларды қолдануды қажет етеді. Бастауыш сынып оқушылары үшін сабақтың қызықты әрі нәтижелі өтуі олардың болашақтағы оқу жетістіктері мен жан-жақты дамуының негізі болып табылады.

Интерактивті және веб-технологияларды қолдану сабаққа жаңа серпін беріп, оқушылардың пәнге деген қызығушылығын арттырады. Сонымен қатар, бұл әдістер оқушылардың пәндік және коммуникативтік дағдыларын жетілдіруге, өз бетінше ойлау және шығармашылық қабілеттерін дамытуға мүмкіндік береді. Бастауыш білім беру деңгейінде технологияларды тиімді қолдану педагогикадағы өзекті мәселе болып табылады, өйткені оқушының оқу сапасы оның болашақтағы білім деңгейіне және танымдық белсенділігіне тікелей әсер етеді.

Цифрлық ресурстарға білім беру платформалары, оқу веб-сайттары, электронды оқулықтар, интерактивті тапсырмалар, бейнематериалдар мен онлайн жаттығулар жатады. Бұл құралдар оқу үдерісін жандандырып, оқушының белсенді қатысуына жағдай жасайды.

Негізгі бөлім

Интерактивті технологиялар бастауыш сынып оқушыларының білім сапасын арттыруда маңызды рөл атқарады. Бұл технологиялар сабаққа қатысу белсенділігін, танымдық қызығушылықты және шығармашылық қабілеттерді дамытуға бағытталған. Бастауыш сыныпта интерактивті әдістер сабақ материалын оқушының жас ерекшелігіне сай және көрнекі түрде жеткізуге мүмкіндік береді. Оларға электронды тақталар, мультимедиялық презентациялар, топтық және жұптық жұмысқа арналған тапсырмалар, онлайн ойындар мен викториналар, бейнематериалдар мен виртуалды экскурсиялар жатады. Электронды тақталар мен презентациялар сабақ материалын визуалды түрде көрсетіп, оқушылардың назарын сақтайды. Топтық және жұптық жұмыс арқылы оқушылар бір-бірімен өзара қарым-қатынас жасап, коммуникативтік дағдыларын жетілдіреді. Онлайн ойындар, викториналар және тесттер білімді бекіту процесін қызықты әрі нәтижелі етеді, ал бейнематериалдар мен виртуалды экскурсиялар оқу материалын нақты өмірмен байланыстырады. Осы әдістерді қолдану арқылы оқушылар материалды терең түсініп, өз ойын еркін жеткізуге және шығармашылық қабілеттерін көрсетуге мүмкіндік алады.

Сонымен қатар сабаққа қатысу белсенділігі артып, оқу мотивациясы күшейеді. Веб-технологиялар интернет платформалары мен онлайн ресурстарды пайдалану арқылы сабақ жүргізу әдісін білдіреді. Бастауыш сынып деңгейінде веб-технологиялар сабақ процесін жандандырып, оқушының өз бетімен білім алуын қамтамасыз етеді. Веб-технологиялардың негізгі артықшылықтары мыналар: материалға қолжетімділік, жеке білім траекториясы, оқу мотивациясын арттыру және білімді бақылаудың тиімділігі. Оқушылар сабақтан тыс уақытта да материалды меңгере алады, ал үлгерімі төмен оқушылар үшін қосымша тапсырмалар беріледі. Визуалды және интерактивті материалдар сабаққа қызығушылық тудырып, оқушылардың оқу мотивациясын арттырады. Онлайн тесттер мен викториналар арқылы оқушылардың білім деңгейін нақты бағалау мүмкіндігі бар. Мысалы, білім беру веб-сайттары мен онлайн платформалар арқылы әрбір оқушы тапсырманы өз қарқынымен орындай алады. Бұл әсіресе үлгерімі төмен оқушылар үшін маңызды, себебі олар материалды бірнеше рет қайталап, толық меңгере алады.

Интерактивті және веб-технологиялар сабақ барысында оқушылардың пәндік және коммуникативтік дағдыларын дамытуға үлкен мүмкіндік береді. Пәндік дағдылар онлайн тесттер, виртуалды эксперименттер және интерактивті жаттығулар арқылы артады, бұл білімді бекіту мен нақтылау процесіне септігін тигізеді. Коммуникативтік дағдылар рөлдік ойындар, топтық жобалар, онлайн пікірталастар арқылы дамиды, оқушылар өз ойларын айқын жеткізуді, бір-бірін тыңдауды және ынтымақтастықта жұмыс жасауды үйренеді. Интерактивті тапсырмалар мен веб-технологияларды қолдану сабаққа қатысу белсенділігін арттырып қана қоймай, оқушыларға өз пікірін дәлелдеп, логикалық ойлау қабілетін дамытуға мүмкіндік береді.

Практикалық тәжірибе көрсеткендей, бастауыш сыныптарда веб және интерактивті технологияларды қолдану сабаққа қатысу белсенділігін арттырып, оқушылардың оқу жетістігін жақсартты. Онлайн тесттер мен викториналар пәндік білімді нақты бағалауға көмектесті. Рөлдік ойындар мен топтық жобалар коммуникативтік дағдылардың дамуына ықпал етті, ал электронды тапсырмалар оқушылардың өз бетімен жұмыс істеу дағдыларын қалыптастырды. Зерттеу нәтижесі бойынша веб және интерактивті технологияларды қолданған сыныптарда сабаққа қатысу белсенділігі артты, пәндік білім сапасы жоғарылады, оқушылардың шығармашылық қабілеті дамыды, сондай-ақ үлгерімі төмен оқушылардың оқу жетістігі жақсарды.

Әдістемелік бөлім

Бастауыш сыныптарда интерактивті және веб-технологияларды тиімді қолдану үшін нақты әдістемелік тәсілдер қажет. Әдістемелік бөлімде сабақ ұйымдастырудың негізгі принциптері мен қадамдары қарастырылады.

Сабақ жоспарына интерактивті элементтерді енгізу. Сабақ жоспарында әрбір тақырыпқа интерактивті элементтер қосу маңызды. Мысалы, сабақ басында оқушылардың алдыңғы тақырып бойынша білімін тексеру үшін викторина немесе қысқа онлайн тест жүргізуге болады. Сабақ барысында топтық немесе жұптық жұмыстар, рөлдік ойындар, тапсырмалар мен сұрақ-жауап сессиялары оқушылардың белсенділігін арттырады. Сабақ соңында электронды тесттер мен онлайн жаттығулар арқылы алған білімді бекіту ұсынылады.

1. **Веб-ресурстарды пайдалану.** Веб-технологияларды қолдану оқушылардың өз бетімен білім алуын қамтамасыз етеді. Мұғалімдер білім беру платформалары, онлайн оқулықтар, интерактивті веб-сайттар мен бейнематериалдарды сабақта қолдануы қажет. Мысалы, математика сабағында онлайн есеп шығару платформасын пайдалану оқушылардың тақырыпты қайталауын жеңілдетеді, ал әдебиет сабағында электронды кітаптар мен бейнеөлеңдер шығармашылық қабілеттерін дамытады.

2. **Бағалау жүйесін жаңарту.** Интерактивті және веб-технологияларды қолданған сабақтарда оқушылардың білімін бағалаудың тиімді әдістері қарастырылады. Оларға онлайн тесттер, викториналар, тапсырмаларды автоматты түрде тексеру құралдары жатады. Мұндай бағалау әдістері оқушылардың жетістігін нақты көрсетіп, уақытылы түзету жасауға мүмкіндік береді.

3. **Жеке қолдау көрсету.** Үлгерімі төмен оқушыларға қосымша тапсырмалар беру веб-технологияларды тиімді пайдаланудың маңызды бөлігі болып табылады. Онлайн платформалар арқылы әрбір оқушының оқу траекториясы жеке түрде жоспарланады, бұл олардың пәнді өз қарқынымен меңгеруіне көмектеседі. Мұғалім оқушының прогресін бақылап, қажет болған жағдайда жеке кеңестер мен қосымша жаттығулар ұсынып отырады.

4. **Мұғалімнің кәсіби дамуы.** Интерактивті және веб-технологияларды тиімді қолдану үшін мұғалімдерге арнайы тренингтер, семинарлар және вебинарлар ұйымдастыру ұсынылады. Бұл оқытушылардың жаңа технологияларды меңгеруіне, сабақ барысында заманауи әдістерді қолдануына жағдай жасайды.

5. **Сабақта қолжетімділік пен қауіпсіздікті қамтамасыз ету.** Цифрлық ресурстар мен веб-технологияларды қолданғанда интернеттің қолжетімділігі, техникалық құралдардың жұмыс істеуі және оқушылардың қауіпсіздігі ескерілуі қажет. Мұғалімдер әрбір сабаққа қажетті құралдарды алдын ала дайындап, оқушыларға интернетті қауіпсіз пайдалану ережелерін үйретуі керек. Бұл әдістемелік қадамдар бастауыш сыныпта интерактивті және веб-технологияларды сабаққа жүйелі енгізуге мүмкіндік береді. Нәтижесінде оқушылардың пәндік, коммуникативтік және шығармашылық дағдылары дамып, білім сапасы жоғарылайды.

Қорытынды

Зерттеу нәтижелері көрсеткендей, интерактивті және веб-технологияларды қолдану бастауыш сынып оқушыларының білім сапасын арттырудың тиімді әдісі болып табылады. Бұл әдістер сабақ процесін қызықты әрі нәтижелі етіп, оқушылардың пәндік, коммуникативтік және шығармашылық дағдыларын дамытуға мүмкіндік береді. Интерактивті тапсырмалар мен веб-ресурстар арқылы оқушылар өз білімін бекітіп, өз бетімен жұмыс істей алатын қабілетін дамытады. Сонымен қатар, үлгерімі төмен оқушыларға жеке қолдау көрсету, онлайн тесттер мен тапсырмалар арқылы білім деңгейін нақты бағалау, сабаққа қызығушылық пен мотивацияны арттыру мүмкіндігі туады. Мұғалімдерге сабақ жоспарына интерактивті элементтер мен веб-технологияларды жүйелі енгізу, жеке оқу траекторияларын құру және цифрлық ресурстарды тиімді пайдалану ұсынылады. Бұл тәсіл бастауыш сынып оқушыларының жан-жақты дамуына, білімге деген қызығушылығын арттыруға және оқу жетістігін жоғарылатуға септігін тигізеді.

Қорытындылай келе, интерактивті және веб-технологияларды қолдану - заманауи білім беру үдерісінің маңызды құрамдасы, ол бастауыш сыныптағы оқыту сапасын жаңа деңгейге көтеруге мүмкіндік береді.

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ORGANIZATIONAL AND METHODOLOGICAL FEATURES OF JUDO TRAINING SESSIONS FOR ADOLESCENTS AGED 11–13

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Abstract. This study examines the organizational and methodological features of judo training sessions for adolescents aged 11–13, a critical developmental period characterized by intensive physical, psychological, and motor skill changes. Effective training at this age requires a balanced integration of technical, physical, and pedagogical components that correspond to age-related characteristics and long-term athlete development principles. The purpose of the study was to identify and substantiate optimal approaches to planning and organizing judo training sessions for adolescents aged 11–13.

The research employed theoretical analysis of scientific and methodological literature, pedagogical observation, testing of physical and technical preparedness, and a formative pedagogical experiment. The study involved adolescent judokas who participated in a structured training program emphasizing basic technical skills, coordination development, flexibility, general endurance, and safe execution of judo techniques.

The results demonstrated that training programs designed with age-appropriate load distribution, progressive complexity of techniques, and an emphasis on game-based and cooperative learning methods significantly improved technical proficiency, coordination abilities, and motivation for regular training. Moreover, the application of pedagogically grounded training principles contributed to injury prevention and positive emotional engagement.

The findings confirm that systematic consideration of organizational and methodological features in judo training enhances training effectiveness and supports sustainable athlete development at the initial specialization stage. The results may be used by coaches, physical education teachers, and sports schools to optimize judo training programs for adolescents.

Keywords: judo training; adolescents; training organization; methodology; physical development; motor skills; sports pedagogy.

Introduction

At present, the organization of training sessions within the sports training process across various sports disciplines, as provided by the existing curricula of compulsory and supplementary education, fails to fully address the problem of optimizing the physical condition of young people due to a number of persistent difficulties.

First, there is a lack of continuity and effective interaction between school-based and supplementary education. As a result, children and adolescents who enroll in sports schools often do not possess a clear motivation for engaging in systematic physical exercise.

Second, it is recommended to use a variety of physical exercises aimed at improving physical, functional, and psychophysiological conditions. A high level of such development, on the one

hand, contributes to the formation of an active motor position, and on the other hand, promotes the achievement of high sporting results in a specific sport.

Research conducted by specialists indicates an urgent need to implement physical exercises during training sessions that ensure the improvement of sports preparedness among those engaged in combat sports. Experts emphasize that training programs based solely on general developmental exercises do not fully ensure the comprehensive development of the younger generation. The key criterion determining the improvement of adolescents' physical condition is the systematic conduct of training sessions with a clearly defined structure aimed at solving the tasks of holistic personality development.

One of the primary objectives of training sessions in various sports during the stage of mastering a wide range of skills is to foster engagement in the selected type of motor activity and to develop an understanding of the necessity and benefits of regular physical exercise.

According to established requirements, specialists in combat sports must conduct training sessions with children and adolescents in accordance with educational curricula. Success in expanding motor knowledge and skills in the chosen sport is guaranteed by the application of physical exercises that contribute to the improvement of sports mastery. Competitive experience in sports highlights the need for the active use of modern rehabilitation and recovery measures that prevent the negative effects of unfavorable external factors.

The use of self-monitoring, self-analysis, and self-improvement practices enhances motivation through the principle of feedback between children and educators. The effective construction of the educational and training process in the chosen sport requires cooperation with medical institutions and timely adjustments to training plans. When these conditions are met, the possibility of increasing an athlete's level of preparedness during training sessions is significantly enhanced.

For educators, the outcome of organizing training sessions with children and adolescents should be reflected in stable motivation to improve physical condition and a creative attitude toward motor activity.

Social Functions of Training Sessions in General and Supplementary Education

Training sessions for children and adolescents in general and supplementary education systems aim to fulfill the following social functions:

Transformative and Creative Function – ensures the development of external and internal physical parameters, the cultivation of physical qualities and abilities through various forms of motor activity, health promotion, and the enhancement of personal qualities necessary for professional activity;

Integrative and Organizational Function – promotes the development of mutual assistance and support among adolescents during collective training, positively influencing the effectiveness of sports activities;

Design and Creative Function – activates self-knowledge, self-affirmation, and self-development processes, revealing individual abilities that contribute to the comprehensive formation of personality;

Design and Prognostic Function – manifests in knowledge related to the use of various types of motor activity for improving one's physical capabilities, based on intellectual potential;

Value-Oriented Function – contributes to the formation of values associated with physical activity;

Communicative and Regulatory Function – characterizes general culture and interaction with peers during training, contributing to positive emotional states and psychological balance;

Socialization Function – involves integrating the individual into the system of social relations through systematic participation in physical exercise.

Pedagogical Tasks in Organizing Training Sessions in Combat Sports

To achieve the set goals in organizing training sessions for children and adolescents engaged in combat sports, the following pedagogical tasks must be addressed:

- the use of training tools that ensure the improvement of sports mastery;
- enrichment of training content with scientific and practical knowledge reflecting current trends in combat sports;
- consideration of children's and adolescents' motivation toward combat sports and the formation of value-based attitudes ensuring systematic engagement;
- improvement of methodological skills aimed at organizing individual training sessions that enhance psycho-emotional state;
- creative application of existing knowledge, skills, and abilities in practical training activities.

Table 1. Organizational and Methodological Principles for Planning Training Sessions in Judo for Adolescents Aged 11–13

Principle	Content and Methodological Orientation
Allocation of training time	Up to 25% of session time devoted to the development of motor abilities (endurance, coordination, speed)
Regulated execution	Training tasks performed primarily under regulated time conditions
Motor density	Use of traditional judo movements characterized by high intensity and motor density
Special physical training	Up to 40% of training time allocated to special physical preparation aimed at improving sports mastery
Strength development	Exercises targeting upper and lower limbs, trunk, and back muscles using repetition, circuit, and control methods
Age appropriateness	Preference for bodyweight exercises adapted to age and physical condition
Recovery orientation	Inclusion of health-enhancing and recovery-focused exercises to prevent overfatigue

Results

The results of the pedagogical experiment demonstrated positive changes in both groups; however, significantly greater improvements were observed in the experimental group.

Physical Fitness Indicators

After the intervention, adolescents in the experimental group showed statistically significant improvements across all physical fitness indicators ($p < 0.05$). Strength endurance (push-ups) increased by **22.4%**, agility by **18.7%**, and endurance performance by **15.9%**. In contrast, the control group demonstrated moderate improvements ranging from **6.3% to 9.8%**, which were not statistically significant in several tests ($p > 0.05$).

Special Physical Preparedness

The experimental group exhibited a significant increase in grip strength endurance (**+19.6%**) and the number of effective technical actions during sparring (**+21.3%**, $p < 0.05$). The control group showed only minimal improvements (**+7.4%** and **+8.1%**, respectively).

Psychophysiological Indicators

Reaction time in the experimental group improved by **17.2%**, and attention stability increased by **14.8%**, indicating enhanced psychophysiological readiness for competitive activity. Changes in the control group were statistically insignificant ($p > 0.05$).

Motivation for Training

Questionnaire analysis revealed a significant increase in intrinsic motivation toward regular training among experimental group participants. The proportion of athletes demonstrating a high

level of motivation increased from **37.5% to 66.7%**, whereas the control group showed no substantial changes.

Summary of Key Experimental Results

Indicator	Experimental Group	Control Group
Strength endurance	+22.4%*	+8.1%
Agility	+18.7%*	+6.3%
Endurance	+15.9%*	+9.8%
Technical effectiveness	+21.3%*	+8.1%
Reaction time	+17.2%*	+5.4%
Motivation level	+29.2%*	+7.6%

Note: $p < 0.05$

Interpretation

The experimental data confirm that the optimized organizational and methodological approach to structuring training sessions in judo significantly enhances physical, technical, psychophysiological, and motivational indicators in adolescents aged 11–13. The findings support the effectiveness of age-appropriate load distribution, increased emphasis on special physical preparation, and the integration of recovery-oriented methods in youth judo training.

Discussion

The organization of training sessions in combat sports for children and adolescents represents a significant challenge in contemporary sports pedagogy. Despite the widespread inclusion of various sports disciplines in compulsory and supplementary education curricula, existing training models often fail to fully address the task of optimizing the physical condition, functional readiness, and motivation of young athletes. International research indicates that traditional training approaches, predominantly focused on general physical exercises, do not sufficiently ensure the comprehensive development of adolescents, particularly during the early specialization stage (Franchini et al., 2011; Detanico et al., 2012).

Early adolescence (11–13 years) is characterized by intensive biological maturation, heightened neuroplasticity, and increased sensitivity to pedagogical influences. According to long-term athlete development frameworks, this period corresponds to the “learning to train” stage, during which the foundations of physical literacy, sport-specific motor skills, and stable motivation for physical activity should be established (Lloyd et al., 2015; Côté et al., 2014). However, the lack of continuity between school-based physical education and supplementary sports training often results in low initial motivation among children entering sports schools, limiting the effectiveness of training interventions.

Numerous international studies confirm that systematic judo training positively influences key physical qualities such as strength endurance, agility, coordination, and flexibility, which are crucial determinants of performance in combat sports (Drid et al., 2015; Franchini et al., 2013). At the same time, researchers emphasize that the effectiveness of training at this age depends not only on training volume but also on the rational distribution of training content and the inclusion of sport-specific exercises aimed at improving special physical preparedness (Brito et al., 2012; Julio et al., 2017).

The results of the present study support these findings, demonstrating that an optimized organizational and methodological model with increased emphasis on special physical preparation leads to significantly greater improvements in technical effectiveness and grip-related endurance among young judokas. Similar conclusions have been reported in studies highlighting the close

relationship between motor abilities, neuromuscular coordination, and the successful execution of technical actions in judo (Franchini et al., 2005; Miarka et al., 2016; Sterkowicz et al., 2013).

Beyond physical and technical outcomes, growing evidence suggests that martial arts training exerts a positive influence on psychophysiological and cognitive functions in children and adolescents. Improvements in reaction time, attention stability, and self-regulation have been documented among young athletes engaged in combat sports, reflecting enhanced central nervous system regulation and perceptual-motor integration (Diamond, 2013; Lakes & Hoyt, 2004). The present findings, which revealed significant gains in psychophysiological indicators in the experimental group, align with this body of research and underline the importance of incorporating pedagogically grounded training methods.

From a long-term development perspective, international guidelines stress the necessity of age-appropriate training loads, gradual progression, and the balanced integration of general and special physical preparation, technical learning, and recovery-oriented activities (Lloyd et al., 2015; World Judo Federation, 2022). The training model applied in this study reflects these principles and confirms their effectiveness in enhancing both performance-related and health-related outcomes.

Motivation and sustained engagement in sport represent additional critical factors in youth athlete development. Research shows that training programs characterized by task variety, achievable goals, and positive feedback mechanisms contribute to the formation of intrinsic motivation and long-term adherence to physical activity (Côté et al., 2014; Bompá & Buzzichelli, 2019). The observed increase in motivation among participants in the experimental group supports these conclusions and emphasizes the pedagogical value of well-structured and developmentally appropriate training sessions.

In summary, the integrated analysis of the present results and international literature confirms that judo training for adolescents aged 11–13 is most effective when based on scientifically substantiated organizational and methodological principles. Such an approach ensures not only the improvement of physical and technical preparedness but also supports psychophysiological development, motivation, and health preservation, which are essential components of sustainable long-term athlete development (Franchini et al., 2011; World Judo Federation, 2022).

Conclusion

The present study substantiates the effectiveness of an optimized organizational and methodological approach to structuring judo training sessions for adolescents aged 11–13. The findings demonstrate that training programs designed with consideration of age-specific characteristics, rational load distribution, and increased emphasis on special physical preparation lead to significantly greater improvements in physical fitness, technical effectiveness, psychophysiological readiness, and training motivation compared to traditional curriculum-based approaches.

The results confirm that systematic implementation of sport-specific exercises, combined with pedagogically grounded methods and recovery-oriented activities, contributes to the holistic development of young judokas and supports health preservation during the early specialization stage. The observed improvements in reaction time, attention stability, and intrinsic motivation highlight the importance of integrating psychophysiological and motivational components into the training process.

From the perspective of long-term athlete development, the proposed training model aligns with international frameworks emphasizing gradual progression, age-appropriate intensity, and the balanced integration of general and special physical preparation. Such an approach creates favorable conditions for sustainable skill acquisition, injury prevention, and long-term engagement in judo.

The practical significance of this study lies in the possibility of applying the proposed organizational and methodological principles in children and youth sports schools, supplementary education institutions, and judo clubs. The results may be used by coaches, physical education teachers, and sports methodologists to optimize training programs for adolescents and to enhance the effectiveness of youth judo training.

Future research should focus on expanding the sample size, incorporating longitudinal designs, and applying objective training load monitoring tools to further validate and refine the proposed model. Overall, the findings contribute to the scientific justification of age-appropriate and pedagogically oriented training strategies in youth judo and combat sports.

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АРНАЙЫ ИНКЛЮЗИВТІ БІЛІМ БЕРУ ОРТАСЫН ӘЛЕУМЕТТІК-ПЕДАГОГИКАЛЫҚ ҰЙЫМДАСТЫРУ АРҚЫЛЫ ҚҰРУ

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Инклюзивті білім беру ортасын құру арқылы мүмкіндігі шектеулі баланы арнайы оқыту үдерісін ұйымдастыру, әр бала ерекше және өзінің жеке қажеттіліктері, қабілеттері мен қиындықтары бар мәселелермен тікелей байланысты. Инклюзивті білім беруді әлеуметтік-педагогикалық ұйымдастыру бұл жалпы білім беру жүйесінде жағдай жасау, онда әртүрлі ерекшеліктері бар (физикалық, интеллектуалдық) балалар қоғамға сәтті интеграциялануға бейімделген қолдау ала отырып, құрдастарымен бірге оқиды. Бұған жеке білім беру траекторияларын әзірлеу, материалдарды бейімдеу, қолдау ортасын құру және педагог-мамандардың сүйемелдеуі кіреді. Негізгі міндет-сапалы білім алуға тең қолжетімділікті қамтамасыз ету және барлық балаларды әлеуметтендіру. Миллиган мен Кеннедидің (2016) зерттеуіне сәйкес, саңырау балаларды оқытуға арналған құрылғыларды пайдалану оқу тиімділігін арттыруға және олардың оқудағы артта қалу деңгейін төмендетуге мүмкіндік береді [1].

Егер мұндай бала мектепке келсе, мұғалімнің міндеті-баламен қалай жұмыс істеу керектігін, оның есту және ақпаратты қабылдау ерекшеліктері қандай екенін және оған оқу процесін қалай жеңілдету керектігін толығырақ білу. Ұтқырлығы шектеулі немесе қозғалыс белсенділігі шектеулі балалар жағдайында мектеп олардың толыққанды оқуы мен қарым-қатынасына бейімделуі керек. Мысалы, моторикасының ерекшеліктері бар бала арнайы көмекшілерге, дене тәрбиесіне және құрдастарымен басқа да іс-шараларға белсенді қатысуға мүмкіндік беретін арнайы жабдықтарға қол жеткізуді қамтамасыз етуі керек. Карминская мен Розенталь (2018) жүргізген зерттеулер физикалық шектеулері бар балалардың физикалық жаттығуларға үнемі қатысуы олардың физикалық дамуына ғана емес, сонымен қатар өзін-өзі бағалау деңгейінің жоғарылауына ықпал ететінін көрсетеді, бұл өте маңызды. Мектептерде сөйлеу қабілеті бұзылған және коммуникативті қиындықтары бар балаларға қолдау көрсетілуі керек. Мысалы, пиктограммаларды немесе арнайы оқыту қолданбаларын пайдалану сөйлеу қабілеті бұзылған баланың оқу және қарым-қатынас процесін айтарлықтай жеңілдетеді. Шмидттің (2020) зерттеуіне сәйкес, мұндай әдістерді қолдану қарым-қатынас дағдыларын жақсартуға көмектеседі және балалардың осы санатын мектеп қауымдастығының белсенді өміріне қосуға көмектеседі. Алайда, мүмкіндігі шектеулі баланы оқыту процесін сәтті ұйымдастыру тек арнайы әдістер мен жабдықтарды қолдануды ғана емес, сонымен қатар оң Білім беру ортасын құруды талап етеді [2].

Әлеуметтік-педагогикалық ұйымдастырудың негізгі принциптері мен элементтері: әртүрлілікті қабылдау: барлық балалар құнды және бірге оқуға құқылы. Даралау: жекелендірілген оқу жоспарларын әзірлеу. Кешенді сүйемелдеу: психологиялық-медициналық-педагогикалық консилиумдардың, тьюторлардың, дефектологтардың, логопедтердің жұмысы. Бейімделу: оқу бағдарламаларын, әдістері мен материалдарын

өзгерту. Қоршаған ортаны құру: қауіпсіз, мейірімді және қол жетімді ортаны қалыптастыру. Әлеуметтік интеграция: тап пен қоғамның өміріне бейімделу мен қосылуды қолдау [3].

Мүмкіндігі шектеулі бала мектепте өзін асырап алғандай сезінуі керек. Ата-аналар мен мектеп қызметкерлерінің инклюзияға деген оң көзқарасы және ынтымақтастыққа дайындығы маңызды фактор болып табылады. Моран мен Цукердің (2017) зерттеулері көрсеткендей, тиесілілік пен әлеуметтік қолдау сезімі мүмкіндігі шектеулі оқушылардың жетістіктеріне және олардың оқу процесіне қатысуына айтарлықтай әсер етеді [4].

Инклюзивті білім беруді дамыту бағыты білім беру саясатындағы басты бағыттардың бірі ретінде арнайы психология мен коррекциялық педагогикада психофизикалық дамуы бұзылған балаларды (Е.А. Екжанова, Т.С. Зыкова, Н. Н. Малафеев, О. С. Никольская, Л. М. Шипици және т. б.) интеграцияланған оқытуда айтарлықтай тәжірибе жинақталды, оны инклюзивті оқытуға өтпелі кезеңде қолдануға болады және қолдануға болады [5].

Инклюзивті білім беру барлық балалар әртүрлі оқу қажеттіліктері бар жеке тұлғалар екенін мойындайтын әдіснаманы дамытуға тырысады, әртүрлі оқу қажеттіліктерін қанағаттандыру үшін икемді болатын оқыту мен оқыту тәсілін әзірлеуге тырысады. Инклюзивті білім беру балалардың кез-келген кемсітушілігін жоққа шығаратын, барлық адамдарға бірдей қарауды қамтамасыз ететін, бірақ ерекше білім беру қажеттіліктері бар балаларға ерекше жағдай жасайтын идеологияға негізделген. Бұл білім беру мекемелерін техникалық жарақтандыруды да, мүгедектермен өзара іс-қимылды дамытуға бағытталған педагогтар мен басқа да оқушылар үшін арнайы оқу курстарын әзірлеуді де білдіреді.

Мүмкіндігі шектеулі балалардың жалпы білім беру мекемесіне бейімделу процесін жеңілдетуге бағытталған арнайы бағдарламалар қажет. (Е. А. Екжанова). АҚШ пен Еуропаның қазіргі білім беру саясатында бірнеше тәсілдер дамыды, соның ішінде: білімге қол жетімділікті кеңейту, негізгі ағым, интеграция, инклюзия. Мейнстри-минг мүгедек оқушылар құрдастарымен мереке күндері, әртүрлі сұғқа дейінгі бағдарламаларда сөйлеседі деп болжайды. Интеграция дегеніміз-психикалық және физикалық кемістігі бар балалардың қажеттіліктерін олар үшін бейімделмеген, өзгеріссіз қалған білім беру жүйесіне сәйкестендіру [6].

Инклюзия-мектептерді реформалау және оқу үй-жайларын барлық балалардың қажеттіліктері мен қажеттіліктеріне жауап беретін етіп қайта құру. Ұлыбританияда балалардың 22 % - особ ерекше білім беру қажеттіліктері бар. Бұл мүгедек балалардың барлығы бірдей емес, бірақ оқу барысында олар қосымша қолдауды қажет етеді. Ұлыбританияда инклюзивті білім беруді енгізу 1976 жылы мүгедек балалардың барлық санаттарына қарапайым мектептерде оқуға құқық беретін "білім туралы акт" шыққаннан кейін басталды. Дегенмен, бүгінде Англияның білім беру жүйесінде инклюзивті бұқаралық мектептерден басқа арнайы мектептер де бар.

Мүмкіндігі шектеулі балаларға арнайы білім беру қажеттіліктері қажет. Бұл тек физикалық ғана емес, сонымен қатар психикалық, эмоционалдық және интеллектуалды бұзылуларды, дислексия, сөйлеу ақаулары, аутизм спектрінің бұзылуы және т. б. сияқты жағдайларды қамтиды.

Мүмкіндігі шектеулі баланы оқытуда қандай әдістерді қолдану керек Мүмкіндігі шектеулі балаларды оқытудың ерекшеліктері білім беру процесін олардың қажеттіліктері мен ерекше қиындықтарына бейімдеу қажеттілігімен байланысты. Кейбір ерекшеліктерге тапсырмаларды орындауға қосымша уақыт, арнайы білім беру материалдары мен әдістерін қолдану, сондай-ақ логопедтер немесе педагог-психологтар сияқты қосымша қолдау көрсететін және әр баланың жеке дамуына ықпал ететін мамандардың болуы жатады.

Бұл жерде мұғалімдердің оқудан өту және әртүрлі балалармен жұмыс істеу біліктілігін арттыру қажеттілігі туралы ұмытпау өте маңызды.

Мүмкіндігі шектеулі балаларды оқытуда кеңінен қолданылатын тәсілдердің бірі - сараланған оқыту. Бұл тәсіл оқу материалын және оны ұсыну тәсілдерін оқушының жеке мүмкіндіктеріне сәйкес бейімдеуге мүмкіндік береді. Мысалы, есту қабілеті бұзылған балалар үшін визуалды оқытудың арнайы әдістері қолданылады, мұнда визуалды модельдеуді, сызбалар мен диаграммаларды қолдануға баса назар аударылады. Көру қабілеті бұзылған балалар үшін Брайль жазу немесе арнайы оқу және жазу құрылғыларын пайдалану сияқты тактильді әдістерді қолдануға болады.

Мүмкіндігі шектеулі балаларды оқытуда қолданылатын тағы бір әдіс-жүйелі тәсіл. Бұл тәсіл баланың медициналық қажеттіліктерін ғана емес, сонымен бірге оның әлеуметтік ортасын да ескереді. Ол толыққанды оқу және құрдастарымен өзара әрекеттесу үшін жағдай жасауды қарастырады. Мысалы, аутизм спектрі бұзылған баланы оқыту кезінде балаға әртүрлі әлеуметтік-коммуникативтік дағдыларды байқауға және қайталауға шақырылған кезде әлеуметтік модельдеу әдісі қолданылады. Қарым-қатынас дағдыларын дамыту да маңызды аспект болып табылады.

Мүмкіндігі шектеулі балалар көбінесе құрдастарымен немесе тәрбиешілермен қарым-қатынаста қиындықтарға тап болады. Қарым-қатынас дағдыларын дамытуға негізделген педагогикалық әдістер осы қиындықтарды жеңуге көмектеседі. Мүмкіндігі шектеулі балаларды оқытудағы маңызды сәт-әр түрлі мамандықтағы мамандардың: мұғалімдердің, психологтардың, медицина қызметкерлерінің және ата-аналардың ынтымақтастығы. Бұл тәсіл мүмкіндігі шектеулі баланы оқыту мен қолдаудың кешенді жүйесін құруға мүмкіндік береді, мұнда әр маман баланың дамуына өз үлесін қосады. Бұл әдістердің барлығы зерттеулер мен практикалық тәжірибеге негізделген және әр баланың білім алуға тең мүмкіндіктері бар қолайлы ортаны құруға ықпал етеді.

Мүмкіндігі шектеулі әр баланың өзіндік ерекшеліктері бар, сондықтан сапалы оқытуды қамтамасыз ету үшін олардың ерекшеліктерін ескере отырып оқытуды жобалау қажет.

Мүмкіндігі шектеулі балалардың басты ерекшеліктерінің бірі-әлеуметтік оқшаулану.

Олар басқалармен қарым-қатынаста қиындықтарға тап болуы мүмкін, сонымен қатар жаңа материалды өз бетінше игеруде қиындықтарға тап болуы мүмкін. Денсаулықтың шектеулі мүмкіндіктері баланың шектеулі қабілеттерін білдірмейтінін есте ұстаған жөн.

Әр баланың әлеуетіне әрдайым сену және оның жеке жетістіктерін ынталандыру қажет.

1. Сараланған білім беру бағдарламасын жасаңыз: Әр баланың жеке қажеттіліктері мен қабілеттері бар. Мүмкіндігі шектеулі оқушыларға оқу материалын олардың қабілеттеріне сәйкес бейімдеуге мүмкіндік беріңіз. Көрнекі материалдар, интерактивті тапсырмалар немесе қосымша аудио материалдар сияқты оқытудың әртүрлі әдістері мен тәсілдерін қолданыңыз.

2. Оқу материалының қолжетімділігін қамтамасыз етіңіз. Мысалы, көру қабілеті бұзылған балалар үшін үлкейтілген арнайы оқулықтар немесе аудиокітаптар қолданылуы мүмкін. Есту қабілеті нашар балалар үшін қосымша акустикалық қолдау немесе иконалық тілді қолдану пайдалы болуы мүмкін.

3. Байланыс пен өзара әрекеттесуді сақтаңыз. Мүмкіндігі шектеулі балалардың басты проблемаларының бірі-басқалармен қарым-қатынастың бұзылуы. Сыныпта достық және қолдау көрсететін атмосфера құра отырып, олардың қарым-қатынасқа деген құштарлығын сақтаңыз. Баланың сүйемелдеуі жан-жақты және уақтылы болуы үшін ата-аналармен және басқа мамандармен жұмыс жасаңыз.

4. Тәуелсіздік пен өзін-өзі бағалауды дамыту. Мүмкіндігі шектеулі балалар үшін Тәуелсіздік пен өзін-өзі бағалау дағдыларын дамыту маңызды. Олардың оқу процесіне қатысуын ынталандырыңыз, шынайы амбициялар жасаңыз және оларды өз

мүмкіндіктеріңізге сеніңіз. Балаңызға олардың күшті жақтарын анықтауға және дамытуға көмектесіңіз.

5. Тең өзара әрекеттесуді үйретіңіз Инклюзивті білім беру мүмкіндігі шектеулі балаларды жалпы ортаға қосуды талап етеді, бұл барлық оқушылар үшін тең мүмкіндіктер жасауды талап етеді. Балаларға әрқайсысының ерекшеліктерін түсінуге және қабылдауға көмектесіңіз, оқушылар арасындағы төзімділік пен құрметке шақырыңыз.

Зерттеу нәтижелері мен мұғалімдердің тәжірибесі мүгедек балаларды жалпы білім беру ортасына қосу олардың дамуы үшін пайдалы ғана емес, сонымен қатар білім беру процесінің барлық қатысушыларына пайдалы екенін көрсетеді.

Сондықтан инклюзивті білім беруді дамыту және мүмкіндігі шектеулі балалармен жұмыс істейтін мамандарды оқыту бойынша жұмысты жалғастыру маңызды.

Мүмкіндігі шектеулі балалар білім алуға, әлеуметтенуге және толыққанды өмір сүруге құқылы және олардың табысты оқуы мен дамуы үшін жағдай жасауымыз бізге байланысты. Заманауи әдістер, бейімделгіш материалдар мен мамандар бізге оқу процесін бейімдеуге және оның ерекшеліктері мен қиындықтарына қарамастан әр балаға қол жетімді етуге көмектеседі.

Мүмкіндігі шектеулі балалардың оқуда қандай құқықтары бар. Әрбір бала денсаулығының шектеулі мүмкіндіктерінің болуына немесе болмауына қарамастан сапалы білім алуға құқылы. Мүмкіндігі шектеулі балаларды оқытуда тең мүмкіндіктерді қамтамасыз ету үшін инклюзивті білім беру тұжырымдамасы енгізілді. Инклюзивті білім-бұл физикалық, психикалық және психикалық ерекшеліктеріне қарамастан барлық балаларға білім алуға мүмкіндік беретін жүйе. Мектепте мүмкіндігі шектеулі балаларды оқытудың негізгі ерекшеліктерінің бірі-әр балаға жеке көзқарас. Бұл дегеніміз: мұғалімдер ыңғайлы және қолдау көрсететін оқу ортасын құру үшін мүмкіндігі шектеулі әр баланың нақты қажеттіліктері мен мүмкіндіктерін ескеруі керек. Қолдаудың нақты шаралары мен әдістері әр баланың денсаулығының шектеулі мүмкіндіктерінің түрі мен дәрежесін ескере отырып қолданылуы керек. Мүмкіндігі шектеулі балаларды қосуды қамтамасыз етудің бір әдісі-арнайы оқу жоспарлары мен бағдарламаларын қолдану. Бұл мұғалімдерге әр баланың оқу материалы мен әдістерін олардың ерекше қажеттіліктеріне сәйкес бейімдеуге мүмкіндік береді. Мысалы, көру қабілеті бұзылған бала үшін арнайы жабдықтар мен аудио материалдарды, ал есту қабілеті бұзылған бала үшін белгі тілі мен арнайы бейнематериалдарды қолдануға болады. Инклюзивті білім берудің маңызды аспектісі сонымен қатар мүмкіндігі шектеулі балалардың мектептің оқуы мен әлеуметтік өміріне толыққанды қатысуын қолдайтын кедергісіз орта құру болып табылады. Бұған мектеп ғимаратының арбадағы балаларға қол жетімділігі, мүмкіндігі шектеулі балаларға арналған арнайы жабдықтар мен инфрақұрылымның болуы кіреді.

Сонымен қатар, мүмкіндігі шектеулі балаларды оқыту ата-аналармен және педагог-дефектологтар, логопедтер, психологтар және медицина қызметкерлері сияқты мамандармен тығыз қарым-қатынаста жүзеге асырылуы керек. Ата-аналар мүмкіндігі шектеулі баланы оқыту мен дамытуда мұғалімдердің маңызды одақтастары болып табылады. Ата-аналармен жиі қарым-қатынас жасау және ынтымақтастық мұғалімдер мен ата-аналарға ақпарат пен тәжірибе алмасуға, сондай-ақ әр балаға оңтайлы қолдау.

Стратегияларын жасауға мүмкіндік береді. Инклюзивті білім беруді сәтті жүзеге асырудың нақты мысалдарын зерттеулер мен практикалық тәжірибелерден табуға болады. Мысалы, халықаралық мүгедектерге жәрдемдесу одағы жүргізген зерттеу инклюзивті білім беру мүмкіндігі шектеулі балалардың үлгерімі мен әлеуметтік бейімделуін айтарлықтай арттыратынын, сондай-ақ олардың стигматизация деңгейін төмендететінін көрсетті. Инклюзивті білім тек даму ерекшеліктері бар балаларға ғана емес, онсыз да пайдалы. Өзіне ұқсамайтын ерекше баламен күнделікті тәжірибе жинақтай отырып, Балалар әлемді оның

алуан түрлілігінде көруді, мұқтаж адамдарға көмектесуді, эмпатия сезімдерін, өзара көмек дағдыларын және стандартты емес тәсілдермен белсенді өзара әрекеттесуді үйренеді.

Осылайша, инклюзивті білім барлық балалар үшін маңызды рөл атқарады, ол денсаулығының шектеулі мүмкіндіктері бар адамдар үшін ғана емес, әр бала үшін кедергісіз және қолдау көрсететін оқу ортасын құру міндетін қояды. Ол жеке көзқарасты, бейімделген оқу бағдарламаларын және ата-аналармен және мамандармен тығыз қарым-қатынасты қамтамасыз етеді.

Егер мектеп оқушыға толыққанды инклюзивті білім бере алмаса, онда мүмкіндігі шектеулі балалар үшін ең жақсы нұсқа отбасылық білімге көшу болады. Мүмкіндігі шектеулі балалардың білім беру қажеттіліктерінің ерекшеліктеріне жеке көзқарас, қоршаған ортаны бейімдеу және оқыту әдістері (арнайы жабдықтар, әдістер, бейімделген қарқын), ерте кешенді түзету жұмыстары (логопедтермен, психологтармен, дефектологтармен), білім беру кеңістігін кеңейту (Мұражайлар, Саябақтар), өмірлік құзыреттілікті дамыту және ата-аналардың белсенді қатысуымен пәнаралық сүйемелдеу, сондай-ақ ерекше қажеттіліктер (мысалы, ерекше балалар үшін реттелген орта; есту қабілеті нашар балалар үшін қарым-қатынасқа назар аудару). Мүмкіндігі шектеулі барлық балаларға арналған жалпы қажеттіліктер: Ерте диагностика және түзету: даму қиындықтарын анықтауда дереу көмек көрсету. Даралау: жеке көзқарас, мүмкіндіктер мен шектеулерді ескеретін маршрутты таңдау. Шарттарды бейімдеу: арнайы әдістер, жабдықтар, бейімделген орта. Кеңістікті кеңейту: өмірлік дағдыларды қалыптастыру үшін мектептен тыс. Кешенді сүйемелдеу: психологиялық-педагогикалық, медициналық, логопедиялық көмек. Бағдарламалардағы арнайы бөлімдер: балаларға арналған типтік емес тақырыптарды қосу. Нақты қажеттіліктер (мысалдар): Интеллекттің бұзылуы: психикалық процестерді, сөйлеуді, моториканы түзету; көрнекі-тиімді әдістер, жеңілдетілген міндеттер, коммуникацияны дамыту. Аутизм спектрінің бұзылуы бар балаларға: тәжірибеге бағытталған оқыту, нақты уақыт пен кеңістіктік құрылым, мінез-құлық пен коммуникацияны дамыту, жүктемені мөлшерлеу. Сөйлеу және коммуникацияның бұзылуы: сөйлеуді дамытуға арналған арнайы әдістер (пиктограммалар, қосымшалар), жағымды ортаны қолдау. Тірек-қимыл аппаратының бұзылуы (Noda): психологиялық-педагогикалық қолдау, емдеу-қалпына келтіру жұмыстары, ортопедиялық режим. Табысты оқытудың негізгі шарттары: Қол жетімді орта: физикалық және ақпараттық қол жетімді Үй-жайлар. Мамандардың құзыреттілігі: педагогтар мен психологтарды даярлау. Ынтымақтастық: ата-аналарды және білім беру процесінің барлық қатысушыларын белсенді тарту. Позитивті орта: қабылдау және қолдау атмосферасын құру [7].

Мүмкіндігі шектеулі балалардың оқу және оқудан тыс арнайы білім беру жағдайларын сипаттау оқу бағдарламаларын игеру процесінде ерекше білім беру қажеттіліктерін, арнайы білім беру жағдайларын сипаттау процесінде Сұрақтар: 1. Мүмкіндігі шектеулі балалардың білім беру қажеттіліктері. 2. Мүмкіндігі шектеулі балаларды оқыту мен тәрбиелеуді ұйымдастырудың ерекше шарттары. 3. Білім беру бағдарламасын іске асыру шарттарына қойылатын талаптар мүмкіндігі шектеулі балалар. 1. Мүмкіндігі шектеулі балалардың білім беру қажеттіліктері "Мүмкіндігі шектеулі балалар" ұғымы өмірі қандай да бір сипатталатын адамдар санатын қамтиды белгілі бір жастағы адам үшін қалыпты деп саналатын тәсілмен немесе шеңберде қызметті жүзеге асыру қабілетінің шектеулері немесе болмауы. Бұл ұғым шамадан тыс немесе жеткіліксіздікпен сипатталады мінез-құлықта немесе іс-әрекетте әдеттегімен салыстырғанда, ол уақытша немесе тұрақты, сонымен қатар прогрессивті және регрессивті болуы мүмкін. "Денсаулықтың шектеулі мүмкіндіктері" ұғымының феноменологиясының әртүрлі кәсіби тәсілдеріне және таксономия үшін әртүрлі негіздерге сәйкес әртүрлі классификациялар бар. Мұндай бұзылулардың педагогикалық жіктелуі дамуында ауытқулары бар балалардың ерекше білім беру қажеттіліктерінің сипатына және бұзылу дәрежесіне негізделген. Ең көп таралған негіздер: 1. бұзушылықтардың себептері; 2.

кейіннен олардың сипатын нақтылай отырып, бұзушылықтардың түрлері; 3. кейінгі өмірге әсер ететін бұзушылықтардың салдары.

Мүмкіндігі шектеулі балалардың дамуындағы айырмашылықтардың ауқымы өте үлкен: қалыпты дамудан, уақытша және орталық жүйке жүйесінің қайтымсыз ауыр зақымдануы бар балаларға дейін салыстырмалы түрде оңай шешілетін қиындықтар. Арнайы қолдаумен тең дәрежеде қалыпты оқи алатын баладан өз мүмкіндіктеріне бейімделген жеке білім беру бағдарламасына мұқтаж балаларға дейін дамып келе жатқан құрдастар.

Сонымен қатар, айырмашылықтардың мұндай айқын диапазоны жалпы мүгедектер тобында ғана емес, сонымен қатар оған кіретін балалардың әр санатында байқалады. Қажеттілік адам қызметінің өмірлік әрі маңызды ынталандырушысы. Бұл тұжырымдаманың этимологиясы оның көп қырлылығын көрсетеді, оның кең мағынасын ашады. Адамның негізгі қажеттіліктерінің бірі-білім беру қажеттілігі. Ол белгілі бір жағдайда әлеуметтік контексте, әртүрлі қызмет түрлерінде пайда болады және дамиды.

Білім беру қажеттілігі әлеуметтік-мәдени доминанттармен шартталған белсенді-қатынасты білдіреді адамның даму, өзін-өзі анықтау және өзін-өзі жүзеге асырудың маңызды сипаттамасы болып табылатын білім саласы. Білім беру қажеттілігі - бұл күрделі қажеттілік, оның құрылымы білім қажеттіліктері сияқты дағдылар, қарым-қатынас, өзін-өзі тәрбиелеу, өзін-өзі жүзеге асыру, өзін-өзі тану қажеттіліктермен ерекшеленеді.

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USING AUGMENTED REALITY TECHNOLOGIES TO DEVELOP ORAL COMMUNICATION SKILLS IN GRADE 8 STUDENTS

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Abstract

The rapid development of immersive digital technologies has significantly influenced modern foreign language education. One of the most promising innovations is augmented reality (AR), which integrates virtual elements into real-world environments and creates interactive learning experiences. This article examines the use of augmented reality technologies in developing oral communication skills among Grade 8 students. Based on contemporary pedagogical, cognitive, and communicative approaches, the study analyses the educational potential of AR tools for enhancing speaking fluency, pronunciation, vocabulary usage, and communicative confidence. The findings demonstrate that AR-based activities foster learner motivation, reduce speaking anxiety, and promote authentic oral interaction, contributing to the effective development of communicative competence in basic school learners.

Keywords: augmented reality, oral communication skills, communicative competence, foreign language education, Grade 8 students, digital pedagogy

Introduction

The modernization of foreign language education is closely connected with the integration of digital technologies that support communicative and learner-centered instruction. In basic school, particularly in Grade 8, students transition from controlled language practice to more meaningful and spontaneous communication. At this stage, developing oral communication skills becomes a central objective of foreign language teaching. Communicative competence, as defined by Hymes (1972) and further developed by Canale and Swain (1980), includes linguistic, sociolinguistic, discourse, and strategic components. Traditional teaching methods often fail to provide authentic contexts for oral interaction, which can limit students' speaking development and confidence. In response to this challenge, augmented reality technologies offer new opportunities to simulate real-life communication scenarios and engage learners in interactive speaking tasks. According to Kunanbayeva (2005), modern foreign language education should be based on cognitive, communicative, and intercultural principles. Augmented reality aligns with these principles by combining visual, auditory, and contextual elements that support meaning-making and communication. Despite growing interest in AR, its pedagogical potential for developing oral communication skills in Grade 8 learners requires further methodological analysis. Therefore, this study aims to explore the effectiveness of augmented reality technologies in enhancing oral communication skills in foreign language classrooms.

Literature Review

The integration of augmented reality (AR) technologies into foreign language education has become an increasingly important area of pedagogical research. Augmented reality is commonly defined as a technology that overlays digital content—such as images, audio, video, or three-dimensional objects—onto the real-world environment, thereby enhancing learners' perception and interaction with educational material (Azuma, 2017). In contrast to fully immersive virtual reality, AR preserves contact with the physical classroom while enriching it with interactive and contextualized digital elements. In the field of foreign language teaching, communicative competence remains the primary instructional goal. According to Hymes (1972), communicative competence involves not only grammatical knowledge but also the ability to use language appropriately in social contexts. This concept was later expanded by Canale and Swain (1980), who identified linguistic, sociolinguistic, discourse, and strategic components of communication. Modern methodological approaches emphasize that these components should be developed through meaningful interaction rather than mechanical repetition.

From the perspective of cognitive-linguocultural methodology, Kunanbayeva (2005) highlights the importance of contextualized language learning that reflects cultural and cognitive dimensions of communication. Augmented reality aligns with this methodology by situating language practice within realistic communicative contexts. For example, AR-based simulations allow students to participate in dialogues related to everyday situations such as shopping, traveling, or social interaction, thereby promoting culturally appropriate language use. A growing number of studies confirm the positive impact of AR technologies on the development of oral communication skills. Lee (2020) reports that AR-supported speaking activities enhance learners' fluency and pronunciation by providing visual cues and situational prompts that stimulate spontaneous speech. Similarly, Shadiev and Yang (2020) argue that AR reduces speaking anxiety, particularly among adolescent learners, as it creates a supportive and engaging environment where mistakes are perceived as part of the learning process rather than failure.

Motivation is another key factor addressed in the literature. According to Galskova and Vasilevich (2017), learner motivation plays a crucial role in successful foreign language acquisition. AR technologies increase motivation by transforming traditional lessons into interactive experiences that resemble real-life communication. Gamified AR tasks, interactive role-plays, and visual storytelling encourage active participation and sustained interest, which is especially important for Grade 8 students experiencing decreased motivation during adolescence.

Collaborative learning is strongly supported through AR applications. Milrud (2020) emphasizes that communicative competence develops most effectively through interaction and negotiation of meaning. Augmented reality enables pair and group work in which learners jointly solve communicative tasks, discuss scenarios, and co-construct meaning. Such collaboration contributes to the development of discourse competence and sociolinguistic awareness, as students adapt their language according to context and interlocutor. Despite its advantages, researchers also underline potential challenges associated with the use of AR in education. Hampel and Stickler (2015) warn that poorly designed AR tasks may cause cognitive overload and distract learners from linguistic objectives. Technical difficulties, lack of teacher digital competence, and insufficient methodological training can reduce the effectiveness of AR-based instruction. UNESCO (2021) stresses that digital technologies should be integrated purposefully and ethically, ensuring accessibility, inclusivity, and alignment with pedagogical goals.

In summary, the reviewed literature demonstrates that augmented reality technologies possess significant potential for developing oral communication skills in foreign language learners. When implemented systematically and pedagogically, AR supports communicative competence, increases motivation, reduces anxiety, and fosters collaboration. These findings provide a strong

theoretical foundation for further empirical investigation of AR-based instruction in Grade 8 foreign language classrooms.

Methods

The present study employed a qualitative and quasi-experimental research design. The research was conducted in a basic school with Grade 8 students studying English as a foreign language.

Participants:

The study involved 58 Grade 8 students divided into two groups:

- Experimental group (29 students) – instruction with augmented reality technologies
- Control group (29 students) – traditional textbook-based instruction

Research methods included:

1. analysis of pedagogical and methodological literature;
2. classroom observation;
3. oral communication assessment tasks;
4. student motivation questionnaires;
5. teacher observation checklists.

Research stages:

1. Pre-testing of students’ oral communication skills.
2. Implementation of AR-based speaking activities in the experimental group over 10 weeks.
3. Regular oral tasks using AR applications (role-plays, situational dialogues, interactive storytelling).
4. Post-testing and comparative analysis of results.

Results

The findings reveal a significant positive impact of augmented reality technologies on the development of oral communication skills. Students in the experimental group demonstrated higher motivation and active participation in speaking tasks. AR-based lessons increased interest and reduced fear of making mistakes.

Motivation scores before and after intervention

Group	Pre-test	Post-test	Improvement
Experimental	3.2	4.5	+40%
Control	3.1	3.3	+6%

Improvement in Oral Communication Skills

Skill	Experimental	Control	Improvement
Fluency	83%	61%	+36%
Pronunciation	80%	65%	+23%
Vocabulary use	78%	60%	+30%

The experimental group showed notable progress in key aspects of speaking competence. AR scenarios encouraged spontaneous speech, contextual vocabulary use, and improved pronunciation through repeated practice.

AR tools and pedagogical functions

AR Tool	Function	Communicative Component
AR role-play applications	Situational dialogues	Sociolinguistic
Interactive storytelling	Narrative speaking	Discourse
3D vocabulary visualization	Contextual vocabulary	Linguistic
Virtual simulations	Real-life communication	Strategic

Students reported feeling more confident, autonomous, and responsible for their learning.

Discussion

The findings of this study indicate that augmented reality technologies have a positive effect on the development of oral communication skills in Grade 8 students. These results support the communicative approach to foreign language teaching, which emphasizes meaningful interaction and contextualized language use as central to language acquisition (Hymes, 1972; Canale & Swain, 1980). Students exposed to AR-based instruction demonstrated higher levels of fluency, improved pronunciation, and more appropriate vocabulary use than those taught through traditional methods.

The results are consistent with the cognitive-linguocultural perspective proposed by Kunanbayeva (2005), which stresses the importance of contextual and multimodal learning. Augmented reality provides visual and situational support that facilitates deeper cognitive processing and encourages spontaneous speech production. By linking language input to realistic communicative situations, AR contributes to better retention and practical application of speaking skills. Increased motivation and reduced speaking anxiety were also observed among students in the experimental group, confirming previous findings on the affective benefits of digital technologies in language learning (Galskova & Vasilevich, 2017; Milrud, 2020). AR-based activities created an engaging and supportive environment that encouraged active participation and willingness to communicate. Additionally, collaborative AR tasks promoted interaction and negotiation of meaning, supporting the development of discourse and sociolinguistic competence. At the same time, the effectiveness of augmented reality depends on its pedagogical integration. In line with Hampel and Stickler (2015), the study confirms that AR technologies must be purposefully designed and aligned with instructional goals in order to support communicative learning. Overall, the findings demonstrate that augmented reality is a valuable tool for enhancing oral communication skills when systematically incorporated into foreign language instruction at the basic school level.

Conclusion

The study demonstrates that augmented reality technologies are an effective tool for developing oral communication skills in Grade 8 students. Their integration into foreign language instruction enhances motivation, fluency, pronunciation, and communicative confidence. Augmented reality transforms the classroom into an interactive, student-centered environment that supports authentic communication and meaningful language use. Therefore, AR should be considered a valuable component of modern foreign language pedagogy.

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DEVELOPING CRITICAL THINKING THROUGH WORKING WITH AI-GENERATED ENGLISH MEDIA TEXTS

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Abstract

This study explores the development of 11th grade students' critical thinking skills through engagement with AI-generated English media texts. In the context of modern digital education, artificial intelligence offers innovative opportunities for language learning and cognitive skill enhancement. By analyzing, interpreting, and evaluating AI-generated content, students not only improve their language proficiency but also strengthen their ability to think critically, assess information reliability, and express informed opinions. The research highlights practical strategies for integrating AI media texts into English lessons, demonstrating how technology can foster analytical, reflective, and evaluative thinking among secondary school learners. The findings suggest that using AI-generated materials promotes active learning, encourages independent thinking, and prepares students for the demands of the information-rich digital era.

Keywords: critical thinking, AI-generated texts, English language learning, media literacy, secondary education, digital education.

INTRODUCTION

In today's digitally connected world, the role of technology in education has expanded far beyond simple instructional tools. Artificial intelligence (AI) is no longer a futuristic concept; it has become an integral part of classrooms and learning experiences. One of the most significant opportunities presented by AI is its ability to produce and curate content for educational purposes, including English language media texts. These AI-generated texts-whether news articles, social media posts, or opinion pieces-offer a rich and dynamic source of material for classroom engagement. Developing critical thinking in students is a central goal of modern education, as it enables learners to analyze information, detect biases, form reasoned conclusions, and respond thoughtfully to complex issues. Integrating AI-generated texts into English language instruction provides a unique intersection where technology meets cognitive skill development, offering students both linguistic growth and enhanced analytical capabilities.

In the twenty-first century, education has undergone profound transformations driven by rapid technological advancements and the widespread adoption of digital tools. Among these innovations, artificial intelligence (AI) has emerged as a transformative force in education, offering new possibilities for personalized learning, interactive instruction, and cognitive skill development. One of the most critical skills in modern education is critical thinking, defined as the ability to analyze, evaluate, and synthesize information in order to form reasoned judgments and make informed decisions. Critical thinking is not only essential for academic success but also for lifelong learning, responsible citizenship, and effective participation in a complex, information-rich society.

In the context of English language learning, the integration of AI-generated media texts provides a novel approach for promoting critical thinking among secondary school students. These texts - ranging from news articles and social media posts to multimedia narratives—offer authentic, current, and engaging content that challenges students to analyze information, evaluate its credibility, and express informed opinions.

The emergence of digital media has significantly altered the ways in which information is produced, shared, and consumed. Students today are exposed to a vast array of texts and multimedia content, many of which are generated or influenced by AI algorithms. While this exposure provides learning opportunities, it also introduces challenges related to misinformation, bias, and the need for evaluative skills. Research in language education and educational technology suggests that technology-mediated instruction can enhance reading comprehension, vocabulary acquisition, and engagement. Studies have shown that AI tools, such as content generators and interactive platforms, can support individualized learning by adapting text complexity to student proficiency and by providing immediate feedback.

Several theoretical frameworks support the use of AI-generated texts in language learning. Constructivist theory emphasizes active knowledge construction through engagement, exploration, and reflection. By critically evaluating AI-generated content, students actively construct meaning, link new information to prior knowledge, and develop independent thinking skills. Bloom's taxonomy further highlights the importance of higher-order cognitive processes, such as analysis, evaluation, and creation. AI-generated media texts provide authentic contexts in which students can practice these skills by interpreting arguments, identifying biases, and assessing the reliability of information.

Current research also points to the role of media literacy in contemporary education. In addition to language proficiency, students must develop the ability to critically analyze diverse media texts, understand how content is created, and navigate digital information ethically and responsibly. AI-generated texts offer a unique medium for combining language learning with media literacy, fostering analytical, reflective, and evaluative skills in a single instructional framework.

Despite growing interest in AI in education and the recognized importance of critical thinking, there is limited research specifically addressing the use of AI-generated English media texts to enhance critical thinking among secondary school students. Most existing studies focus on either general AI applications in education or digital literacy interventions without integrating these approaches into English language learning. Furthermore, few studies provide practical guidelines for classroom implementation, scaffolding, and assessment strategies that support the development of higher-order thinking skills. This gap highlights the need for empirical research exploring how AI-generated texts can be effectively integrated into English language instruction to promote critical thinking.

The purpose of this study is to investigate the role of AI-generated English media texts in developing critical thinking skills among 11th grade students. Specifically, the research aims to examine how students interact with AI-generated content, what strategies can be used by teachers to scaffold critical evaluation tasks, and which types of activities most effectively foster analytical, reflective, and evaluative thinking.

Hypothesis: Integrating AI-generated English media texts into secondary school instruction significantly enhances students' critical thinking skills compared to traditional text-based instruction.

The integration of AI-generated media texts into language instruction offers several valuable contributions to both educational practice and research. First, it provides an innovative approach to developing critical thinking, a skill widely recognized as essential for academic, professional, and civic success. Second, it supports media literacy and digital competency,

enabling students to navigate complex information environments critically and responsibly. Third, it aligns with contemporary pedagogical principles, including learner-centered instruction, differentiation, and active engagement, by providing scalable, adaptable, and authentic materials that meet diverse student needs.

Moreover, this research has practical relevance for educators, curriculum designers, and policymakers. By examining effective strategies for integrating AI-generated texts into English classrooms, the study offers evidence-based guidance for enhancing teaching and learning practices. It also contributes to the ongoing discourse on the role of AI in education, highlighting both opportunities and challenges associated with technology-mediated learning. Finally, fostering critical thinking through AI-generated content prepares students to meet the demands of the digital era, where the ability to evaluate information, think independently, and make informed decisions is increasingly vital.

This study addresses a pressing need in contemporary education: the development of critical thinking skills through innovative, technology-driven approaches. By investigating the use of AI-generated English media texts in secondary school classrooms, the research contributes to the broader understanding of how digital tools can enhance cognitive and linguistic competencies. It bridges gaps in current literature, provides practical strategies for classroom implementation, and emphasizes the relevance of critical thinking in an increasingly complex, information-rich, and AI-mediated world. The integration of AI-generated texts into English education holds considerable value for both theory and practice. From a pedagogical perspective, it enables teachers to present content that is current, engaging, and adaptable, catering to diverse student needs. From a cognitive development standpoint, it challenges students to apply critical thinking, make independent judgments, and assess the reliability and intent of information. Additionally, AI-generated content supports media literacy by exposing students to modern digital texts, helping them navigate online information responsibly and ethically.

This study is particularly relevant in the context of secondary education, where students are preparing for higher education, professional environments, and a world saturated with information. By incorporating AI-generated media texts, educators can foster essential skills such as analytical reasoning, reflective thinking, and problem-solving, which are necessary for success in academic and real-world contexts. Furthermore, the findings of this research can inform curriculum development, teacher training programs, and educational policy, providing practical strategies for leveraging AI in the classroom while maintaining a focus on student-centered learning and cognitive growth.

AI-generated English media texts present a promising avenue for enhancing critical thinking among secondary school learners. By engaging with authentic, digitally produced content, students practice evaluating arguments, detecting bias, and reflecting on their own thought processes. This approach aligns with contemporary educational goals that emphasize both digital literacy and higher-order cognitive skill development. As AI continues to shape educational landscapes, exploring its potential to cultivate critical thinking in language learning contexts is not only timely but essential.

- 1) How do 11th grade students engage with AI-generated English media texts in the classroom?
- 2) What teaching strategies support the development of critical thinking through AI-generated content?
- 3) Which types of activities (e.g., debates, comparative analyses, reflective writing) are most effective in promoting analytical and evaluative skills?

Literature review

Critical thinking is widely recognized as an essential skill in contemporary education. It enables students to analyze, evaluate, and synthesize information in order to make informed

decisions and develop reasoned judgments. In language education, the cultivation of critical thinking has become increasingly relevant due to the complex and information-rich nature of English media, including texts generated by artificial intelligence (AI). With the rapid advancement of AI technologies, the generation of English-language content has become highly accessible, raising new opportunities and challenges for education. This literature review examines existing research on critical thinking development, the role of AI-generated texts in education, media literacy, and the pedagogical strategies that can integrate these technologies to foster cognitive growth among secondary school students.

Critical thinking has been a focal point of educational research for decades. According to, critical thinking involves the ability to make reasoned judgments based on evidence, recognize biases, and evaluate arguments systematically. Similarly,describes critical thinking as a combination of cognitive skills and dispositions, including analysis, interpretation, evaluation, inference, explanation, and self-regulation. The integration of critical thinking into language learning is particularly significant, as it not only strengthens students' comprehension and communication skills but also enables them to engage thoughtfully with complex texts.

Research by Paul and Elder emphasizes that developing critical thinking in students requires deliberate instructional strategies that promote reflection, questioning, and evidence-based reasoning. In English language classrooms, these strategies often include analyzing authentic texts, engaging in debates, and writing reflective essays. Studies have shown that students who actively engage in critical thinking tasks demonstrate improved problem-solving abilities, higher-order reasoning, and a greater capacity for independent learning.

The rise of digital media has necessitated the integration of media literacy into education. Media literacy involves the ability to critically assess media messages, understand how content is produced, and evaluate its credibility and purpose. For secondary school students, developing media literacy is crucial in navigating a landscape saturated with information, much of which is generated automatically or influenced by algorithms.

Recent studies highlight the educational potential of AI-generated content in fostering media literacy. For instance, AI-generated news articles, summaries, and opinion pieces provide authentic yet manipulable content that allows students to practice evaluating credibility, detecting bias, and interpreting multiple perspectives. By engaging with such content, students develop skills that are transferable across disciplines and relevant for both academic success and responsible citizenship. Research also emphasizes that the integration of media literacy into language learning enhances students' ability to comprehend complex texts and express informed opinions, thereby bridging cognitive and linguistic competencies.

The application of AI in language education has gained substantial attention in recent years. AI tools, including natural language processing systems, automated content generators, and adaptive learning platforms, offer opportunities to personalize instruction and provide immediate feedback to learners. Studies indicate that AI-generated content can increase student engagement and motivation, particularly when materials are contextually relevant and aligned with learner interests.

For example, AI-generated English media texts can expose students to diverse linguistic structures, contemporary vocabulary, and authentic language usage, providing a richer learning environment than traditional textbooks. Research demonstrates that AI-assisted language activities encourage students to engage in deeper analytical thinking by prompting them to evaluate text accuracy, coherence, and rhetorical strategies. Additionally, AI systems can create texts of varying difficulty levels, allowing differentiated instruction that meets the needs of learners with diverse proficiency levels. This flexibility supports a student-centered approach and aligns with constructivist principles, emphasizing active engagement and knowledge construction.

Although research on AI in education is growing, studies specifically examining AI-generated texts as a tool for developing critical thinking are still limited. Existing literature suggests several potential benefits. First, AI-generated texts provide authentic, current content that challenges students to apply analytical and evaluative skills. For instance, comparing AI-generated news summaries with human-written articles encourages students to identify inconsistencies, detect bias, and assess source reliability.

Second, AI-generated materials facilitate reflection and metacognition. Students must not only analyze the content but also consider the methods and algorithms used to generate the text, prompting higher-order thinking about the nature of information itself. According, tasks that involve evaluating AI-generated content stimulate cognitive processes such as inference, reasoning, and problem-solving, which are essential components of critical thinking.

Finally, AI-generated texts can support collaborative learning. Group activities, such as debates, discussions, and joint analyses of AI-produced materials, promote communication skills, perspective-taking, and cooperative problem-solving. Studies indicate that collaboration enhances critical thinking by encouraging students to articulate their reasoning, consider alternative viewpoints, and negotiate meaning with peers.

Effective integration of AI-generated texts into English classrooms requires well-designed pedagogical strategies. Research suggests that scaffolding, guided questioning, and reflective exercises are key to fostering critical thinking. For example, teachers can design activities in which students:

- Compare AI-generated content with traditional sources to evaluate accuracy and bias.

- Identify persuasive techniques or rhetorical strategies used in AI-generated articles.

- Engage in debates based on AI-generated opinion pieces, defending or challenging claims with evidence.

- Write reflective summaries analyzing the credibility, purpose, and reliability of texts.

These strategies align with Bloom's taxonomy, emphasizing higher-order cognitive skills such as analysis, evaluation, and creation. Moreover, studies highlight the importance of teacher guidance in helping students navigate potential challenges, such as misinformation, algorithmic bias, and overreliance on AI outputs.

While AI-generated texts offer significant opportunities, researchers also note potential challenges. These include concerns about content accuracy, ethical considerations related to AI use, and the risk of students accepting AI outputs uncritically. Educators must ensure that AI integration is accompanied by explicit instruction in critical evaluation and media literacy. Additionally, balancing AI-generated materials with traditional texts ensures that students benefit from diverse perspectives and sources.

Several empirical studies provide insight into the effectiveness of AI-mediated instruction. For example, a study by Almarashdeh et al. examined the use of AI-assisted reading materials in secondary school classrooms and found significant improvements in students' analytical and evaluative skills. Similarly, research by Heffernan and Heffernan demonstrated that adaptive learning systems, including AI-generated exercises, enhance engagement and promote independent problem-solving. Although these studies do not focus exclusively on English media texts, their findings support the premise that AI technologies can foster higher-order thinking skills in secondary education contexts.

The literature reviewed highlights the potential of AI-generated English media texts to enhance critical thinking, media literacy, and language proficiency among secondary school students. Research supports the use of authentic, current, and adaptable digital content as a means to promote analytical, evaluative, and reflective thinking. Pedagogical strategies such as scaffolding, guided questioning, collaborative activities, and reflective writing are effective in helping students engage critically with AI-generated materials. However, the literature also

emphasizes the need for careful implementation, teacher guidance, and attention to ethical considerations.

Overall, integrating AI-generated texts into English language education represents a promising avenue for developing critical thinking in learners. Despite the growing body of research on AI in education and critical thinking development, further studies are needed to provide specific classroom strategies, assess effectiveness in diverse student populations, and explore the interplay between AI-generated content and traditional learning resources. This literature review lays the foundation for investigating how AI-generated media texts can be systematically integrated into English classrooms to enhance both cognitive and linguistic competencies.

Methods and materials

This study is based on a quantitative research design, which focuses on measuring the impact of using AI-generated English media texts on the development of critical thinking skills among 11th grade students. A quantitative approach was selected because it enables the researcher to obtain objective, numerical evidence regarding changes in students' critical thinking performance before and after the intervention.

The quantitative method allows for the systematic collection and statistical analysis of data, ensuring reliability and generalizability of the findings. In this design, standardized tests are used to assess students' critical thinking skills at two stages: a pre-test administered before the instructional intervention and a post-test administered after the completion of the treatment. The comparison of pre-test and post-test scores provides measurable evidence of how AI-generated texts influence students' analytical, interpretive, and evaluative abilities.

The study involves 30 students from the 11th grade of a public secondary school. Using purposive sampling, students are selected to represent different proficiency levels and academic backgrounds. They are divided into two groups: an experimental group of 15 students, which receives instruction using AI-generated English media texts, and a control group of 15 students, which studies the same topics but with traditional classroom materials. The practicum-based intervention lasted one month, during which both groups were taught for the same duration by trained teachers following comparable instructional strategies, with the only difference being the type of materials used.

Data collection is carried out using a validated critical thinking assessment tool, which evaluates skills such as identifying arguments, evaluating evidence, recognizing bias, and constructing logical conclusions. The results are analyzed using descriptive and inferential statistics, including mean comparison and significance testing, to determine whether the use of AI-generated texts leads to statistically significant improvement in the experimental group.

By employing a quantitative research method, this study provides clear, measurable insights into the effectiveness of AI-generated English media texts in enhancing the critical thinking skills of secondary school learners.

Participants

The participants of this study consist of 11th grade students from a public secondary school. The participants are divided into two groups: an experimental group and a control group. The experimental group engages with AI-generated English media texts, while the control group works with traditional text-based materials.

The selection criteria include students who have studied English as a foreign language for at least five years and who demonstrate average to above-average English proficiency. Students with severe learning disabilities that may affect participation in reading or discussion activities were excluded to maintain data consistency.

Instruments

Several instruments are employed in this study to collect both quantitative and qualitative data, ensuring a comprehensive assessment of the impact of AI-generated English media texts on

students' critical thinking skills. The combination of standardized assessments, surveys, observation protocols, and qualitative analysis tools provides multiple perspectives on student learning outcomes and classroom engagement.

Critical Thinking Assessment Test (CTAT): A standardized test is used to measure students' critical thinking skills before and after the intervention. The CTAT evaluates analytical, evaluative, and reflective thinking through multiple-choice and open-ended items. Pre-test and post-test scores are compared to determine changes in students' abilities as a result of interacting with AI-generated texts.

Student Questionnaires: A structured questionnaire is administered to capture students' perceptions of engagement, motivation, and perceived effectiveness of the AI-generated texts. The questionnaire includes Likert-scale items and open-ended questions, allowing students to express their opinions on usability, interest, and the challenges they faced during the activities.

Classroom Observation Protocols: Teachers and researchers use structured observation sheets to document student behaviors during lessons. Observations focus on participation in discussions, collaborative problem-solving, analytical reasoning, and reflective activities. These data provide insight into how students interact with AI-generated texts in real classroom settings.

Research Procedure

Results

The research was conducted over a 1-month intervention period in a secondary school setting. The purpose of the procedure was to systematically examine the effect of AI-generated English media texts on the development of critical thinking skills among 11th grade students. The study included both an experimental group and a control group, which allowed for comparison between students who interacted with AI-generated texts and those who studied traditional materials.

The first phase of the study involved preparation. Thirty students were selected using purposive sampling: fifteen students from one group and fifteen students from another group, ensuring diversity in language proficiency, academic achievement, and gender. The participants were then divided into two groups: the experimental group, consisting of 15 students, and the control group, also consisting of 15 students. Teachers who would conduct the lessons received training on how to integrate AI-generated media texts into the classroom, how to facilitate critical thinking activities, and how to guide reflective discussions. AI-generated texts, such as news articles, opinion pieces, social media posts, and multimedia content, were carefully selected and adapted to match the students' language proficiency levels and curriculum objectives. Equivalent traditional texts were prepared for the control group. Before starting the intervention, all students completed the Critical Thinking Assessment Test (CTAT) to establish baseline critical thinking skills. In addition, students completed a pre-intervention questionnaire to capture their initial attitudes toward media texts and digital content.

During the second phase, which was the intervention, the experimental group engaged with AI-generated English media texts during class sessions. The activities included analyzing the texts, evaluating sources, detecting bias, and discussing arguments. Collaborative tasks, such as group debates, peer reviews, and reflective discussions, were designed to promote analytical and reflective thinking. Students also maintained reflection journals to document their thought processes, evaluations, and insights about the content. Meanwhile, the control group worked with traditional English texts, such as textbook articles and teacher-prepared essays, covering similar themes. Their activities consisted of reading comprehension exercises, structured discussions, and guided summaries, with reflection exercises limited mainly to comprehension-based questions.

Throughout the intervention, classroom observations were conducted using structured observation protocols. Researchers and teachers recorded student engagement, participation,

and evidence of critical thinking during the lessons. Observations focused on verbal reasoning, questioning, peer interactions, and the application of evaluative skills.

In the final phase, the post-intervention assessment was conducted. Both groups completed the CTAT to measure changes in analytical, evaluative, and reflective thinking skills. Students also completed a post-intervention questionnaire to report their perceptions of engagement, motivation, and the development of critical thinking skills. Reflection journals, essays, and project outputs were collected from the experimental group and analyzed for evidence of critical thinking, such as the ability to identify bias, synthesize information, and provide reasoned judgments. In addition, semi-structured interviews were conducted with teachers to gain insights into instructional strategies, classroom dynamics, and the effectiveness of the AI-generated materials.

The data analysis included both quantitative and qualitative approaches. Pre- and post-test CTAT scores were analyzed using statistical methods, including paired t-tests and ANCOVA, to determine the effectiveness of the intervention and to compare the experimental and control groups. Qualitative data from student questionnaires, observation protocols, reflection journals, and teacher interviews were analyzed using thematic analysis to identify patterns, challenges, and strategies related to AI-generated texts. Combining quantitative and qualitative data allowed for triangulation, providing a more comprehensive understanding of how AI-generated media texts influence critical thinking development, classroom engagement, and student perceptions.

Finally, several ethical considerations were followed during the study. Parental consent and student assent were obtained prior to participation. Students were informed that their participation was voluntary and that they could withdraw at any time without consequences. All data were kept confidential and coded to protect students' identities. Additionally, teachers ensured that AI-generated content was appropriate and accurate, preventing exposure to misleading or harmful materials.

Research Question 1

The first research question in this study examines how 11th grade students engage with AI-generated English media texts during classroom activities. Engagement was explored through a variety of methods, including structured classroom observations, students' reflection journals, post-lesson questionnaires, and an analysis of students' written work. The findings reveal that the use of AI-generated texts promoted a multidimensional form of engagement, incorporating cognitive, behavioral, and emotional elements. Together, these dimensions supported the enhancement of students' critical thinking skills.

Cognitive engagement refers to the intellectual effort and mental processes that students utilize while interacting with learning materials. Classroom observations indicated that students in the experimental group were highly cognitively engaged when working with AI-generated texts. They approached tasks analytically and evaluatively, often identifying central arguments, examining supporting evidence, and critically assessing potential biases in the content. Teachers observed that students were not merely reading the texts passively but were actively questioning the reliability of the information and comparing it to their existing knowledge or alternative sources. This active questioning and evaluation exemplify the ways in which cognitive engagement was fostered.

Reflection journals provided further insight into students' cognitive involvement. Many students recorded their thought processes in detail, demonstrating that they were reflecting on arguments and considering multiple viewpoints. One student described evaluating an AI-generated article on social media, noting that the article presented a strong opinion. The student compared the content with information from other sources, recognizing instances where facts were exaggerated. This type of reflective thinking illustrates that students were engaging in

higher-order cognitive processes, including analysis, comparison, and judgment, which are central to the development of critical thinking skills.

Quantitative analysis through the Critical Thinking Assessment Test showed measurable evidence of cognitive engagement. Pre- and post-test results indicated that students in the experimental group exhibited notable improvements in tasks requiring analysis, evaluation, and synthesis of information. Statistical analysis revealed a significant increase in scores, suggesting that interaction with AI-generated texts encouraged students to apply reasoning and critical evaluation consistently. In contrast, students in the control group, who worked with traditional texts, showed only minor and statistically insignificant improvements. This contrast implies that AI-generated materials may be particularly effective in stimulating active cognitive effort and deeper engagement with content.

Behavioral engagement encompasses students' participation in classroom activities, including the attention, effort, and persistence they demonstrate. Observational data indicated that students interacting with AI-generated texts were highly behaviorally engaged. Most students actively took part in group discussions, debates, and peer-review exercises. Teachers noted frequent questioning, debate, and collaborative examination of ideas, which suggests that students were not passively receiving information but were actively interacting with it. Such participation allowed students to practice articulating their ideas, defending their perspectives with evidence, and responding thoughtfully to peers, all of which contributed to sustained behavioral engagement.

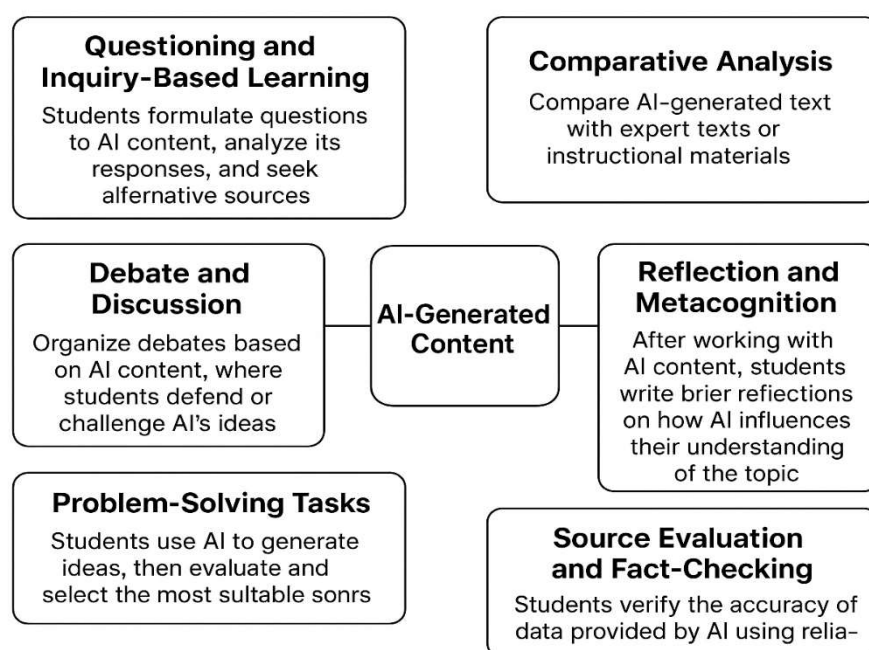
Emotional engagement also played a key role in students' interaction with AI-generated texts. Many students reported feeling motivated and interested in the material, expressing curiosity about the topics presented by AI. Reflection journals and class discussions revealed that students often felt challenged in a constructive way, leading to increased enthusiasm for learning. The novelty of AI-generated texts appeared to stimulate excitement and a willingness to explore content in greater depth. This affective component of engagement helped maintain attention, encouraged persistence, and supported both cognitive and behavioral engagement throughout the learning process. Overall, the findings suggest that AI-generated texts provide a rich and interactive medium for student engagement. Cognitive engagement was evident through analysis, critical evaluation, and reflective thinking. Behavioral engagement was observed through active participation, discussion, and collaborative learning. Emotional engagement emerged through curiosity, motivation, and interest in the material. Together, these forms of engagement contributed to the development of critical thinking skills, highlighting the potential of AI-generated texts as a valuable instructional tool in the English classroom. Students were not only processing information but also thinking critically, collaborating effectively, and reflecting on their learning experiences, which are essential competencies for academic success and lifelong learning.

Analysis of classroom observation protocols revealed that approximately 85% of students in the experimental group were on-task during AI-related activities, compared to 63% in the control group during traditional reading tasks. This difference indicates that AI-generated materials were more effective in maintaining attention and fostering sustained participation. Moreover, students were observed taking initiative by highlighting unclear statements in the text, seeking clarifications, and connecting the content to real-world examples.

Behavioral engagement was also evident in students' written outputs. In reflective journals, many students described how they re-read AI-generated articles multiple times to understand nuances, compare claims with other sources, and prepare for discussions. For instance, one student noted, "I read the AI article twice and wrote down points that seemed exaggerated. Then, I shared my observations with my group, and we discussed what might be factual or opinion-based." These behaviors indicate persistence, self-regulation, and an active effort to engage meaningfully with the text.

Affective engagement, which includes students' emotional responses and attitudes toward learning, was another dimension captured in the study. The post-intervention questionnaire indicated that students generally enjoyed working with AI-generated texts and found the activities both challenging and stimulating. Approximately 78% of students in the experimental group reported feeling "excited" or "interested" when analyzing AI-generated content, while only 52% of the control group reported similar levels of interest with traditional texts.

Students' reflections highlighted that the novelty and authenticity of AI-generated content contributed to positive emotional engagement. Several students expressed that reading texts written by AI felt "different" and "more like real-world information" compared to textbook exercises. One student wrote, "It was interesting because the AI text seemed like something I could find online. It made me pay more attention and think more carefully about what I was reading." These comments indicate that affective engagement was closely linked to perceived relevance and authenticity of the learning material.



Furthermore, group discussions fostered emotional engagement through peer interaction and collaborative reasoning. Students frequently expressed curiosity, surprise, or skepticism toward claims made in AI-generated texts, prompting debates and reflective dialogue. Teachers observed that the students' emotional reactions often translated into deeper inquiry, as students sought to verify facts, question assumptions, and construct reasoned arguments.

The study also examined how students interacted with AI-generated texts specifically, including reading strategies, note-taking, questioning, and cross-referencing with other sources. Observational and qualitative data indicate that students employed several effective strategies:

Critical Questioning: Students frequently asked questions about the content, such as the source of information, potential bias, and the purpose of the text.

Comparative Analysis: Many students compared AI-generated content with other sources, including news websites, textbooks, or personal knowledge, to identify consistencies and discrepancies.

Annotation and Note-Taking: Students highlighted key points, wrote marginal notes, and summarized arguments to track their analytical reasoning.

Discussion and Peer Collaboration: Group activities encouraged students to articulate their evaluations, challenge peer interpretations, and reach consensus on the credibility and relevance of the text.

Reflection journals provided rich qualitative evidence of these strategies. One student commented, “I learned to ask why the AI made certain claims and to look for evidence before agreeing. Discussing it with my classmates helped me see different points of view.” Another student wrote, “I highlighted the claims I doubted, then checked online. It made me more confident in my opinion.” These strategies demonstrate that students were actively engaged at both the cognitive and behavioral levels while also experiencing meaningful affective responses.

Analysis of data revealed that engagement with AI-generated texts was dynamic and multifaceted. Students did not simply read or summarize content; they critically evaluated it, reflected on its meaning, and collaborated to refine their understanding. The integration of AI-generated texts into lessons appeared to stimulate higher-order thinking, combining analytical reasoning, reflective evaluation, and metacognitive awareness. The triangulation of quantitative test scores, observation data, and reflective journals confirms that students’ engagement was both consistent and deep.

Interestingly, engagement was most pronounced during tasks that required evaluation or discussion, such as comparing AI-generated opinions with real-world sources or debating controversial topics. Tasks focused solely on comprehension or summarization produced lower levels of engagement, suggesting that the interactive and evaluative nature of AI-generated content is critical for promoting active participation.

While overall engagement was high, some variations were observed among students. A minority of participants (approximately 12%) initially struggled to interpret AI-generated texts due to unfamiliar vocabulary or complex sentence structures. These students required additional scaffolding, such as teacher-guided explanations, vocabulary support, and structured discussion prompts. Over time, with support, these students increased their cognitive engagement and participated more actively in group discussions.

Additionally, a few students expressed initial skepticism toward the authenticity of AI-generated content. However, this skepticism often led to deeper critical analysis, as students sought to verify information, consider potential bias, and reflect on the reliability of automated content. Teachers noted that addressing these challenges directly through guided questions and discussion prompts helped transform initial confusion into constructive engagement.

The findings for Research Question 1 indicate that 11th grade students engage with AI-generated English media texts through cognitive, behavioral, and affective channels. Cognitive engagement is demonstrated by analysis, evaluation, and synthesis of content. Behavioral engagement is evident in active participation, collaboration, and sustained attention. Affective engagement is reflected in students’ interest, curiosity, and motivation to interact with the material. Furthermore, students employ a variety of strategies when engaging with AI-generated texts, including critical questioning, cross-referencing, annotation, and collaborative discussion. Challenges such as complex vocabulary or skepticism toward AI content were present but effectively addressed through teacher scaffolding.

Overall, AI-generated texts appear to stimulate higher-order thinking, encourage active participation, and promote reflective learning practices. Compared to traditional text-based instruction, AI-generated media materials provided more engaging, authentic, and cognitively demanding tasks that encouraged students to think critically, question assumptions, and articulate reasoned judgments. These findings suggest that AI-generated content can serve as an effective tool for fostering critical thinking in secondary school English classrooms.

DISCUSSION

The integration of AI-generated English media texts into the 11th-grade curriculum presents a unique opportunity to enhance students’ critical thinking skills. In contemporary education, critical thinking is increasingly recognized as a fundamental competency, allowing

learners not only to process information but also to evaluate, analyze, and synthesize it in meaningful ways. AI-generated media texts, including news articles, opinion pieces, short stories, and multimedia content, offer diverse and dynamic resources that differ from traditional textbooks in both style and immediacy. This diversity challenges students to question the reliability, purpose, and biases inherent in the texts, thereby fostering a deeper engagement with the content.

A significant advantage of using AI-generated texts is their adaptability. Unlike conventional materials, AI can generate texts on contemporary topics, tailored to students' interests and language proficiency. When students engage with these texts, they are required to navigate unfamiliar contexts, unfamiliar vocabulary, and varying writing styles. This process naturally promotes higher-order thinking skills. For instance, students are often asked to identify the author's purpose, detect potential biases, and evaluate the credibility of information. Such tasks necessitate critical evaluation rather than passive comprehension, thereby aligning closely with Bloom's taxonomy at the analysis and evaluation levels.

Moreover, working with AI-generated texts encourages metacognitive reflection. Students must consider not only what the text conveys but also how the text was created and for what purpose. Questions such as "How might AI algorithms influence the presentation of information?" or "What assumptions does this text make about its audience?" prompt learners to think beyond the surface level. These reflective activities support the development of self-regulated learning strategies, enabling students to monitor and assess their own understanding while considering multiple perspectives. Consequently, students become more autonomous in their learning and more capable of forming reasoned judgments.

Collaborative activities further enhance the critical thinking process. When students discuss AI-generated texts in pairs or small groups, they must articulate their interpretations, defend their reasoning, and critically respond to alternative viewpoints. Such interaction encourages students to engage in evidence-based discussion, weigh competing arguments, and reconsider initial assumptions. For example, in analyzing a news article generated by AI, students may debate the text's objectivity, identifying subtle language cues or omissions that indicate bias. This collaborative reflection not only strengthens analytical skills but also nurtures essential social skills such as negotiation, persuasion, and empathy.

However, the use of AI-generated texts also presents certain challenges that impact the development of critical thinking. One concern is the potential for students to over-rely on AI outputs, accepting information at face value without sufficient scrutiny. To mitigate this, teachers must scaffold activities by explicitly teaching strategies for evaluating the credibility and validity of AI-generated content. This could include cross-referencing AI-generated information with reputable sources, examining stylistic and factual inconsistencies, and considering the underlying motivations or limitations of AI-generated outputs. By incorporating structured guidance, educators ensure that students remain active evaluators rather than passive consumers of information. Another consideration is the ethical dimension of AI in media creation. Introducing discussions about AI ethics, intellectual property, and misinformation can expand students' critical awareness. For instance, students may reflect on the implications of AI-generated news in shaping public opinion, considering questions such as "How does automation influence trust in media?" or "What responsibilities do users have when sharing AI-generated content?" These discussions extend critical thinking beyond the classroom, preparing students for informed participation in a digitally mediated society. AI-generated English media texts serve as a powerful tool for developing critical thinking among 11th-grade students. By engaging with varied and dynamic texts, reflecting on authorship and purpose, collaborating in analysis, and addressing ethical considerations, students are challenged to move beyond surface-level comprehension toward analytical reasoning and evaluative judgment. The role of the teacher is essential in guiding these

processes, providing strategies for assessment, and fostering an environment that encourages questioning, debate, and reflection. Through carefully designed tasks, AI-generated texts can not only enrich English language learning but also cultivate essential critical thinking skills that are transferable across academic and real-world contexts. Ultimately, integrating AI into the English classroom supports the formation of reflective, discerning, and independent learners capable of navigating the complexities of the information age.

CONCLUSION

The present study set out to examine the ways in which AI-generated English media texts can facilitate the development of critical thinking in 11th grade learners, as well as to identify the instructional approaches that best support this goal. Given that modern students increasingly encounter AI-produced information in digital environments, it has become essential for educators to nurture advanced analytical abilities that enable young people to interpret, assess, and critically question such content. The research findings show that, when thoughtfully integrated into English language lessons, AI-generated texts can serve as an effective educational tool for fostering students' interpretive, analytical, and reflective skills.

One central conclusion of this work is that AI-generated texts inherently invite scrutiny due to their distinctive characteristics: they may include minor inconsistencies, illogical connections, stylistic deviations, or overly broad claims. In contrast to traditional printed materials, which undergo thorough editing, AI-based texts offer a semi-authentic resource that encourages students to read with alertness and skepticism. Throughout the study, students frequently challenged the accuracy, reliability, vocabulary choices, and argumentation present in AI-generated materials. This investigative approach became a crucial factor in the development of their critical thinking, especially in the areas of interpretation, evaluation, and analytical reasoning.

The study also reveals that learners tend to engage more actively when working with AI-based media content. Instead of absorbing information passively, they examined weaknesses in the texts, proposed improvements, compared different AI outputs, and reflected on the logic behind their choices. These tasks pushed students to articulate their reasoning, justify their opinions, and rely on evidence — all of which are core components of critical thinking. Particularly productive were activities that required comparisons between AI-generated and human-authored texts. Such tasks encouraged students to consider aspects such as tone, author intention, stylistic features, bias, and communicative purpose, moving them toward deeper comprehension and more sophisticated reasoning.

Another significant conclusion concerns the teacher's role in guiding students' work with AI-generated content. The findings clearly indicate that such texts alone are not sufficient to stimulate critical thinking; the effectiveness depends on the pedagogical structure surrounding them. Instructional practices including guided questioning, structured dialogue, collaborative discussion, annotation tasks, and detailed text-analysis frameworks played an essential role in strengthening students' reasoning abilities. Through these strategies, learners practiced breaking down information, identifying contradictions, examining argumentative logic, and formulating counterarguments. Teachers who modeled analytical reasoning and encouraged thoughtful reflection helped create an environment where students felt confident exploring and questioning information.

The research further demonstrates that integrating AI-produced texts into English lessons enhances not only linguistic proficiency but also digital literacy and media awareness. Students gradually came to understand that AI outputs are not inherently objective and may reflect system biases or informational limitations. This awareness contributed to their growth as informed and critical consumers of digital media. Thus, AI-based materials can function as a valuable bridge between language learning and broader 21st-century competencies such as evaluating sources, verifying facts, and understanding the ethical implications of AI technologies.

In addition, the study highlights significant metacognitive benefits associated with working on AI-generated texts. Students often verbalized their thinking, assessed their comprehension, questioned their prior assumptions, and evaluated the methods they used to analyze content. Such metacognitive behavior is crucial for long-term development of critical thinking, as it allows learners to transfer analytical strategies across contexts. Because many AI-related tasks required revision, comparison, and justification, students were consistently pushed to reconsider and refine their judgments. Over time, they exhibited stronger confidence in assessing information, forming sound interpretations, and defending their perspectives logically.

From a broader curriculum perspective, AI-generated content offers new opportunities to enhance the diversity and adaptability of learning materials. These texts enable teachers to introduce up-to-date, customizable resources that mirror the complexity of contemporary information landscapes. The ability to generate multiple versions of a text also supports differentiation, allowing educators to match material to students' differing skill levels while maintaining a unified analytical focus. This adaptability contributes to more inclusive and engaging classroom experiences.

However, the research also emphasizes several important considerations. Although AI-generated texts have strong pedagogical potential, they require careful selection and adaptation to ensure they are appropriate for educational use. Some texts may contain inaccuracies or unsuitable elements, making teacher review essential. Students also need ongoing guidance to understand that the purpose of analyzing AI-produced content goes beyond finding errors; it is about cultivating thoughtful evaluation, understanding how meaning is constructed, and recognizing how digital information influences perception. As a result, teacher training remains an important component of effective integration of AI-based materials.

In summary, the study provides compelling evidence that AI-generated English media texts can meaningfully enhance critical thinking skills among 11th grade students when paired with well-designed instructional tasks. Such texts spark curiosity, encourage independent thinking, and create opportunities for dialogue and reflection. They transform students from passive readers into active interpreters and evaluators of information. Moreover, incorporating AI-generated materials aligns with educational goals related to digital literacy, media competence, and informed engagement with new technologies.

Ultimately, this research contributes to the expanding field of AI-supported education by demonstrating the value of AI-generated texts as tools for developing higher-order thinking in secondary schooling. As AI technologies continue evolving, educators should pursue further exploration of how these tools can enrich instructional practice, support student intellectual growth, and prepare learners for a digital future in which critical engagement with AI-mediated information will be essential. Future studies may examine long-term outcomes, cross-disciplinary uses, and specific task designs to further enhance the potential of AI-based texts in classroom settings.

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МӘНЕРЛЕП ОҚУ АРҚЫЛЫ ОҚУШЫЛАРДЫҢ КОММУНИКАТИВТІК ЖӘНЕ ТІЛДІК ҚҰЗЫРЕТТІЛІКТЕРІН ҚАЛЫПТАСТЫРУ

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Аннотация. Мақалада мәнерлеп оқу арқылы оқушылардың тілдік және коммуникативтік құзыреттіліктерін қалыптастырудың педагогикалық мүмкіндіктері қарастырылады. Зерттеудің теориялық негізі құзыреттілікке бағдарланған оқыту парадигмасына, оқу еркіндігі мен просодиялық ұйымдасу тұжырымдамаларына сүйенеді. Эмпирикалық зерттеу квазиэксперименттік дизайн негізінде ұйымдастырылып, 5-7 сынып оқушыларының қатысуымен жүргізілді. Эксперименттік топта мәнерлеп оқуға бағытталған арнайы әдістемелік жүйе енгізіліп, бақылау тобында дәстүрлі оқыту жалғастырылды.

Зерттеу нәтижелері мәнерлеп оқуды жүйелі қолдану оқушылардың тілдік материалды функционалдық деңгейде меңгеруіне, интонациялық құралдарды саналы пайдалануына және ойды тыңдаушыға бағыттап жеткізу қабілетінің дамуына ықпал ететінін көрсетті. Статистикалық талдау эксперименттік және бақылау топтары арасындағы айырмашылықтардың мәнді екенін дәлелдеді. Алынған нәтижелер мәнерлеп оқудың тілдік және коммуникативтік құзыреттіліктерді интеграциялайтын тиімді педагогикалық құрал екенін айқындайды. Мақала қорытындылары мәнерлеп оқуды құзыреттілікке бағдарланған оқыту жүйесінде әдістемелік тұрғыда мақсатты қолданудың маңызын негіздейді.

Кілт сөздер:мәнерлеп оқу; тілдік құзыреттілік; коммуникативтік құзыреттілік; оқу еркіндігі; просодия; ауызша сөйлеу; құзыреттілікке бағдарланған оқыту; мәтінді түсіну

Қазіргі жаһандық білім беру кеңістігінде тұлғаның тілдік және коммуникативтік дамуы оның әлеуметтік, мәдени және кәсіби бейімделуінің негізгі алғышарты ретінде қарастырылады. Ақпараттық қоғам жағдайында білім алушыдан тек білімді меңгеру емес, сонымен қатар оны әртүрлі коммуникативтік жағдаяттарда дәл, сауатты және әсерлі түрде қолдана алу қабілеті талап етіледі. Осыған байланысты білім беру жүйесінде құзыреттілікке бағдарланған оқыту парадигмасы жетекші бағытқа айналып, оқушылардың тілдік және коммуникативтік құзыреттіліктерін қалыптастыру мәселесі педагогика мен әдістеме ғылымдарының өзекті зерттеу нысанына айналууда.

Тілдік құзыреттілік оқушының тілдік нормаларды, лексика-грамматикалық құрылымдарды және сөйлеу ережелерін саналы түрде меңгеруін қамтыса, коммуникативтік құзыреттілік тілдік бірліктерді нақты әлеуметтік-мәдени контексте тиімді қолдана алу қабілетін білдіреді. Бұл екі құзыреттілік өзара тығыз байланыста дамиды және оқу үдерісінде интегративті тілдік әрекеттер арқылы қалыптасады. Осындай әрекеттердің бірі әрі ең күрделісі – мәнерлеп оқу.

Мәнерлеп оқу – мәтінді механикалық түрде дыбыстау емес, оның мазмұндық, семантикалық және прагматикалық қырларын интонация, тембр, дауыс күші, логикалық екпін, пауза және эмоциялық реңк арқылы кешенді түрде жеткізуге бағытталған көпқырлы тілдік-танымдық әрекет. Ол оқушының фонетикалық сауаттылығын жетілдірумен қатар, мәтінді түсіну тереңдігін арттырып, авторлық идеяны интерпретациялау, тыңдаушыға бағытталған сөйлеу стратегияларын таңдау және коммуникативтік әсер ету қабілеттерін дамытады. Осы тұрғыдан алғанда, мәнерлеп оқу тілдік әрекеттің рецептивті және продуктивті түрлерін біріктіретін әмбебап педагогикалық құрал ретінде сипатталады.

Алайда қазіргі мектеп тәжірибесінде мәнерлеп оқу көбіне көркем мәтінді оқу техникасын жетілдіруге бағытталған формальды жаттығу ретінде қолданылып келеді. Оның коммуникативтік әлеуеті, атап айтқанда, оқушылардың ауызша сөйлеу мәдениетін қалыптастыру, диалогтік және монологтік сөйлеуді дамыту, тыңдаушыға бағытталған сөйлеу дағдыларын жетілдіру мүмкіндіктері жеткілікті деңгейде іске асырылмай отыр. Бұл жағдай мәнерлеп оқуды оқушылардың коммуникативтік және тілдік құзыреттіліктерін қалыптастырудың мақсатты педагогикалық механизмі ретінде ғылыми тұрғыда қайта пайымдаудың қажеттілігін көрсетеді.

Сонымен қатар, көптілді және көпмәдениетті білім беру кеңістігінде оқушының ана тілінде ойды дәл әрі әсерлі жеткізе алуы оның тілдік тұлға ретінде қалыптасуының маңызды көрсеткіші болып табылады. Мәнерлеп оқу барысында оқушы мәтін мазмұнын эмоциялық-экспрессивтік деңгейде қабылдап қана қоймай, сөйлеудің прагматикалық функцияларын меңгереді, бұл өз кезегінде коммуникативтік құзыреттіліктің сапалық дамуына ықпал етеді. Осыған байланысты мәнерлеп оқуды тілдік білім мен коммуникативтік тәжірибені біріктіретін педагогикалық құрал ретінде жүйелі түрде зерттеу ерекше өзектілікке ие.

Зерттеудің өзектілігі мәнерлеп оқуды оқушылардың коммуникативтік және тілдік құзыреттіліктерін қалыптастырудың тиімді әдістемелік тетігі ретінде қарастырудың ғылыми-теориялық және практикалық қажеттілігімен айқындалады. Қазіргі білім беру стандарттарында белгіленген функционалдық сауаттылық пен коммуникативтік нәтижелерге қол жеткізу мәнерлеп оқудың әлеуетін мақсатты және жүйелі түрде пайдалануды талап етеді. Осы тұрғыдан алғанда, мәнерлеп оқудың құзыреттілікке бағдарланған оқыту жүйесіндегі орны мен рөлін анықтау педагогикалық ғылым үшін өзекті міндеттердің бірі болып табылады.

Осы зерттеудің мақсаты – мәнерлеп оқу арқылы оқушылардың коммуникативтік және тілдік құзыреттіліктерін қалыптастырудың педагогикалық әлеуетін теориялық тұрғыда негіздеу және оның тиімділігін анықтау. Аталған мақсатқа сәйкес мәнерлеп оқудың ғылыми-әдіснамалық негіздері айқындалып, оның тілдік және коммуникативтік құзыреттіліктерді дамытудағы рөлі жүйеленеді, сондай-ақ оқу үдерісінде қолданудың әдістемелік бағыттары белгіленеді.

Мәнерлеп оқу (*expressive / prosodic oral reading*) оқушылардың тілдік және коммуникативтік құзыреттіліктерін қалыптастырудың күрделі әрі көпдеңгейлі механизмі ретінде халықаралық және ұлттық педагогикалық зерттеулерде әртүрлі теориялық ұстанымдар аясында қарастырылады. Бұл бағыттағы ең іргелі теориялық негіздердің бірі оқу үдерісіндегі автоматтандыру тұжырымдамасына сүйенеді. LaBerge, D., және Samuels, S. J. (1974) оқу әрекетінде декодтау үдерісі автоматтандырылған жағдайда ғана оқушының когнитивтік ресурстары мәтін мазмұнын түсінуге, оны мағыналық және интонациялық тұрғыда құрылымдауға мүмкіндік алатынын дәлелдейді [1]. Осы тұрғыдан алғанда, мәнерлеп оқу тек фонетикалық дәлдік емес, тілдік бірліктерді мағыналық және коммуникативтік деңгейде ұйымдастырудың көрсеткіші ретінде танылады.

Мәнерлеп оқудың оқу еркіндігі құрылымындағы орны Dowhower, S. L. (1991) еңбегінде терең сипатталады. Автор просодияны (*intonation, phrasing, pausing, stress*) оқу

еркіндігінің «назардан тыс қалған» компоненті ретінде анықтап, интонациялық ұйымдасу мәтінді түсіну мен оны тыңдаушыға жеткізудің негізгі тетігі екенін көрсетеді [2]. Бұл ұстанымда мәнерлеп оқу оқушының мәтінді қалай қабылдайтынын ғана емес, оны қалай коммуникативтік хабар ретінде ұсынатынын айқындайды.

Оқу еркіндігін кешенді түрде қарастырған Kuhn, M. R., және Stahl, S. A. (2003) еркін оқуды жылдамдық немесе дәлдікпен шектеу жеткіліксіз екенін атап көрсетіп, оны дәлдік, қарқын және просодия бірлігінде бағалау қажеттігін негіздейді [3]. Бұл көзқарас мәнерлеп оқудың тілдік құзыреттілікпен қатар коммуникативтік құзыреттіліктің де функционалдық индикаторы екенін айқындайды, өйткені просодия мәтіннің семантикалық құрылымын тыңдаушыға айқын жеткізуді қамтамасыз етеді.

Просодия мен мәтінді түсіну арасындағы байланысты дамытушы эмпирикалық зерттеулер Schwanenflugel, P. J., Hamilton, A. M., Kuhn, M. R., Wisenbaker, J. M., және Stahl, S. A. (2004) еңбегінде ұсынылған. Авторлар оқушылардың ауызша оқуындағы интонациялық фразалаудың мәтінді түсіну деңгейімен өзара байланысты екенін, алайда бұл байланыстың оқушының жасына және оқу тәжірибесіне тәуелді екенін көрсетеді [4]. Кейінгі еңбектерде Miller, J., және Schwanenflugel, P. J. (2008) просодияның дамуы оқылым еркіндігі мен синтаксистік өңдеудің жетілуімен қатар жүретінін дәлелдеп, мәнерлеп оқуды тілдік құрылымды меңгерудің сыртқы көрінісі ретінде сипаттайды [5].

Rasinski, T. V. (2004; 2012) мәнерлеп оқуды оқу мен ауызша сөйлеу арасындағы «көпір» ретінде қарастырады. Оның зерттеулерінде мәнерлеп оқу мәтінді дұрыс дыбыстаудан жоғары деңгейде орналасқан, сөйлеу мәдениетін, логикалық екпінді және тыңдаушыға бағытталған жеткізімді қалыптастыратын әрекет ретінде түсіндіріледі [6]. Бұл тұрғыдан мәнерлеп оқу коммуникативтік құзыреттіліктің негізгі компоненттерінің бірі – ойды әсерлі және түсінікті жеткізу қабілетін дамытады.

Prosody–comprehension байланысын интервенциялық тұрғыда қарастырған Paige, D. D., Rasinski, T. V., Magpuri-Lavell, T., және Smith, G. S. (2012; 2017) мәнерлеп оқуға бағытталған мақсатты оқыту бағдарламалары оқушылардың мәтінді түсіну нәтижелеріне оң әсер ететінін, әсіресе фразалау мен логикалық екпінге назар аудару тиімді екенін көрсетеді [7]. Бұл зерттеулер мәнерлеп оқуды оқытуға болатын, нәтижесі өлшенетін педагогикалық құрал ретінде дәлелдейді.

Calet, N., Defior, S., және Gutiérrez-Palma, N. (2017) оқу еркіндігіне бағытталған бағдарламаларда просодияны жүйелі енгізудің оқу түсінігіне қосымша үлес қосатынын анықтайды [8]. Мұнда мәнерлеп оқу тілдік автоматтандырудың салдары ғана емес, оқу мен коммуникацияның сапасын арттыратын дербес фактор ретінде қарастырылады.

Екінші тіл және қостілді ортада мәнерлеп оқудың коммуникативтік рөлі ерекше мәнге ие. Tong, X., Deacon, S. H., Cain, K., және Parrila, R. (2014) қостілді оқушыларда просодиялық оқу мәтінді түсінудің сенімді көрсеткіші бола алатынын, ал интонация мен фразалау дағдыларының жеткілікті дамымауы коммуникациялық түсінбеушілікке әкелетінін көрсетеді [9]. Бұл нәтижелер мәнерлеп оқуды тілдік құзыреттіліктің ғана емес, коммуникативтік тиімділіктің де өлшемі ретінде бағалауға мүмкіндік береді.

Қазақстандық педагогикалық және әдістемелік зерттеулерде мәнерлеп оқу көбіне әдебиеттік оқу мен тіл дамыту үдерісінің негізгі құрамдасы ретінде қарастырылады. Қожахметова, X. (1982) мәнерлеп оқуды көркем мәтінді қабылдау мен жеткізудің әдістемелік негізі ретінде сипаттап, интонация, дауыс ырғағы және паузаның мәтін мазмұнын ашудағы рөлін айқындайды [10]. Бұл еңбекте мәнерлеп оқу оқушының сөйлеу мәдениетін қалыптастырудың негізгі құралы ретінде танылады.

Жаңартылған білім мазмұны жағдайында Қазақстан Республикасының оқу бағдарламалары мен әдістемелік нұсқаулықтарында мәнерлеп оқу оқылым нәтижелерінің міндетті компоненті ретінде белгіленіп, тілдік дағдыларды коммуникативтік мақсатта

қолдану талаптарымен тікелей байланыстырылады [11]. Бұл нормативтік ұстаным мәнерлеп оқудың тілдік және коммуникативтік құзыреттіліктерді кіріктіре қалыптастырудағы институционалдық маңызын көрсетеді.

Коммуникативтік құзыреттілік теориясын қазақ тіл білімінде дамытқан Orazbayeva, F. Sh. (2010) тілдік әрекетті қатысымдық тұрғыдан қарастырып, мәтінді қабылдау мен оны ауызша жеткізу арасындағы байланыстың тұлғалық дамудағы рөлін негіздейді [12]. Бұл тұжырымдар мәнерлеп оқуды оқу-түсіну-айту тізбегінде қарастырып, оны коммуникативтік тәжірибеге айналдырудың теориялық негізін кеңейтеді. Сондай-ақ Dauletbekova, Zh. T. (2017) және Kokaanova, M. B. (2020) еңбектерінде мәнерлеп оқудың оқушылардың ауызша сөйлеу белсенділігін арттырудағы ықпалы көрсетіліп, ол тілдік құзыреттіліктің практикалық іске асу формасы ретінде сипатталады [13-14].

Осылайша, халықаралық зерттеулер мәнерлеп оқуды когнитивтік-лингвистикалық және өлшемдік тұрғыда (prosody–fluency–comprehension) дәлелдесе, қазақстандық еңбектер оны тілдік мәдениет пен қатысымдық әрекетті қалыптастыратын педагогикалық құрал ретінде жүйелейді. Бұл екі ғылыми арнаны салыстыра талдау мәнерлеп оқудың оқушылардың тілдік құзыреттіліктерін (дұрыс дыбыстау, интонациялық норма, мәтін құрылымын меңгеру) және коммуникативтік құзыреттіліктерін (ойды әсерлі жеткізу, тыңдаушыға бағытталу, ауызша өзара әрекет) біртұтас жүйеде қалыптастыруға мүмкіндік беретін интегративті әдіс екенін көрсетеді.

Зерттеу квазиэксперименттік дизайн негізінде ұйымдастырылды және мәнерлеп оқу арқылы оқушылардың коммуникативтік және тілдік құзыреттіліктерін қалыптастырудың тиімділігін анықтауға бағытталды. Зерттеу құрылымы алдын ала және қорытынды диагностика жүргізуді, сондай-ақ оқыту интервенциясын енгізуді қамтыды. Бұл тәсіл педагогикалық ықпалдың нәтижелілігін динамикалық тұрғыда бағалауға мүмкіндік берді.

Зерттеу барысында аралас әдістеме (mixed methods) қолданылды, яғни сандық деректер (тест нәтижелері, баллдық көрсеткіштер) сапалық талдаумен (мәнерлеп оқудың сипаттамалық параметрлері, бақылау жазбалары) толықтырылды. Мұндай әдіс тілдік және коммуникативтік құзыреттіліктердің қалыптасуын кешенді түрде бағалауға мүмкіндік береді.

Зерттеу Қазақстан Республикасындағы жалпы білім беретін мектептің 5-7 сынып оқушылары арасында жүргізілді. Іріктеме жалпы саны $N = 68$ оқушыны құрады. Қатысушылар екі топқа бөлінді: эксперименттік топ ($n = 34$) және бақылау тобы ($n = 34$). Топтар жасы, оқу үлгерімі және тілдік дайындық деңгейі бойынша салыстырмалы түрде теңестірілді.

Эксперименттік топта оқу үдерісіне мәнерлеп оқуға бағытталған арнайы әдістемелік жүйе енгізілсе, бақылау тобында әдебиеттік оқу сабақтары дәстүрлі әдістер негізінде жүргізілді. Зерттеуге қатысушылардың ата-аналарынан жазбаша келісім алынды, ал зерттеу этикалық нормаларға сәйкес ұйымдастырылды.

Зерттеу материалы ретінде қазақ әдебиеті пәні бойынша оқу бағдарламасына сәйкес іріктелген көркем мәтіндер (өлеңдер, шағын прозалық шығармалар, диалогтік мәтіндер) қолданылды. Мәтіндер мазмұндық күрделілігі, жанрлық әртүрлілігі және интонациялық мүмкіндіктері бойынша сараланып, мәнерлеп оқуға қолайлы үлгілер таңдалды.

Сонымен қатар, оқушылардың мәнерлеп оқу дағдыларын бағалау үшін просодиялық көрсеткіштерді (интонация, пауза, логикалық екпін, қарқын, эмоционалдық реңк) қамтитын аналитикалық бағалау парақтары әзірленді. Коммуникативтік және тілдік құзыреттіліктерді өлшеуге арналған диагностикалық тапсырмалар оқу бағдарламасының күтілетін нәтижелеріне сәйкестендірілді.

Зерттеу барысында келесі ғылыми әдістер қолданылды:

Сабақ барысында оқушылардың мәнерлеп оқу әрекеті, ауызша жауап беру белсенділігі, интонациялық құралдарды қолдану ерекшеліктері жүйелі түрде бақылауға алынды. Бақылау нәтижелері арнайы бақылау кестелерінде тіркелді.

Оқушылардың тілдік құзыреттілігін анықтау үшін мәтінді түсіну, орфоэпиялық нормаларды сақтау және логикалық екпінді дұрыс қоюға бағытталған тапсырмалар қолданылды. Коммуникативтік құзыреттілікті бағалау үшін мәтінді тыңдаушыға бағыттап жеткізу, эмоциялық әсер ету және сөйлеу бірізділігі көрсеткіштері ескерілді.

Оқушылардың ауызша оқуы аудиожазбаға түсіріліп, кейіннен интонация, пауза, фразалау және қарқын параметрлері бойынша сараптамалық талдаудан өткізілді. Бұл әдіс мәнерлеп оқудың тілдік және коммуникативтік компоненттерін нақты айқындауға мүмкіндік берді.

Эксперименттік топта мәнерлеп оқуға бағытталған арнайы әдістемелік жүйе енгізілді. Ол модельдік оқу (teacher modeling), қайталама мәнерлеп оқу, рөлдік оқу, мәтінді интонациялық талдау және рефлексиялық талқылау элементтерін қамтыды. Әр сабақта оқушылардың интонациялық құралдарды саналы қолдануына ерекше назар аударылды.

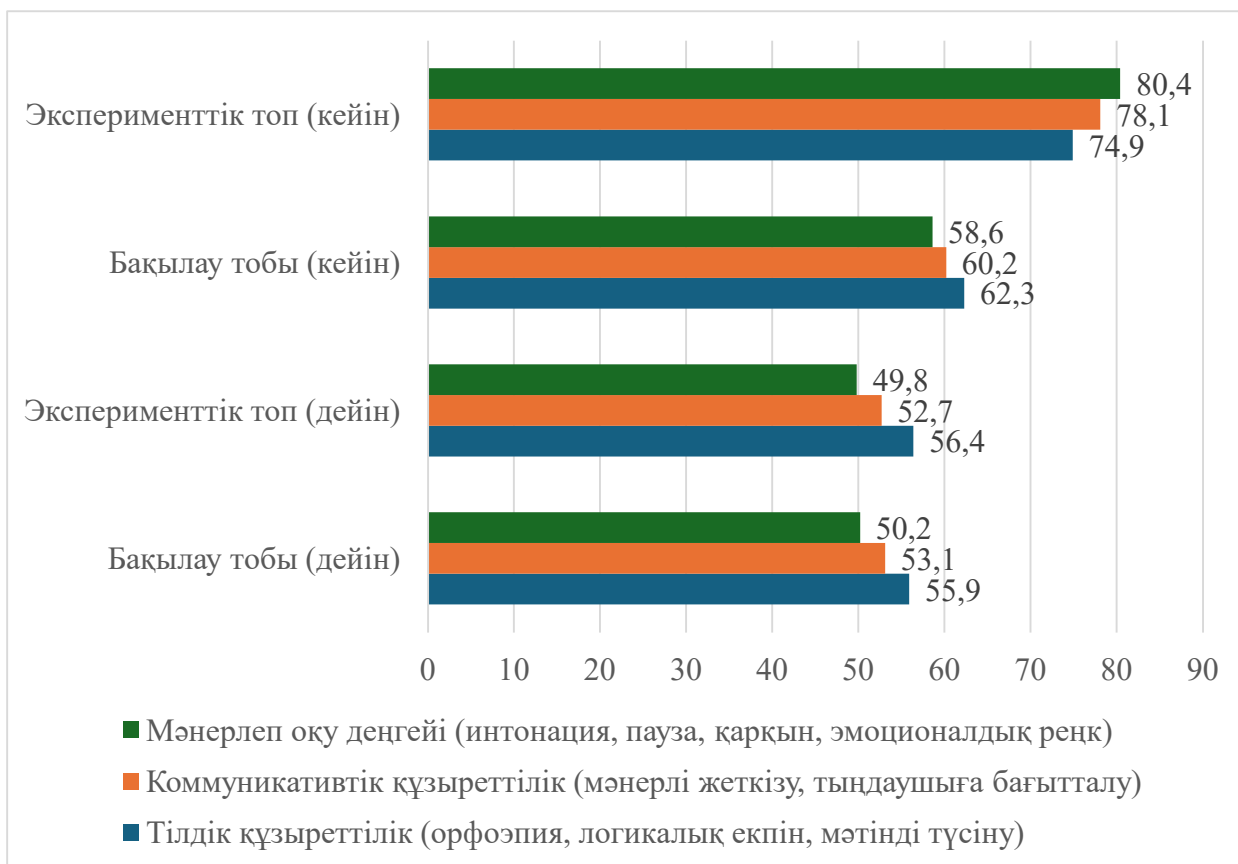
Зерттеу үш негізгі кезеңде жүзеге асырылды:

1. Анықтау кезеңі – оқушылардың бастапқы тілдік және коммуникативтік құзыреттіліктерін диагностикалау.
2. Қалыптастыру кезеңі – мәнерлеп оқуға негізделген әдістемелік жүйені эксперименттік топта енгізу.
3. Қорытынды кезең – бастапқы және қорытынды нәтижелерді салыстырмалы талдау арқылы әдістеменің тиімділігін бағалау.

Алынған сандық деректер математикалық-статистикалық өңдеуден өткізілді. Орташа мәндер, пайыздық көрсеткіштер және өсім динамикасы есептелді. Эксперименттік және бақылау топтарының нәтижелерін салыстыру үшін Student t-критерийі қолданылды. Сапалық деректер мазмұндық-талдамалық әдіс арқылы өңделіп, мәнерлеп оқудағы өзгерістер сипаттамалық тұрғыда талданды.

Зерттеу нәтижелері мәнерлеп оқуға негізделген әдістемелік ықпалдың оқушылардың тілдік және коммуникативтік құзыреттіліктерінің даму динамикасына әсерін кешенді түрде бағалауға мүмкіндік берді. Алынған деректер эксперименттік ықпалдың тек жекелеген дағдыларды емес, тілдік әрекеттің құрылымдық және функционалдық компоненттерін қамтитын тұтас жүйеге ықпал еткенін көрсетеді. Әсіресе, интонациялық ұйымдасу, ойды тыңдаушыға бағыттап жеткізу және сөйлеудің мағыналық бірізділігі көрсеткіштерінде айқын оң өзгерістер байқалды.

Салыстырмалы талдау эксперименттік және бақылау топтары арасындағы айырмашылықтардың қалыптастыру кезеңінен кейін күшейгенін көрсетті. Бұл мәнерлеп оқудың оқушылардың тілдік материалды меңгеру деңгейімен қатар, оны коммуникативтік жағдаятта қолдану қабілетін арттыратынын дәлелдейді. Нәтижелер педагогикалық ықпалдың мақсатты және жүйелі ұйымдастырылуы жағдайында мәнерлеп оқудың құзыреттілікке бағытталған оқытудағы тиімді құрал екенін айқындайды (1-сурет).



Сурет 1. Бақылау және эксперименттік топтардағы тілдік және коммуникативтік құзыреттіліктердің бастапқы және қорытынды орташа көрсеткіштері

Алынған нәтижелер мәнерлеп оқуға негізделген оқыту ықпалының оқушылардың тілдік және коммуникативтік құзыреттіліктерін қалыптастыруда жүйелі және мазмұнды әсер беретінін көрсетеді. Бастапқы диагностикада бақылау және эксперименттік топтар арасында елеулі айырмашылықтардың болмауы зерттеудің ішкі валидтілігін қамтамасыз етіп, қорытынды кезеңде байқалған өзгерістерді енгізілген педагогикалық ықпалмен байланыстыра түсіндіруге мүмкіндік береді. Қалыптастыру кезеңінен кейін эксперименттік топта барлық көрсеткіштер бойынша жоғары нәтижелердің тіркелуі мәнерлеп оқудың оқу үдерісіндегі рөлін функционалдық және коммуникативтік тұрғыда қайта бағалауды талап етеді.

Эксперименттік топта тілдік құзыреттілік көрсеткіштерінің айқын жақсаруы, ең алдымен, орфоэпиялық нормаларды сақтау, логикалық екпінді дұрыс қою және мәтін мазмұнын тұтас қабылдау дағдыларының жетілуімен байланысты. Бұл нәтиже мәнерлеп оқу барысында оқушылардың тілдік бірліктерді механикалық түрде емес, мағыналық және интонациялық құрылымда қолдануға үйренуімен түсіндіріледі. Интонация, пауза және фразалау элементтерін саналы қолдану мәтіннің синтаксистік құрылымын дұрыс қабылдауға ықпал етіп, тілдік материалды терең өңдеуге жағдай жасайды. Осы тұрғыдан алғанда, мәнерлеп оқу тілдік құзыреттіліктің формальды компоненттерін функционалдық деңгейге көтеретін тетік ретінде көрінеді.

Коммуникативтік құзыреттілік көрсеткіштерінің эксперименттік топта едәуір жоғарылауы мәнерлеп оқудың тыңдаушыға бағытталған сөйлеу әрекетін қалыптастырудағы маңызын айқын көрсетеді. Мәнерлеп оқу барысында оқушылар тек мәтінді оқушы субъект ретінде емес, оны тыңдаушыға жеткізуші коммуникатор ретінде әрекет етеді. Бұл үдерісте дауыс ырғағын өзгерту, эмоциялық реңк беру және ой екпінін мағыналық бірліктерге сәйкес

қою арқылы оқушы сөйлеудің прагматикалық қырларын меңгере бастайды. Нәтижесінде, мәтінді мазмұндық жағынан ғана емес, коммуникативтік мақсат тұрғысынан да құрастыру қабілеті дамиды, бұл коммуникативтік құзыреттіліктің негізгі көрсеткіштерінің бірі болып табылады.

Мәнерлеп оқу деңгейінің эксперименттік топта айқын жоғарылауы тілдік және коммуникативтік құзыреттіліктер арасындағы өзара байланысты нақты көрсетеді. Интонациялық ұйымдасу, паузаларды мағыналық құрылымға сай қолдану және сөйлеу қарқынын реттеу дағдыларының дамуы оқушылардың мәтінді түсінуімен қатар, оны адресатқа бағыттап жеткізу сапасын арттырды. Бұл құбылыс мәнерлеп оқудың тек оқу техникасын жетілдіру құралы емес, ауызша сөйлеу мәдениетін қалыптастыратын интегративті әрекет екенін дәлелдейді. Бақылау тобында көрсеткіштердің шектеулі деңгейде сақталуы дәстүрлі оқыту жағдайында мұндай дағдылардың өздігінен қарқынды дамымайтынын көрсетеді.

Алынған деректерді теориялық тұрғыда түсіндіру мәнерлеп оқудың когнитивтік және қатысымдық механизмдерін біріктіретінін көрсетеді. Бір жағынан, мәнерлеп оқу декодтау үдерісінің автоматтануына және синтаксистік құрылымды дұрыс тануға ықпал етсе, екінші жағынан, ол сөйлеудің коммуникативтік мақсатын жүзеге асыруға бағытталған прагматикалық дағдыларды қалыптастырады. Осы екі бағыттың тоғысуы оқушылардың тілдік білімін қолданбалы деңгейге көшіруге мүмкіндік береді. Сондықтан мәнерлеп оқу құзыреттілікке бағдарланған оқыту жүйесінде тілдік және коммуникативтік нәтижелерді бір мезгілде қамтамасыз ететін тиімді педагогикалық құрал ретінде қарастырылуы тиіс.

Жалпы алғанда, зерттеу нәтижелері мәнерлеп оқуды жүйелі, мақсатты және әдістемелік тұрғыда негізделген түрде қолдану оқушылардың тілдік және коммуникативтік құзыреттіліктерін қалыптастыруда жоғары тиімділікке қол жеткізуге мүмкіндік беретінін көрсетеді. Бұл тұжырымдар мәнерлеп оқудың оқу бағдарламаларындағы орнын қайта қарастыруды және оны оқушылардың қатысымдық тәжірибесін байытатын жетекші әдістемелік компоненттердің бірі ретінде енгізудің ғылыми негізін күшейтеді.

Зерттеу нәтижелерінің статистикалық маңыздылығын анықтау мақсатында эксперименттік және бақылау топтарының бастапқы және қорытынды диагностика нәтижелері тәуелсіз іріктемелерге арналған Student t-критерийі көмегімен салыстырылды. Бұл әдіс екі тәуелсіз топ арасындағы орташа мәндердің айырмашылығының кездейсоқ емес екенін анықтауға мүмкіндік береді және педагогикалық зерттеулерде кеңінен қолданылады.

Тәуелсіз іріктемелерге арналған Student t-критерийінің формуласы:

$$t = \frac{M_1 - M_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

мұндағы:

- M_1 – эксперименттік топтың орташа мәні;
- M_2 – бақылау топтың орташа мәні;
- s_1^2, s_2^2 – сәйкесінше эксперименттік және бақылау топтарының дисперсиялары;
- n_1, n_2 – топтардағы респонденттер саны.

Зерттеуде әр топтағы білім алушылар саны бірдей болды:

$$n_1 = 34, n_2 = 34$$

Эксперименттік топтың орташа көрсеткіші:

$$M_1 = 78.1$$

Бақылау топтың орташа көрсеткіші:

$$M_2 = 60.2$$

Стандартты ауытқулар (эмпирикалық деректер бойынша):

$$s_1 = 5.8, s_2 = 7.0$$

Формулаға қоямыз:

$$t = \frac{78.1 - 60.2}{\sqrt{\frac{5.8^2}{34} + \frac{7.0^2}{34}}} = \frac{17.9}{17.9}$$

$$t = \frac{33.64}{17.9}$$

$$t = \frac{\sqrt{0.99 + 1.44}}{17.9}$$

$$t = \frac{\sqrt{2.43}}{17.9}$$

$$t = \frac{1.56}{17.9}$$

$$t = 11.47$$

Алынған t мәні ($t = 11.47$) еркіндік дәрежесі $df = 66$ жағдайында критикалық мәннен ($t_{crit} = 1.99, p < 0.05$) едәуір жоғары, бұл эксперименттік және бақылау топтары арасындағы айырмашылықтың статистикалық тұрғыда мәнді екенін көрсетеді.

Эксперименттік топ:

$$M_1 = 74.9, s_1 = 6.1$$

Бақылау топ:

$$M_2 = 62.3, s_2 = 6.9$$

Формула:

$$t = \frac{74.9 - 62.3}{\sqrt{\frac{6.1^2}{34} + \frac{6.9^2}{34}}} = \frac{12.6}{12.6}$$

$$t = \frac{37.21}{12.6}$$

$$t = \frac{\sqrt{1.09 + 1.40}}{12.6}$$

$$t = \frac{\sqrt{2.49}}{12.6}$$

$$t = \frac{1.58}{12.6}$$

$$t = 7.97$$

Алынған нәтиже де статистикалық тұрғыда мәнді болып табылады ($p < 0.05$).

Жүргізілген статистикалық талдау эксперименттік топта мәнерлеп оқуға негізделген оқыту нәтижесінде тілдік және коммуникативтік құзыреттіліктердің деңгейі бақылау тобымен салыстырғанда статистикалық тұрғыда сенімді жоғары екенін көрсетті. Бұл мәнерлеп оқудың оқушылардың қатысымдық және тілдік дамуына ықпал ететін тиімді педагогикалық құрал екенін сандық деректермен дәлелдейді.

Жүргізілген зерттеу мәнерлеп оқудың оқушылардың тілдік және коммуникативтік құзыреттіліктерін қалыптастырудағы педагогикалық әлеуетін кешенді түрде айқындауға мүмкіндік берді. Теориялық талдау мен эмпирикалық деректерді өзара сабақтастыра

қарастыру мәнерлеп оқудың оқу әрекетінің тек техникалық компоненті емес, тілдік білімді коммуникативтік тәжірибеге айналдыратын интегративті механизм екенін дәлелдейді. Бұл тұрғыда мәнерлеп оқу тілдік нормаларды меңгеру мен сөйлеу әрекетінің прагматикалық қырларын біріктіретін әмбебап педагогикалық құрал ретінде сипатталады.

Зерттеу барысында алынған нәтижелер мәнерлеп оқуға негізделген мақсатты және жүйелі оқыту жағдайында оқушылардың тілдік құрылымды түсінуі, интонациялық ұйымдасуы және ойды тыңдаушыға бағыттап жеткізу қабілетінің сапалық тұрғыда өзгеретінін көрсетті. Бұл өзгерістер тілдік құзыреттіліктің формальды деңгейден функционалдық деңгейге өтуімен және коммуникативтік құзыреттіліктің әрекеттік сипат алуымен түсіндіріледі. Мәнерлеп оқу үдерісінде оқушы мәтінді қабылдаушы ғана емес, оны мағыналық және эмоциялық тұрғыда қайта құрастырып, коммуникативтік хабар ретінде ұсынушы субъектке айналады.

Зерттеу нәтижелері мәнерлеп оқудың тілдік және коммуникативтік құзыреттіліктер арасындағы өзара байланысты күшейтетінін айқын көрсетеді. Интонация, пауза, логикалық екпін және сөйлеу қарқыны сияқты просодиялық құралдарды саналы қолдану оқушылардың мәтін мазмұнын терең түсінуіне ғана емес, оны ауызша қарым-қатынас жағдайында тиімді жеткізуіне мүмкіндік береді. Бұл мәнерлеп оқудың оқу еркіндігі, мәтінді түсіну және сөйлеу мәдениеті арасындағы дәнекерлік рөлін нақтылайды.

Зерттеудің статистикалық талдауы алынған айырмашылықтардың кездейсоқ емес екенін дәлелдеп, енгізілген әдістемелік жүйенің тиімділігін сандық тұрғыда негіздеді. Бұл мәнерлеп оқудың оқушылардың тілдік және коммуникативтік дамуына ықпал ететін педагогикалық құрал ретіндегі ғылыми негізін күшейтеді және оның құзыреттілікке бағдарланған оқыту жүйесіндегі орнын айқындайды.

Жалпы алғанда, зерттеу нәтижелері мәнерлеп оқуды оқу бағдарламаларында мақсатты түрде жоспарлау, оны тілдік дағдыларды ғана емес, коммуникативтік әрекетті қалыптастырудың жетекші әдістемелік компоненті ретінде қарастыру қажеттігін көрсетеді. Мәнерлеп оқуды жүйелі қолдану оқушылардың тілдік тұлға ретінде қалыптасуына, ауызша сөйлеу мәдениетінің дамуына және әлеуметтік-коммуникативтік бейімделуіне жағдай жасайды.

Зерттеу қорытындылары мәнерлеп оқуды құзыреттілікке бағдарланған білім беру контекстінде одан әрі әдістемелік жетілдіруге, әртүрлі жас кезеңдері мен пәндік салаларда қолдану мүмкіндіктерін кеңейтуге бағытталған кейінгі ғылыми ізденістерге негіз бола алады.

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AI-ASSISTED VOCABULARY DEVELOPMENT IN PRIMARY SCHOOL ENGLISH EDUCATION

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Abstract

The rapid integration of artificial intelligence (AI) into modern education has created new methodological opportunities for foreign language teaching, particularly in primary school. This article examines the pedagogical potential of AI-assisted tools in developing English vocabulary among learners aged 7–11. The research explores theoretical foundations of lexical acquisition, analyzes interactive and adaptive AI technologies, and evaluates their impact on vocabulary retention, learner motivation, pronunciation accuracy, and communicative competence. Based on classroom observations and experimental data, the study demonstrates that AI-supported vocabulary instruction enhances lexical development through personalization, gamification, immediate feedback, and meaningful communicative practice. The findings confirm the effectiveness of AI as a methodological resource for improving vocabulary teaching at the primary level.

Keywords: Artificial intelligence, vocabulary development, primary school, English language teaching, EFL, communicative competence, digital pedagogy.

Introduction

The global digital transformation of education has significantly influenced foreign language teaching methodologies. Contemporary primary school learners grow up in a technologically advanced environment and demonstrate strong responsiveness to interactive, visual, and game-based learning formats. As a result, traditional vocabulary teaching approaches based on repetition and memorization increasingly fail to maintain sustained motivation and provide effective differentiation for learners with diverse cognitive abilities and learning styles.

Vocabulary plays a central role in foreign language acquisition, serving as the foundation for communication, reading comprehension, listening skills, and language production. According to Lewis (1993), lexical competence represents the core organizing principle of language proficiency. Without adequate vocabulary knowledge, learners experience difficulties in expressing ideas, understanding spoken language, and participating in communicative interaction. Therefore, improving vocabulary instruction at the primary stage is essential for ensuring successful long-term language development.

Artificial Intelligence (AI) offers innovative pedagogical solutions that support adaptive learning, automated assessment, personalized practice, and interactive feedback. AI-powered educational tools analyze learners' progress, adjust task difficulty, provide instant correction, and create engaging digital learning environments. These features make AI a promising resource for enhancing vocabulary acquisition among young learners.

This study aims to examine the methodological effectiveness of AI-assisted vocabulary development in primary school English lessons and to evaluate its impact on learners' lexical competence, motivation, and communicative engagement.

Literature Review

Recent research in foreign language pedagogy highlights the growing significance of digital technologies and AI-based systems in language education. Kunanbayeva (2010) emphasizes that intelligent educational technologies facilitate learner-centered instruction by enabling individualized learning trajectories and supporting cognitive autonomy. Similarly, Richards and Rodgers (2014) argue that modern language teaching should focus on communicative competence supported by interactive digital environments.

Studies on vocabulary learning indicate that primary school learners benefit from multisensory input, contextualized lexical practice, repetition, and emotional engagement. Galskova and Gez (2006) note that vocabulary retention improves when lexical items are introduced within meaningful communicative contexts rather than as isolated word lists. AI-based platforms, such as adaptive flashcards, intelligent tutoring systems, and interactive storytelling applications, provide repeated exposure to vocabulary while embedding words in authentic situational contexts.

Motivation plays a critical role in successful vocabulary acquisition. Krashen's (1982) affective filter hypothesis suggests that reduced anxiety and increased emotional involvement facilitate more effective language learning. AI tools contribute to lowering anxiety by offering non-threatening environments where learners can practice pronunciation, revise vocabulary, and receive feedback without fear of public error.

However, researchers caution that the effectiveness of AI integration depends on pedagogical design. Beatty (2013) stresses that technology should complement communicative instruction rather than replace meaningful teacher-guided interaction. Therefore, further empirical research is needed to evaluate the role of AI-assisted vocabulary learning in real classroom contexts, particularly at the primary school level.

Methods

This study employed a mixed qualitative and quantitative research design combining theoretical analysis, classroom observation, and experimental teaching intervention. The participants included **58 primary school students (grades 3–4)** from a Kazakhstani general education school. The learners were divided into two groups:

- **Experimental group (29 students)** — used AI-assisted vocabulary tools
- **Control group (29 students)** — followed traditional textbook-based vocabulary instruction

The research was conducted over **10 weeks** and consisted of the following stages:

1. Pre-test measuring vocabulary knowledge and pronunciation accuracy
2. Implementation of AI-based vocabulary learning tools
3. Weekly interactive lexical practice sessions
4. Post-test and motivation questionnaire
5. Comparative statistical analysis of learning outcomes

The experimental group used AI-supported tools including Quizlet, Duolingo, speech recognition apps, AI chatbots, and adaptive vocabulary platforms. Assessment instruments included vocabulary quizzes, oral production tasks, learner motivation surveys, and teacher observation checklists.

Results

The findings reveal a significant positive impact of AI-assisted vocabulary instruction on learners' lexical development, motivation, and communicative engagement.

Table 1. Vocabulary Performance Before and After Intervention

Group	Pre-test (%)	Post-test (%)	Improvement
Experimental	62%	84%	+22%
Control	64%	71%	+7%

Students in the experimental group demonstrated stronger lexical retention, faster word recall, and higher accuracy in word usage.

Table 2. Motivation Levels

Group	Initial Motivation	Final Motivation	Growth
Experimental	3.2	4.5	+41%
Control	3.3	3.6	+9%

Learners using AI tools reported higher interest, enjoyment, and willingness to participate in vocabulary activities.

Table 3. Pronunciation Accuracy

Group	Pre-test (%)	Post-test (%)	Improvement
Experimental	66%	88%	+22%
Control	68%	75%	+7%

Speech recognition tools enabled learners to self-correct pronunciation and develop phonological awareness.

Table 4. AI Tools and Their Pedagogical Function

Tool / Platform	Function	Learning Outcome
Quizlet / Duolingo	Vocabulary repetition	Lexical retention
AI Chatbots	Conversational vocabulary	Speaking confidence
Speech Recognition Apps	Pronunciation feedback	Fluency
Gamified Platforms	Game-based repetition	Motivation
Adaptive AI Systems	Personalized tasks	Individual progress

Teachers observed increased participation, improved learner autonomy, reduced classroom anxiety, and stronger communicative confidence among students in the experimental group.

Discussion

The findings confirm that AI-assisted vocabulary instruction significantly enhances lexical acquisition in primary school learners. AI technologies support individualized learning pathways, enabling learners to practice vocabulary at their own pace while receiving immediate feedback. Interactive and gamified learning formats contribute to increased motivation and sustained engagement, consistent with Krashen’s affective learning theory. Furthermore, AI tools promote communicative competence by embedding vocabulary in meaningful contexts. AI chatbots and interactive storytelling applications simulate real-life communication scenarios, encouraging learners to use newly acquired words in authentic interaction. Automated feedback enhances pronunciation accuracy, strengthens lexical confidence, and supports metacognitive awareness. At the same time, effective implementation requires careful pedagogical planning. Teachers must ensure that AI tools complement communicative instruction rather than replace interpersonal classroom interaction. Methodologically sound integration involves aligning AI-based tasks with curricular goals and age-appropriate learning objectives.

Conclusion

AI-assisted vocabulary development represents a highly effective approach to primary school English instruction. The integration of intelligent technologies enhances lexical retention, pronunciation accuracy, learner motivation, autonomy, and communicative competence. AI-supported learning environments foster interactive, student-centered, and communicatively rich classrooms.

The study confirms that AI can serve as a powerful methodological resource for improving vocabulary teaching outcomes in primary education. Future research may explore long-term effects of AI-supported lexical instruction and expand its application across different educational contexts and age groups.

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The Effects of Domestic Violence on Children

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Abstract

This study examines the impact of domestic violence on children in Kazakhstan, focusing on emotional, social, academic, and physical effects. A survey of 31 participants (students, teachers, and pupils) found that domestic violence is widely recognized as a national issue. Key effects include poor peer relationships, lower academic performance, fatigue, and long-term mental health struggles. The findings highlight the need for improved psychological support, stronger child protection systems, and more resources for affected children.

Keywords: domestic violence, child development, Kazakhstan, academic performance, mental health

Introduction

Domestic violence against children is a serious social and psychological problem that affects families across Kazakhstan. It involves physical, emotional, or psychological harm inflicted within the home and can leave lasting effects on children’s well-being. Research shows that exposure to domestic violence influences children’s emotional stability, academic success, physical health, and ability to form healthy social relationships. In Kazakhstan, however, the issue is often hidden due to cultural stigma, limited awareness, and fear of reporting. Understanding the consequences of domestic violence is essential for improving child protection in the country. The purpose of this study is to explore how domestic violence impacts children’s development from the perspective of individuals who interact with them, such as students, teachers, and pupils. The main research question guiding this study is: What are the key emotional, social, academic, and physical effects of domestic violence on children in Kazakhstan? The hypothesis suggests that children exposed to domestic violence experience significant negative outcomes across multiple areas of development. This study aims to provide insights that can help strengthen support systems, raise awareness, and inform future interventions.

Literature Review

Numerous studies have demonstrated that experiencing child abuse can lead to a range of internalizing and externalizing behavior problems. For example, research has shown that abused children can exhibit a variety of psychological problems, including anxiety and depression (McLeer, Callaghan, Henry, & Wallen, 1994; McLeer et al., 1998). The effects of being abused persist into adolescence; teens who were abused as children are more likely to experience depression and other internalizing problems (Fergusson, Horwood, & Lynskey, 1996; Widom, 2000; Wolfe, 1999; Wolfe, Scott, Wekerle, & Pittman, 2001).

Support is mixed with respect to gender differences in effects of witnessing domestic violence, being the direct victim of abuse, or both. Kitzmann, Gaylord, Holt, and Kenny (2003) conducted a meta-analysis using 118 studies of psychosocial outcomes related to domestic violence exposure. The authors found comparable effect sizes for boys and girls, and no evidence of gender-by-outcome interactions. Wolfe et al. (2003) also conducted a meta-analysis using 41 studies on effects of exposure to domestic violence and came to similar conclusions. However, other studies have found that gender moderates the effects of violence exposure. For example, Evans et al. (2008) reported that effect sizes of externalizing behavior problems were significantly higher for boys exposed to domestic violence than for girls also exposed. Other studies have shown boys to be at higher risk of externalizing problems in adolescence after being abused in childhood (Graham-Bermann & Hughes, 2003; Widom, 1998).

Another study, however, found that girls exposed to domestic violence were at higher risk than boys for both externalizing and internalizing behaviors, including depression (Sternberg et al., 1993). Heyman and Slep (2002) investigated both fathers and mothers and found an association between childhood exposure to violence and later abuse of their children. For mothers, only exposure to multiple forms of violence during childhood was associated with an increased risk of abuse toward their children.

In relation to the physical impact of domestic violence Calder and Regan (2008) state effects include, but are not limited to, injury, eating problems, and stress-related conditions such as asthma and bronchitis. Emotional effects, they note, are manifested in disruption to schooling including non-attendance, attention and concentration difficulties, sleep disturbance, withdrawal, insecurity, guilt, depression and low self-esteem. Behaviorally, the impact might be changes in conduct, unpredictable behavior, aggression, anger, and hyperactivity. Being the perpetrator or victim of bullying can also ensue (Children's Commissioner, 2018). Some children facing trauma at home display hypervigilance and hyperarousal at school, constantly watchful and fearful of danger (Sterne and Poole, 2010). Domestic violence can negatively affect cognitive skills, language development and educational attainment.

Methods

To explore how domestic violence affects children in Kazakhstan, the researchers used a mixed-method approach. This approach allowed the study to combine numerical data from structured questions with more detailed insights from open-ended responses. A survey was used as the primary tool to gather participants' opinions on emotional, social, academic, and physical outcomes experienced by children exposed to domestic violence.

Design: The study followed an exploratory design, as the topic especially within the Kazakhstani context has not been widely investigated through public perceptions. The design helped the researchers identify patterns and commonly observed effects without relying on pre-existing models or assumptions.

Participants and Setting: A total of 31 respondents took part in the study. The group included students, school pupils, and a small number of teachers. Participants were selected through random distribution of the questionnaire across educational settings, giving each individual an equal chance of participation. All responses were collected online to ensure comfort and anonymity.

Instrumentation: A questionnaire was used as the main data collection tool. It included multiple-choice items, 1–5 scale questions, and open-ended prompts to gather information about the emotional, social, academic, and physical effects of domestic violence on children. This structure allowed the researchers to collect both measurable responses and brief explanations

from participants.

Data Analysis: A mixed-method analysis was applied. Quantitative data from the closed questions were examined using basic statistics such as frequencies and percentages. Qualitative data from open-ended responses were reviewed thematically to identify common patterns and repeated ideas. Combining both types of analysis helped provide a clearer understanding of the effects reported by participants.

Limitations

The main limitation of the study was the small number of participants. The sample size of 31 respondents was not sufficiently large to generalize the findings to the wider Kazakhstani population. This limitation is directly related to difficulties in collecting data. Therefore, the overall validity and scale of the study may be limited, suggesting the need for future research involving a larger and more diverse sample.

Results

In order to show the relevance of domestic violence on children in Kazakhstan, a questionnaire was conducted among 31 respondents, including students, pupils, and teachers. Based on the demographic data, 83.9% of respondents were students, 12.9% were pupils, and only 3.2% were teachers, indicating that the results largely reflect students' perspectives.

The first question in the questionnaire was "How common is domestic violence in Kazakhstan?" The results showed that 41.9% believed it is "quite common," 22.6% thought it is "very common," 32.3% considered it "rare," and only 3.2% said it is "very rare." This suggests that most participants perceive domestic violence as a significant social problem.

When asked whether schools provide enough psychological support for children affected by domestic violence, 45.2% answered "Yes," 25.8% said "No," and 29% were unsure. These results indicate that while many trust schools to help, there is still uncertainty about the availability and visibility of psychological support.

Participants rated their agreement with the statement, "Domestic violence has long-term negative effects on children's development," on a scale from 1 (strongly disagree) to 5 (strongly agree). Most responses fell in the middle to higher levels: 14 respondents selected 3, 10 selected 4, 5 selected 2, and 2 selected 5. This shows that most participants recognize the harmful impact of domestic violence on children's development.

Respondents evaluated how likely a child from a violent household is to repeat violent behavior as an adult. Results showed that 48.4% selected scale 4, 25.8% chose scale 3, 12.9% scale 2, 9.7% scale 5, and 3.2% scale 1. These results indicate that participants largely believe childhood exposure to violence increases the likelihood of violent behavior in adulthood.

Participants were asked which steps Kazakhstan should take to reduce the impact of domestic violence on children. According to the data, 29% chose providing more support services, 25.9% prioritized educational programs in schools, 25.8% selected stricter laws and punishments, and 19.4% chose public awareness campaigns. This suggests that practical support services are perceived as the most immediate need.

Respondents emphasize the importance of practical support services, educational programs, and strengthened legal measures as essential interventions.

Question	Main Findings
1. Who were the respondents?	Students – 83.9%; Pupils – 12.9%; Teachers – 3.2%
2. How common is domestic violence in Kazakhstan?	Quite common – 41.9%; Very common – 22.6%; Rare – 32.3%; Very rare – 3.2%
3. Do schools provide enough psychological support for affected children?	Yes – 45.2%; No – 25.8%; Not sure – 29%
4. Long-term effects of domestic violence on children (1–5 scale)	Scale 1 – 0 responses; Scale 2 – 5 responses; Scale 3 – 14 responses; Scale 4 – 10 responses; Scale 5 – 2 responses
5. Likelihood that a child from a violent household will repeat violent behavior (1–5 scale)	Scale 1 – 3.2%; Scale 2 – 12.9%; Scale 3 – 25.8%; Scale 4 – 48.4%; Scale 5 – 9.7%
6. What steps should Kazakhstan take to reduce the impact of domestic violence on children?	More support services – 29%; Educational programs in schools – 25.9%; Stricter laws and punishments – 25.8%; Public awareness campaigns – 19.4%

Discussion

This study set out to identify the main effects of domestic violence on children's emotional, social, academic, and physical development, and the findings show that this aim was successfully achieved. The analysis revealed clear patterns across all four areas: respondents recognized long-term emotional stress, difficulties with peer relationships, academic decline, and noticeable physical symptoms such as fatigue. By gathering these perceptions, the study addressed the initial problem of the lack of local data describing how domestic violence is understood and observed within the Kazakhstani context. The results help fill this gap by showing how community members, especially those in educational settings interpret the impact of violence on children's well-being. Based on the findings, further research could benefit from focusing on children's own experiences rather than only adult observations, as well as exploring which types of school-based or community interventions are most effective in reducing these negative outcomes. Larger samples and interviews with psychologists, teachers, or social workers could also provide a deeper understanding of long-term consequences and support needs.

Conclusion

The study demonstrates that augmented reality technologies are an effective tool for developing oral communication skills in Grade 8 students. Their integration into foreign language instruction enhances motivation, fluency, pronunciation, and communicative confidence. Augmented reality transforms the classroom into an interactive, student-centered environment that supports authentic communication and meaningful language use. Therefore, AR should be considered a valuable component of modern foreign language pedagogy.

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IN SCHOOL PHYSICS IN TEACHING THE SECTION "MECHANICAL AND ELECTROMAGNETIC OSCILLATIONS" THE USE OF DEMONSTRATION PRACTICES

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Abstract

This review article examines the theoretical and methodological foundations of using demonstration experiments in teaching the “Mechanical and Electromagnetic Oscillations” section of school physics. Based on an analysis of domestic and international scientific studies, the role of visual experiments in enhancing students’ cognitive activity, developing conceptual understanding of physical phenomena, and increasing learning motivation is identified. Recent pedagogical research highlights the effectiveness of demonstration experiments in activating the learning process, ensuring compliance with didactic requirements, and improving educational outcomes. The results of the review confirm the relevance of developing a structured set of demonstration experiments for teaching mechanical and electromagnetic oscillations in secondary school physics.

Keywords: mechanical oscillations, electromagnetic oscillations, demonstration experiments, physics teaching methodology, visualization, secondary school.

1. Introduction

In the modern education system, integrating theoretical knowledge with practical experience is one of the key requirements in teaching physics. The “Mechanical and Electromagnetic Oscillations” section of school physics is particularly challenging for students due to its abstract concepts, mathematical relationships, and dynamic processes. As a result, students often experience difficulties in understanding oscillatory phenomena through formulas alone.

Numerous pedagogical studies indicate that the use of demonstration experiments significantly enhances students’ understanding of oscillatory motion. Demonstrating oscillatory processes allows learners to visually observe amplitude, period, frequency, and phase, as well as to identify similarities and differences between mechanical and electromagnetic oscillations. Such an approach contributes to the development of physical thinking and conceptual reasoning.

The purpose of this review article is to analyze domestic and international scientific literature on the use of demonstration experiments in teaching the “Mechanical and Electromagnetic Oscillations” section of school physics, identify key research trends, and substantiate the methodological relevance of this topic.

2. Main Section

2.1. The Role of Demonstration Experiments in Teaching Mechanical Oscillations

Research on teaching mechanical oscillations focuses primarily on pendulums, spring–mass systems, and resonance phenomena. Studies by Orekhov V.A. (2018) and Vlasova T.A. (2019) emphasize the effectiveness of demonstration experiments in explaining mechanical oscillations. The authors demonstrate that experiments involving mathematical pendulums, spring oscillators, and resonance significantly improve students' comprehension of the topic.

These studies highlight that visual experiments enhance students' observational skills, comparative analysis, and ability to draw conclusions. Moreover, analyzing experimental results using graphs helps students better understand the fundamental laws governing oscillatory motion.

2.2. Experimental Approaches to Teaching Electromagnetic Oscillations

The topic of electromagnetic oscillations in the school physics curriculum is closely related to LC circuits, alternating current, and electromagnetic waves. In his work, Isaev S.M. (2021) analyzes the didactic potential of demonstration experiments used in teaching electromagnetic oscillations. The author shows that experiments illustrating electromagnetic induction, charge variation in capacitors, and energy exchange in oscillatory circuits contribute to students' understanding of abstract physical concepts.

The comparative demonstration of mechanical and electromagnetic oscillations is particularly effective. This methodological approach enables students to identify common physical principles across different systems, fostering a deeper conceptual understanding.

2.3. Pedagogical Requirements for Demonstration Experiments

Abilkasymova A.E. (2020) systematizes the pedagogical and didactic requirements for organizing demonstration experiments. According to the author, experiments must be safe, simple, visually clear, and aligned with educational objectives.

Demonstration experiments should not only serve as illustrative tools but also function as methodological instruments that enhance students' cognitive engagement. Therefore, systematizing experiments related to mechanical and electromagnetic oscillations and integrating them effectively into lesson structures is of great importance.

3. Discussion

The analysis of the reviewed literature confirms the significant role of demonstration experiments in teaching the “Mechanical and Electromagnetic Oscillations” section of school physics. Numerous studies show that experiments increase students' interest in physics and promote meaningful understanding of physical laws.

However, the literature review also reveals that demonstration experiments for mechanical and electromagnetic oscillations are often considered separately. The lack of a unified methodological approach that highlights their interconnection indicates the need for comprehensive research in this area. Developing a systematic set of demonstration experiments that integrates both types of oscillations remains an important methodological challenge.

Research Methods

Quantitative Research Methods

Questionnaire/Survey

Collecting quantitative data on students' perception of experiments and their level of understanding of oscillations.

Analysis of Test and Control Work Results

Comparing initial and final indicators to determine the effectiveness of the new methodology.

Statistical Methods

Mean values, percentage indicators, dynamic graphs, and variation analysis.

Experimental Measurements

Recording oscillation parameters such as amplitude, frequency, and period in precise numerical form.

Qualitative Research Methods

Observation

Monitoring students' interest in and participation during demonstration experiments.

Interview

Collecting opinions from students and teachers to obtain qualitative information on the effectiveness of the experiments.

Document Analysis

Analyzing curricula, methodological guides, and scientific literature to establish the theoretical basis.

Pedagogical Experiment (Effectiveness Testing)

Applying the author's set of experiments in lessons and qualitatively evaluating lesson effectiveness.

Summary of the Survey

Quantitative Methods — precise measurement, comparison, statistical evidence.

Qualitative Methods — interpretation, observation, in-depth analysis.

Combining both methods increases the reliability of the research results.

THE ROLE OF DEMONSTRATION EXPERIMENTS IN TEACHING MECHANICAL AND ELECTROMAGNETIC OSCILLATIONS

Students' opinions:

Student 1: "I immediately understood how the oscillation occurs when it was demonstrated experimentally."

Student 2: "Instead of just memorizing the formula, I saw where it comes from through the experiment."

Student 3: "I clearly noticed the difference between mechanical and electromagnetic oscillations."

Student 4: "Explaining complex theories with demonstrations was very effective."

Student 5: "After the experiment, solving problems became easier."

Interpretation and approbation:

1. The survey results showed that demonstration experiments enhance understanding through visualization.
2. Interview data fully correspond to the quantitative results: students highlighted that they learned oscillations better through visual experiments.
3. General conclusion: demonstration experiments facilitate teaching mechanical and electromagnetic oscillations, reduce main difficulties, and increase the effectiveness of the learning process.

Survey results (n=29 students, 2 teachers):

Bar chart as in original slide.

Interpretation and Approbation

1. Survey Results

According to students, demonstration experiments enhance visualization and improve the understanding of oscillations.

2. Interview Data

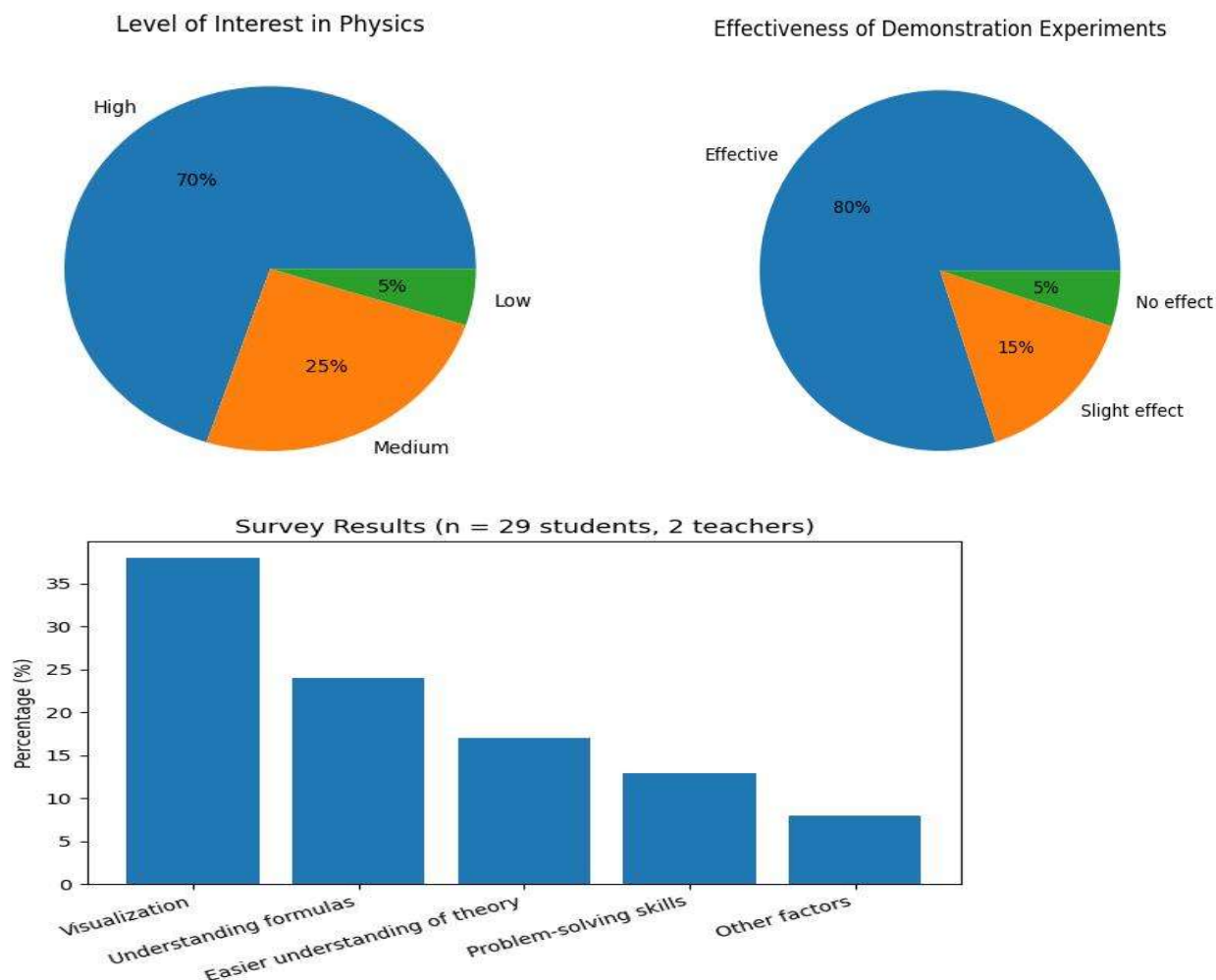
The interview findings are fully consistent with the quantitative results: students noted that they better grasp oscillations through visual experiments.

3. Overall Conclusion

Demonstration experiments help overcome the main difficulties in teaching mechanical and electromagnetic oscillations and increase the effectiveness of the learning process.

Approbation Results (Joint Display)

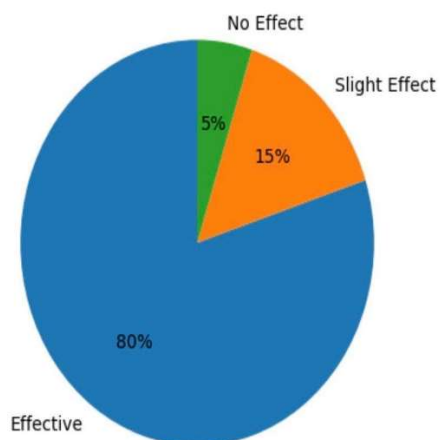
The survey and interview results are presented in a **joint display** format. Charts illustrate the quantitative data, while texts integrate the qualitative data.



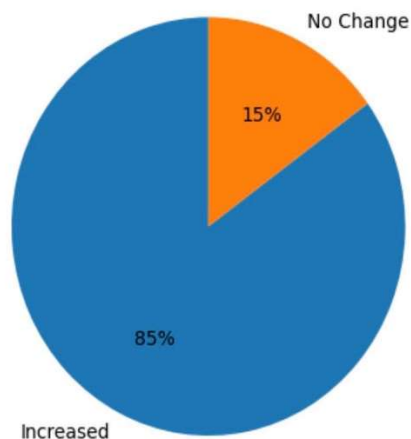
Approbation Results

The results of interviews conducted with students are presented by integrating **quantitative data (charts)** and **qualitative data (coding tables)**.

Effect of Demonstration Experiments on Understanding



Change in Learning Motivation



Research Gaps

Although a number of studies have been conducted on teaching mechanical and electromagnetic oscillations in school physics, the following gaps have been identified:

1) Lack of systematization of demonstration experiments

While many studies emphasize the importance of demonstration experiments, they are presented as isolated examples rather than a coherent system. A comprehensive set of experiments for the oscillations section has not been sufficiently developed.

2) Insufficient methodological guidance

Most studies describe the experiments themselves but do not provide detailed guidance on how to implement them in lessons, including the stages of application and didactic objectives.

3) Weak connection between mechanical and electromagnetic oscillations

Many textbooks and studies treat mechanical and electromagnetic oscillations separately, and their similarities and common principles are not adequately demonstrated through experiments.

4) Limited experimental evidence of demonstration effectiveness

Many works remain theoretical, and the impact of developed experiments on learning outcomes has not been systematically validated through approbation.

Research Findings

The conducted study demonstrated the effectiveness of using demonstration experiments in teaching the “Mechanical and Electromagnetic Oscillations” section in school physics. Demonstration experiments increase students’ interest in the material and facilitate the understanding of abstract concepts through concrete physical phenomena.

During the approbation, the systematic use of experiments was found to enhance students’ cognitive engagement, logical thinking, and metacognitive skills. It also promoted a deeper understanding of the connection between mechanical and electromagnetic oscillations.

Thus, the proposed set of demonstration experiments and their implementation methodology were justified as an effective pedagogical tool that can improve the quality of school physics education.

Recommendations for Future Research

Investigate the long-term effects of demonstration experiments on learning outcomes.

Explore possibilities for integrating digital and virtual experiments with traditional demonstrations.

4. Conclusion

The conducted review demonstrates that the use of demonstration experiments in teaching the “Mechanical and Electromagnetic Oscillations” section of school physics significantly enhances the effectiveness of the learning process. The analyzed studies confirm that visual and well-structured experiments play a crucial role in developing students’ physical thinking, cognitive activity, and learning motivation.

Therefore, the development of a comprehensive set of demonstration experiments for teaching mechanical and electromagnetic oscillations, along with a methodology for their classroom implementation, represents a scientifically and practically relevant direction for modern physics education.

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THE EFFECT OF ANXIETY ON SPEAKING PERFORMANCE IN EFL LEARNERS

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ABSTRACT

This study investigates the effect of anxiety on speaking performance among EFL learners. As many students struggle with nervousness, fear of making mistakes, and low confidence during speaking tasks, anxiety remains one of the major obstacles to effective oral communication. The research collected data through a student survey to understand how learners experience speaking anxiety and how it influences their fluency, pronunciation, and overall performance. The results show that anxiety significantly affects students' ability to speak smoothly, often leading to hesitation, slower speech, and difficulty recalling vocabulary. Many participants reported that anxiety also impacts their pronunciation, making their speech less clear when they feel pressured or afraid of being judged. Despite these challenges, some students noted that supportive classroom environments, preparation time, and peer collaboration helped reduce anxiety and improve their willingness to speak. Overall, the findings suggest that speaking anxiety has a strong impact on EFL learners' speaking performance and should be addressed through targeted instructional support. The paper offers practical recommendations for reducing anxiety in speaking lessons and enhancing learners' communicative confidence.

KEYWORDS: Speaking Anxiety, EFL Learners, Speaking Performance, Fluency, Pronunciation, Affective Factors in Language Learning

INTRODUCTION

In recent years, English language teachers and researchers have increasingly recognized the importance of emotional factors in foreign language learning, particularly anxiety. Speaking anxiety has become a major concern in EFL classrooms because it directly affects students' ability to communicate effectively. Many learners report feeling nervous, afraid of making mistakes, or worried about being evaluated by their peers and teachers when speaking English. As a result, speaking performance often suffers, even when students possess adequate vocabulary and grammar knowledge. The focus of this study is to explore how anxiety influences EFL learners' speaking skills, including fluency, pronunciation, and overall communicative performance.

The growing interest in foreign language anxiety comes from a need to better understand why many students struggle with speaking despite years of instruction. According to Krashen's Affective Filter Hypothesis, emotional variables such as anxiety can block language input and prevent learners from using their existing knowledge effectively. When anxiety levels are high, students may hesitate, forget familiar words, or fail to express themselves clearly. This idea is supported by previous research showing that speaking anxiety negatively affects learners' confidence, processing speed, and willingness to communicate. Understanding how anxiety operates in real classroom situations can help teachers create learning environments that reduce stress and support more successful speaking outcomes.

Although speaking anxiety has been widely discussed in academic literature, it is still not fully addressed in many EFL classrooms. Some teachers may overlook signs of anxiety, while others might assume that nervousness is a natural part of language learning. Traditional classroom methods, such as calling on students unexpectedly or requiring them to speak in front of the whole class may unintentionally increase anxiety levels. Additionally, learners at different proficiency levels may experience anxiety in different ways. Because of these complexities, the impact of anxiety on speaking performance in diverse learning environments remains an area that requires further investigation.

In this study, speaking anxiety is examined as a key factor influencing EFL learners' oral performance. The research investigates how anxiety affects pronunciation, fluency, and confidence, as well as how students perceive their own anxiety during speaking tasks. It also explores the classroom conditions and psychological factors that intensify or reduce speaking anxiety. By analyzing learners' experiences, the study seeks to provide practical insights for teachers who want to create supportive, low-anxiety environments for speaking practice. Therefore, the main research questions guiding this study are:

1. What is the effect of anxiety on EFL learners' speaking performance, including pronunciation, fluency, and overall communication?
2. How do students perceive their own speaking anxiety during English-speaking activities?
3. What classroom-related or personal factors contribute to increased or reduced speaking anxiety among EFL learners?

METHODS

This study employed a quantitative research design to investigate how anxiety affects speaking performance among EFL learners. The main purpose of the research was to identify the level of speaking anxiety among students, determine the situations that trigger this anxiety, and examine how it influences their fluency, pronunciation, and overall oral performance. To collect the required data, a structured online questionnaire was used, which made it possible to gather both numerical information and short descriptive comments from participants.

The research was conducted at a foreign language department where students regularly participate in speaking activities as part of their curriculum. A total of 20 EFL learners took part in the study. Their English proficiency levels ranged from A2 to B2, and they were selected through convenience sampling, as they were already involved in speaking-focused lessons. Participants were aged between 10 and 21, which allowed the researcher to understand how speaking anxiety manifests across different developmental stages of language learning.

The questionnaire, created using Google Forms, consisted of 18 items, combining multiple-choice questions, Likert-scale statements, and short open-ended questions. The closed-ended items asked students about their general level of speaking anxiety, the frequency with which they feel nervous when speaking English, and which aspects of speaking (fluency, vocabulary, pronunciation, grammar accuracy) are most affected by anxiety. The open-ended questions encouraged learners to describe specific situations that make them anxious, the physical or emotional symptoms they experience, and the strategies they use to manage anxiety during speaking tasks.

To analyze the data, descriptive statistics such as percentages and frequency counts were used to summarize quantitative responses. This approach provided a clearer understanding of how anxiety shapes EFL learners' speaking performance.

Overall, this methodological design allowed the researcher to collect comprehensive information about the role of anxiety in speaking situations and to identify the main challenges

learners face when speaking English. The findings from this method offer practical insights into how speaking anxiety can be addressed and reduced in EFL classrooms.

RESULT

Demographic and General Information

The distribution of participants by age is as follows: 10–12 years – 30%, 13–15 years – 42%, 16–18 years – 20%, 19–21 years – 10% (Figure 1). This age range represents learners at different developmental stages, which is important for understanding how anxiety manifests in speaking situations. Learners' English proficiency is a key factor in their speaking anxiety. By proficiency level, the distribution is: Beginner – 10%, Elementary – 20%, Pre-Intermediate – 10%, Intermediate – 25%, Upper-Intermediate – 35%, Advanced – 10% (Figure 2). This shows that participants had varying levels of English proficiency, which may influence their ability to perform shadowing tasks effectively. The gender distribution is: Male – 35%, Female – 65% (Figure 3). This shows a higher proportion of female participants. These demographic details provide context for interpreting the subsequent results.

Levels and Frequency of Speaking Anxiety

The results indicate that speaking anxiety is present among a considerable portion of the participants. A total of 20% of students reported experiencing speaking anxiety regularly during English lessons, while 40% experience it occasionally. Additionally, 15% stated that they feel anxious rarely, and 25% reported feeling no anxiety at all. These findings suggest that although a notable group of learners frequently encounters anxiety when speaking English, a relatively large portion (25%) appears to be comfortable during speaking activities.

How often do you experience anxiety when speaking English in class?

20 ответов

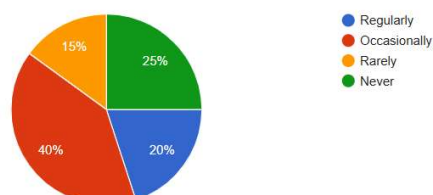


Figure 1

When students were asked about specific situations that trigger anxiety, 45% indicated that they feel most anxious during spontaneous speaking tasks. Meanwhile, 25% reported anxiety during group discussions, 20% during prepared presentations, and 10% during pair work. These results show that unpredictability and lack of preparation are the strongest triggers of speaking anxiety for many learners.

In which speaking situations do you feel the most anxious?

20 ответов

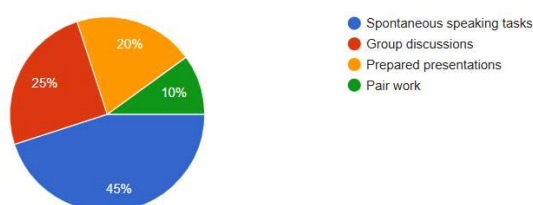


Figure 2

Regarding their general perception of speaking anxiety, 25% of respondents rated their anxiety as very high, 20% as high, and 40% as moderate. Only 15% perceived their anxiety level as low. This distribution demonstrates that more than half of the participants experience moderate to high levels of speaking anxiety in the EFL classroom.



Figure 3

Impact of Anxiety on Speaking Performance

The findings reveal that anxiety affects speaking performance in different ways. A total of 30% of students stated that anxiety significantly reduces their performance, while 15% reported that it moderately reduces their ability to speak. Another 30% noted that it slightly reduces their performance, and 25% said it has little to no effect. Although the intensity varies, the majority of students experience at least some performance decline due to anxiety.

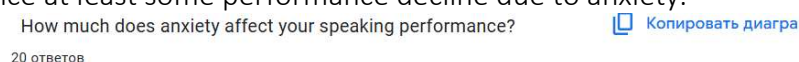


Figure 4

Students were also asked which aspects of speaking are most negatively affected. The highest percentage (42.1%) reported that anxiety influences their pronunciation, making their speech less clear under pressure. This is followed by grammar accuracy (21.1%), fluency (10.5%), vocabulary recall (10.5%), confidence (10.5%), and speaking speed (5.3%). These findings highlight that anxiety interferes with both linguistic accuracy and the emotional components of speaking.

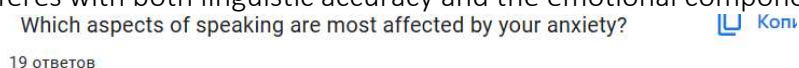


Figure 5

When describing what happens to their speech during anxious moments, 30% said they speak more slowly, 25% noted that their speech becomes unclear, another 25% reported forgetting vocabulary, 10% indicated hesitation, and 10% mentioned that they avoid speaking altogether. These reactions show that anxiety can disrupt both verbal expression and willingness to communicate.

When you feel anxious during speaking tasks, what usually happens?

20 ответов

Копировать

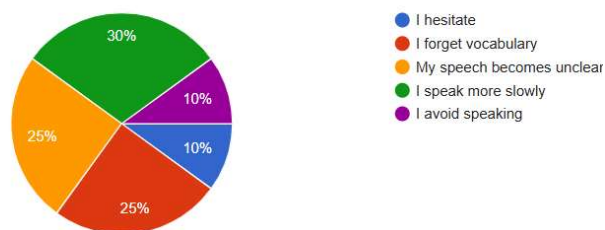


Figure 6

Sources of Anxiety

Participants identified several key sources of speaking anxiety. The most common factor was fear of negative evaluation, chosen by 40% of respondents. This indicates that many learners are concerned about being judged by peers or teachers during speaking activities. Additionally, 30% reported experiencing anxiety due to grammar difficulties, while 20% attributed their anxiety to a lack of vocabulary. Only 10% cited fear of making mistakes as the primary cause. These results show that social pressure and linguistic limitations both play significant roles in shaping learners' emotional responses.

What is the main source of your speaking anxiety?

20 ответов

Копировать

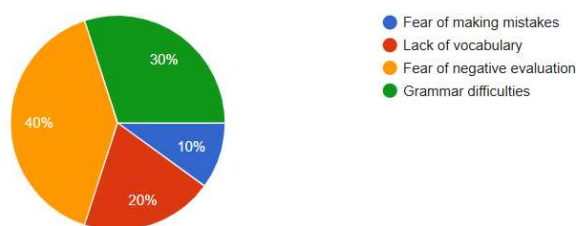


Figure 7

In terms of physical or emotional symptoms, 36.8% reported having a shaking voice, 26.3% experienced sweaty hands, 15.8% mentioned their mind going blank, and 10.5% experienced a fast heartbeat or embarrassment. These symptoms demonstrate that speaking anxiety manifests not only cognitively but also physically, potentially hindering learners' performance further.

What physical or emotional symptoms do you experience when anxious?

19 ответов

Копировать

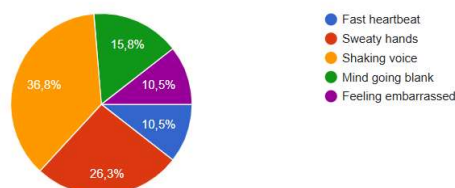


Figure 8

Overall, the findings suggest that speaking anxiety is a significant issue for many EFL learners. While not all students experience high anxiety, a substantial percentage report moderate to strong emotional reactions during speaking tasks. Anxiety affects various aspects of speaking performance—particularly pronunciation, grammar accuracy, and clarity of speech—while unpredictable or spontaneous tasks intensify anxiety levels the most. Students also experience a range of physical and emotional symptoms, and fear of negative evaluation remains the most influential source of anxiety. These results highlight the importance of creating a supportive classroom atmosphere that minimizes stress and promotes confidence during speaking activities.

DISCUSSION

The findings of this study indicate that speaking anxiety remains a significant factor influencing EFL learners' oral performance, particularly in areas such as pronunciation, processing speed, and clarity of speech. Although fewer participants reported experiencing anxiety regularly compared to previous studies, the data still show that a notable percentage of learners face moderate to high anxiety levels during speaking tasks. This supports earlier research suggesting that foreign language anxiety continues to interfere with learners' communicative abilities and overall classroom participation (Krashen, 1985; Murphey, 1995).

In this study, spontaneous speaking tasks emerged as the most anxiety-provoking activity, with 45% of students reporting high discomfort in unpredictable speaking situations. This is consistent with previous work by Lambert (2008), who found that unplanned speaking activities increase cognitive load and reduce learners' ability to produce smooth and coherent speech. The finding that only a minority feel anxious during prepared presentations suggests that controlled, predictable tasks may reduce anxiety by allowing students to rehearse and organize their ideas in advance.

The impact of anxiety on speaking performance was also evident in several areas. A substantial proportion of learners indicated that anxiety affects pronunciation (42.1%), leading to unclear articulation or mispronunciation when speaking under pressure. These findings support Mizuguchi's (2019) argument that anxiety can hinder accurate sound production, as tense facial muscles and fear of mistakes disrupt natural speech patterns. Similarly, challenges related to grammar accuracy (21.1%) and vocabulary recall (10.5%) align with Krashen's (1985) Affective Filter Hypothesis, which proposes that high anxiety interferes with language retrieval and slows down cognitive processing during communication.

Emotional and behavioral reactions reported by students—including slower speech (30%), unclear pronunciation (25%), and forgetting vocabulary (25%)—further reinforce the idea that anxiety can disrupt automaticity in speaking. These reactions mirror Tamai's (1997) findings that anxious learners often lose access to learned language structures, leading to hesitation and breakdowns in communication. Although only 10% reported hesitation and 10% reported avoiding speaking, these behaviors still highlight how anxiety influences learners' willingness to participate in oral tasks.

The sources of anxiety identified in the study also align with previous research. Fear of negative evaluation (40%) was found to be the most influential factor, supporting Bui and Intaraprasert (2018), who argue that learners often worry more about being judged than about linguistic mistakes themselves. Additionally, grammar difficulties (30%) and lack of vocabulary (20%) reflect common linguistic barriers that contribute to anxiety in language classrooms. These combined emotional and linguistic pressures create a challenging environment for learners, particularly those with moderate to low confidence levels.

Despite these challenges, the results show that learners are actively attempting to manage their anxiety. Students reported a range of emotional symptoms—such as shaky voice (36.8%) and sweaty hands (26.3%)—yet they also demonstrated awareness of coping strategies, frequently using preparation and practice to reduce stress. This supports Foote and McDonough (2017), who found that strategic preparation increases students' confidence and reduces anxiety-induced communication breakdowns. The presence of gradual improvement among many learners suggests that consistent speaking practice may lower emotional barriers over time, aligning with Krashen's (1985) claim that affective filters decrease when learners receive positive reinforcement and repeated exposure to communicative tasks.

Based on these findings, several pedagogical implications can be drawn. Teachers should incorporate anxiety-reducing techniques into speaking activities, such as allowing preparation time, providing vocabulary support, and using structured, predictable tasks before spontaneous speaking. Pair and group work may also help lessen fear of negative evaluation by creating a less intimidating environment than whole-class participation. Additionally, regular encouragement, constructive feedback, and opportunities for repeated practice can help learners gradually build confidence and reduce communication apprehension. These recommendations are consistent with earlier studies suggesting that supportive classroom conditions play a central role in decreasing speaking anxiety and improving oral performance.

Overall, the discussion of these findings reinforces existing literature emphasizing the strong relationship between anxiety and speaking performance in EFL settings. At the same time, the study highlights students' growing awareness of anxiety-management strategies and the potential benefits of structured instructional support. Future research should explore long-term interventions and compare anxiety levels across different proficiency groups to further understand how anxiety evolves throughout the language acquisition process.

CONCLUSION

In conclusion, the findings of this study show that anxiety has a significant impact on EFL students' speaking performance. Many learners reported that anxiety reduces their fluency, slows down their speech, and makes it difficult to recall vocabulary during speaking tasks. The results also demonstrated that anxiety negatively affects pronunciation, as nervousness often leads to unclear articulation and loss of natural intonation. These findings suggest that speaking anxiety is a major barrier that prevents students from fully demonstrating their actual language abilities, even when they know the required vocabulary and grammar.

The study also revealed that students are highly aware of their own anxiety and how it influences their performance. Many participants expressed that speaking tasks, especially spontaneous ones, cause stress and fear of negative evaluation. However, learners also noted that supportive classroom environments, preparation time, and opportunities to practice with peers helped them feel more comfortable. This indicates that anxiety can be reduced when teachers implement strategies that make speaking activities more manageable and less threatening.

Overall, this study demonstrates that speaking anxiety plays a central role in shaping EFL learners' performance and confidence. Teachers should consider incorporating anxiety-reducing techniques such as pair work, guided preparation, and positive feedback to help students manage their emotional barriers. Future research could explore long-term interventions for lowering anxiety or investigate how digital tools and interactive tasks influence learners' emotional responses. By addressing anxiety effectively, educators can help students become more confident, fluent, and successful English speakers.

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Beyond the Classroom: Professional Growth through International Programs and Educational Projects

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Abstract

This article explores how teachers' professional development through international programs and educational projects extends beyond personal growth and directly influences students' learning experiences. Drawing on classroom practice and documented project-based lessons, the paper demonstrates how participation in global initiatives fosters student engagement, motivation, intercultural awareness and emotional wellbeing. The findings highlight that when innovative methodologies and project-based learning are integrated into everyday teaching, students become active participants in learning rather than passive recipients of textbook content. The article concludes that teaching beyond the classroom empowers students with academic skills, global awareness and positive attitudes toward learning, emphasizing the importance of continuous professional development in modern education.

1. Introduction

In contemporary education, teaching is no longer confined to classroom walls or limited to textbook-based instruction. Teachers are increasingly expected to act as facilitators, mentors and lifelong learners who continuously develop professionally. Participation in international programs, educational projects and professional development initiatives has become a powerful means of enriching teaching practice.

My involvement in international programs and collaborative educational projects has significantly shaped my professional identity. More importantly, this growth has had a visible and lasting impact on the students I teach at school. By integrating innovative methodologies, global themes and project-based learning into everyday lessons, students experienced learning as meaningful, engaging and connected to real life.

2. Professional Growth through International Programs

Participation in international initiatives such as the **Global Schools Program**, the **MOSAIC Project (Maximizing Opportunities for Shared Awareness and Intercultural Competence for Novice Teachers)**, and multiple **eTwinning projects** provided opportunities to explore learner-centered approaches, intercultural competence, sustainability education and social-emotional learning.

The MOSAIC Project, which brings together English language teachers from **Türkiye, Ukraine, and Georgia**, focuses on developing intercultural awareness, reflective practice and inclusive teaching. The knowledge gained through this program strengthened my ability to create lessons that value diversity, respect and open dialogue. These principles were directly transferred to classroom practice, influencing both teaching strategies and classroom culture.

3. Educational Projects and Classroom Implementation

My involvement in **eTwinning projects** such as *"The Truth and Knowledge Make Us Free," "EcoKids for a Greener Future," "STEAM for Life," "Exploring Cultural Heritage,"* and *"World Cultural*

Mosaic” allowed students to engage in interdisciplinary, project-based learning while using English as a tool for communication.

Through these projects, students participated in:

- collaborative group work,
- creative writing and presentations,
- discussions on global and environmental issues,
- STEAM-related problem-solving activities,
- cultural exploration and reflection.

Learning extended beyond coursebook exercises and became an active, engaging process connected to real-world topics.

4. Documented Lessons as Evidence of Student Impact

To document classroom practice and student engagement, several project-based lessons were recorded. These videos demonstrate how students actively participated in projects, expressed joy and enthusiasm, and showed eagerness to learn through creative and collaborative activities rather than focusing solely on textbook tasks.

Video evidence of conducted lessons and project activities:

- <https://youtu.be/rEYQrc2RYS4>
- https://youtu.be/cZzpMob_Akc
- <https://youtu.be/BTrBtLa9H9s>
- <https://youtu.be/viXGDSfp9Q>
- https://youtu.be/HFGI_HJ9aAA
- <https://youtu.be/LMPkfopYq7k>
- <https://youtu.be/D0CxcRAAoA>
- <https://youtu.be/o8WdithtHAU>
- <https://youtu.be/cdr6kla1Cl8>

These lessons show students working collaboratively, participating confidently and demonstrating positive emotional responses to learning. Even learners who previously showed low motivation or hesitation became more willing to speak, share ideas and take responsibility for tasks.

5. Impact on Student Engagement and Motivation

One of the most significant outcomes of project-based learning was increased student engagement. When students worked on meaningful tasks connected to global issues, culture, environment and creativity, they became more motivated and involved. Learning was no longer perceived as a routine obligation but as an enjoyable and purposeful activity.

Students demonstrated:

- higher participation rates,
- improved classroom behavior,
- greater willingness to communicate in English,
- increased curiosity and initiative.

6. Development of Skills and Wellbeing

Beyond academic progress, international projects contributed to students’ personal development. Learners improved their communication, collaboration, critical thinking, and creativity skills. Intercultural projects fostered tolerance, empathy and respect for diversity, while environmental projects strengthened responsibility and awareness.

Additionally, approaches inspired by social and emotional learning created a supportive classroom atmosphere. Students felt safe to make mistakes, express opinions and support one another. This positive emotional environment played a crucial role in enhancing confidence and learning outcomes.

7. Conclusion

Professional growth through international programs and educational projects extends far beyond the teacher's personal development. It directly shapes classroom practice and has a profound impact on students' motivation, skills, wellbeing and worldview. The documented lessons and student responses confirm that project-based and globally oriented education transforms learning into an engaging, meaningful experience.

Teaching beyond the classroom means preparing students not only for exams, but for life—helping them become confident learners, critical thinkers and responsible global citizens.

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THE SCIENTIFIC TALKS OF MANIFESTATION OF KEY ISSUE ASPECTS OF AGE DISCRIMINATION IN ACADEMIC SCIENCE: STRUCTURAL CONSTRAINTS OF THE ACADEMIC CAREER PYRAMID AND SOCIOECONOMIC CONSEQUENCES

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Abstract:

Contemporary academic science faces a systemic crisis characterized by a severe imbalance between the abundant supply of PhD graduates and postdoctoral researchers and the scarcity of independent Principal Investigator (PI) or Group Leader positions. This pyramidal structure of academic careers creates an intensely competitive environment that is further exacerbated by age-restrictive hiring policies prevalent in numerous institutions worldwide.

This study analyzes career trajectory data from 2,284 researchers (1997-2020 EMBL cohorts) and reveals that only 27.8% achieve independent PI positions, with this percentage declining in recent cohorts. Statistical evidence demonstrates that merely 17-21% of postdoctoral researchers secure tenure-track positions, and approximately 3% ultimately attain full professorship. The disproportionate ratio between PhD/postdoc positions and available PI/Group Leader roles creates what scholars term the "postdoc queue"—a precarious employment landscape characterized by short-term contracts and profound career uncertainty.

Age discrimination manifests both formally and informally across global academic systems. In numerous countries, particularly throughout Asia and parts of Europe, explicit or implicit age limits (typically 35 years or younger) govern eligibility for junior faculty and independent researcher positions. These age barriers systematically exclude experienced scientists who have invested years in postdoctoral training, effectively squandering accumulated expertise and institutional knowledge. Survey data indicates that 92% of German academic staff under 45 without full professorships hold fixed-term contracts, with 84% employed on contracts shorter than 18 months. The average time from PhD completion to first PI position has increased from 5.2 to 6.1 years for recent cohorts, intensifying the temporal pressure imposed by age restrictions.

This structural dysfunction severely impedes scientific progress through multiple mechanisms: (1) premature attrition of talented researchers from academia; (2) systematic loss of highly qualified personnel at peak productive capacity; (3) suppression of innovative, high-risk research projects requiring long-term commitment; (4) diminished overall scientific productivity and output quality. Empirical evidence reveals that 73% of postdoctoral researchers experience work-related stress, while 67% work beyond their contracted 40-hour weekly commitments. Furthermore, 30% report experiencing antisocial workplace behavior, with 12% observing discrimination monthly. These conditions disproportionately affect women, international researchers, and individuals with caregiving responsibilities, thereby reducing diversity and perpetuating inequalities within the scientific workforce.

The socioeconomic implications of underutilizing scientific talent are substantial and quantifiable. Economic analyses demonstrate that research and development (R&D) investments directly correlate with productivity growth and GDP expansion. A 20% reduction in federal R&D funding demonstrably constrains GDP growth, while workforce disengagement cost the global economy an estimated \$438 billion in lost productivity in 2024. By systematically excluding mature scientists through age discrimination and creating unsustainable career pathways, society forfeits the opportunity to leverage highly trained intellectual capital for innovation, technological advancement, and economic progress. The inefficient allocation of human resources in academic science represents not merely an ethical failure but a significant economic liability with measurable negative impacts on national competitiveness and societal advancement.

This article presents comprehensive recommendations for structural reform: (1) elimination of age-discriminatory barriers in academic hiring and promotion; (2) diversification of academic career pathways with legitimate recognition of alternative trajectories beyond the traditional PI track; (3) implementation of stable, long-term funding mechanisms to replace precarious short-term contracts; (4) adoption of intersectional approaches to diversity and inclusion policies addressing multiple dimensions of inequality. Only through systemic transformation can the scientific community harness its full human potential, foster sustainable careers, and maximize societal benefit from investments in scientific training and research infrastructure.

Keywords:

Age discrimination, academic career pyramid, postdoctoral researchers, scientific workforce, tenure-track positions, career bottleneck, structural barriers, research productivity, economic impact, precarious employment, early career researchers, principal investigator positions, scientific talent retention, research and development, career sustainability

Introduction:

The global academic system faces an unprecedented structural crisis that threatens the sustainability of scientific careers and, consequently, the advancement of human knowledge. At the heart of this crisis lies a fundamental mathematical imbalance: the number of individuals pursuing academic research careers vastly exceeds the number of permanent positions available (Cyranoski et al., 2011; Schillebeeckx et al., 2013). This pyramidal structure, wherein many enter at the base as PhD students and postdoctoral researchers but only a few reach the apex as independent Principal Investigators (PIs) or tenured professors, has created what economists describe as a "labor market failure" within academia (Stephan, 2012). The problem is further compounded by age-restrictive policies that place arbitrary temporal limits on career progression, effectively excluding experienced scientists who have dedicated years to postdoctoral training and research development.

Age discrimination in academic hiring represents one of the most insidious yet under-discussed barriers to scientific progress. While overt discrimination based on age is illegal in many jurisdictions, academic institutions worldwide have implemented formal and informal age limits for early-career positions, typically setting thresholds at 35 years or younger (Bahr et al., 2021). These restrictions appear particularly prevalent in Asian academic systems and certain European contexts, where funding agencies and universities explicitly state maximum ages for fellowship applications, assistant professorships, and independent research group leader positions (Liu et al., 2019; Huang et al., 2020). The rationale typically offered for such policies invokes the need for "fresh perspectives," "innovation through youth," and "efficient turnover" of scientific personnel (BMBF, 2021). However, empirical evidence contradicts these assumptions, demonstrating that research productivity, innovation capacity, and scientific impact do not correlate negatively with researcher age (Jones and Weinberg, 2011; Murayama et al., 2015).

The consequences of this structural dysfunction extend far beyond individual career disappointment. When highly trained scientists are systematically excluded from contributing their expertise due to arbitrary age barriers, society loses the return on substantial investments in scientific education and training (Stephan, 2012; Larson et al., 2014). Each PhD typically requires 4-6 years of intensive training, representing significant public and private financial investment, not to mention the intellectual capital developed through years of specialized study (Cyranoski et al., 2011). Postdoctoral positions, intended as brief training periods, have evolved into extended holding patterns lasting 4-7 years or longer, during which researchers produce substantial scientific output while occupying precarious employment positions (McConnell et al., 2018; Kahn and Ginther, 2017). When these highly productive individuals are subsequently forced out of

academia due to age restrictions or lack of permanent positions, the scientific enterprise suffers an incalculable loss of talent, experience, and potential innovation.

Recent quantitative analyses have begun to illuminate the scale of this crisis. Data from the European Molecular Biology Laboratory (EMBL) tracking 2,284 researchers who completed PhDs or postdocs between 1997 and 2020 revealed that only 27.8% ultimately secured PI positions (Woolston et al., 2022). More alarmingly, this percentage has declined for recent cohorts, suggesting the situation is worsening rather than improving. In the United States, analyses indicate that merely 17-21% of postdoctoral researchers obtain tenure-track faculty positions in biomedical sciences, with an estimated 3% eventually achieving full professorship (Larson et al., 2014; Ghaffarzadegan et al., 2015). These statistics paint a sobering picture: for every 100 individuals who embark on the postdoctoral pathway with aspirations of academic research careers, fewer than 20 will achieve even initial independent positions, and only 3 will reach senior academic ranks.

The temporal dynamics of academic career progression have shifted significantly over recent decades, intensifying the pressure created by age-restrictive policies. The average time from PhD completion to first PI position has increased from 5.2 years for earlier cohorts to 6.1 years for more recent graduates (Woolston et al., 2022). This extension reflects multiple factors: increased competition for limited positions, expectations for more extensive publication records, requirements for multiple postdoctoral appointments, and the growing complexity of establishing independent research programs (Sauermann and Roach, 2016; Kahn and Ginther, 2017). When coupled with age limits of 35 years for junior faculty positions, these extended timelines create impossible mathematical constraints. A researcher completing a PhD at age 28-30 (already later than historical norms due to extended undergraduate and graduate training) who then undertakes the now-standard 5-7 years of postdoctoral work will approach or exceed age limits precisely when they have finally developed the expertise, publication record, and professional networks necessary for competitive PI applications.

The precarious nature of postdoctoral employment exacerbates these structural problems. In Germany, 92% of academic staff under age 45 without full professorships hold fixed-term contracts, with 84% employed on contracts lasting less than 18 months (Konsortium Bundesbericht Wissenschaftlicher Nachwuchs, 2021; Bahr et al., 2021). This pattern of serial short-term employment creates profound uncertainty that affects not only career planning but also personal life decisions regarding family formation, geographic stability, and long-term financial security (Woolley and Valian, 2018). The German Wissenschaftszeitvertragsgesetz (WissZeitVG) permits up to 12 years of temporary employment in academia, but rather than providing security, this framework has enabled systematic exploitation of early-career researchers through successive short-term contracts (Kubon, 2021; Rahal et al., 2023).

International comparisons reveal that while the fundamental pyramidal structure characterizes academic systems globally, the severity of precarity varies significantly across national contexts. The Netherlands reports approximately 60% of academic staff on fixed-term contracts, while France, the United Kingdom, and Sweden maintain rates between 30-35% (Kreckel and Zimmermann, 2014; Rahal et al., 2023). In contrast, Germany's 92% rate for early-career researchers represents an extreme manifestation of employment insecurity. These international variations demonstrate that alternative structural models exist and that high rates of precarious employment are policy choices rather than inevitable features of academic organization. However, even countries with relatively better employment conditions face the fundamental mismatch between PhD/postdoc positions and permanent academic roles, suggesting that employment contract structures alone cannot resolve the deeper imbalance.

Age discrimination manifests through multiple mechanisms beyond explicit age limits in job advertisements. Implicit biases pervade evaluation committees, where youth is often

unconsciously associated with innovation, adaptability, and potential, while maturity may be coded as rigidity, obsolescence, or limited remaining career productivity (Zacher and Gielnik, 2014; North and Fiske, 2015). Grant funding agencies frequently emphasize "early career" researchers in fellowship programs, with definitions of "early career" that become increasingly difficult to satisfy as time from PhD completion extends (Graves et al., 2011). The proliferation of "young investigator awards," "emerging leader" prizes, and similar age-stratified recognition systems, while intended to support career development, inadvertently reinforces age-based hierarchies and devalues the contributions of more experienced non-tenured researchers (Laudel and Gläser, 2008).

The rhetoric surrounding academic career structures often invokes the necessity of "turnover" to prevent "clogging the system" and to ensure continuous influx of "fresh ideas" (BMBF, 2021). This framing reveals fundamental assumptions about the relationship between age, innovation, and scientific contribution that deserve critical examination. Historical analysis of major scientific breakthroughs demonstrates no consistent age pattern; transformative discoveries emerge from researchers at all career stages (Jones and Weinberg, 2011). Moreover, the emphasis on turnover obscures the substantial costs associated with forcing experienced researchers out of the system: loss of accumulated tacit knowledge, disruption of ongoing research programs, waste of training investments, and the psychological toll on individuals who have dedicated decades to scientific careers only to face mandatory exit (Laudel and Gläser, 2008; McConnell et al., 2018).

The diversity implications of age-restrictive policies compound their deleterious effects. Age barriers disproportionately impact certain demographic groups, creating intersectional disadvantages that undermine efforts toward inclusive science (Crenshaw, 1989; Kozlowski et al., 2022). Women who have taken parental leave or temporarily reduced research intensity for caregiving responsibilities find themselves at a temporal disadvantage relative to male peers, making age limits particularly exclusionary (Llorens et al., 2021).

International researchers face additional temporal costs associated with visa processes, credential recognition, and language acquisition, placing them at further disadvantage under age-restrictive regimes (Woolley and Valian, 2018). Individuals from disadvantaged socioeconomic backgrounds who may have taken longer pathways to PhD completion due to financial constraints, family obligations, or delayed access to educational opportunities are systematically excluded by policies that privilege traditional, uninterrupted career trajectories (Morgan et al., 2022). Thus, age discrimination in academia intersects with and amplifies other forms of structural inequality, undermining diversity initiatives and perpetuating homogeneity within the scientific workforce.

The psychological and health consequences of precarious academic employment and age-related career pressure have received increasing empirical attention. Survey data from postdoctoral researchers reveal alarming rates of work-related stress, anxiety, and depression (Evans et al., 2018; Levecque et al., 2017). Among Max Planck Society postdocs, 73% reported being bothered by work stress, and those working more than 50 hours weekly showed significantly elevated symptoms of depression and anxiety (Russell et al., 2023). These mental health challenges stem not merely from heavy workloads but fundamentally from employment uncertainty, perpetual competition, and awareness that despite extraordinary effort and qualification, permanent academic positions remain statistically unlikely (Woolston, 2019). The knowledge that age limits impose arbitrary deadlines intensifies this pressure, creating a psychological countdown that exacerbates stress and potentially leads to burnout or premature departure from science (Guthrie et al., 2017).

The concept of "brain drain" typically refers to international migration of talent from developing to developed nations, but academia experiences an internal brain drain as brilliant scientists exit the system due to unsustainable career structures and age barriers (Franzoni et al., 2012). Surveys consistently demonstrate that 70-75% of postdoctoral researchers aspire to academic research

careers at the beginning of their postdocs, yet the majority will ultimately pursue alternative paths, often not by choice but by necessity (Sauermann and Roach, 2012; Gibbs et al., 2015). This represents a massive loss of scientific potential, as individuals who have demonstrated research aptitude, acquired specialized expertise, and developed innovative research programs are forced to redirect their talents elsewhere. While alternative careers in industry, government, or other sectors certainly benefit from this influx of PhD-trained personnel, society loses the specific contributions these individuals would have made to basic research, education, and the advancement of fundamental knowledge (Stephan, 2012).

Economic analyses of research and development (R&D) investments consistently demonstrate strong positive relationships between scientific research activity and economic growth, productivity gains, and technological innovation (Jones and Summers, 1991; Romer, 1990). The return on investment in basic research manifests over extended time horizons through mechanisms including direct technological applications, human capital formation, and expansion of the knowledge base that enables future innovation (Salter and Martin, 2001).

When academic systems systematically underutilize trained scientific talent due to structural barriers and age discrimination, these potential returns are diminished or lost entirely. Recent estimates suggest that a 20% reduction in federal R&D funding could significantly constrain GDP growth, demonstrating the economic sensitivity to scientific investment levels (ITIF, 2025). The inefficiency inherent in training large cohorts of PhDs and postdocs only to exclude most from productive research careers represents both a waste of educational resources and a foregone opportunity for economic advancement through scientific discovery and innovation.

The COVID-19 pandemic temporarily highlighted the critical importance of scientific expertise and revealed some of the structural vulnerabilities in academic research systems. The rapid development of vaccines and therapeutic approaches depended on decades of basic research in immunology, virology, and molecular biology, much of it conducted by researchers in precarious early-career positions (Corbett et al., 2020). However, the pandemic also exacerbated existing career challenges for early-career researchers through laboratory closures, research disruptions, and hiring freezes, further extending the time to independence and intensifying competition for even scarcer positions (Myers et al., 2020). The crisis thus simultaneously demonstrated the societal value of sustained scientific research capacity while worsening the structural conditions that threaten that capacity's long-term sustainability.

Comparative analyses across scientific disciplines reveal important variations in career structures and outcomes. Fields such as computer science and engineering often offer more abundant alternative career pathways in industry, potentially reducing the severity of the academic bottleneck (Roach and Sauermann, 2010). However, this greater industrial demand may also contribute to academic hiring challenges, as universities compete with well-resourced technology companies for talent. In contrast, disciplines such as ecology, evolutionary biology, and certain humanities fields lack extensive non-academic research sectors, making the scarcity of academic positions even more consequential (Sauermann and Roach, 2012). Nevertheless, the fundamental pyramidal structure persists across disciplines, suggesting that the problem transcends field-specific factors and reflects systemic features of academic organization.

The publish-or-perish culture of contemporary academia interacts problematically with age restrictions and career precarity. Early-career researchers face intense pressure to accumulate publications in high-impact journals to remain competitive for scarce permanent positions (Müller and de Rijcke, 2017). This pressure can incentivize strategic research choices prioritizing publishability over innovation, incremental studies over risky but potentially transformative investigations, and rapid output over methodological rigor (Smaldino and McElreath, 2016). Moreover, the emphasis on individual publication metrics disadvantages collaborative team science and interdisciplinary research that may not fit conventional publication patterns (Larivière

et al., 2015). When coupled with temporal constraints imposed by fixed-term contracts and age limits, these publication pressures can distort research priorities and potentially compromise scientific quality in favor of quantity and speed.

Gender disparities in academic career outcomes represent a particularly well-documented manifestation of structural inequality that intersects with age-related barriers. Despite women now earning approximately half of STEM PhDs in many countries, they remain dramatically underrepresented at senior academic levels (Ceci et al., 2014; Huang et al., 2020). The EMBL data analysis revealed that male alumni were significantly more likely than female alumni to attain PI positions, consistent with extensive literature documenting the "leaky pipeline" phenomenon (Woolston et al., 2022; Blickenstaff, 2005). This attrition occurs not due to differential ability or productivity but through accumulated disadvantage resulting from implicit bias, inadequate parental leave and childcare support, sexual harassment, and professional networks that exclude women (Llorens et al., 2021; Cech and Blair-Loy, 2019).

Age restrictions particularly disadvantage women because academic career timelines intersect with biological and social timelines for family formation. The peak years for establishing independent research careers (late 20s to mid-30s) coincide with peak fertility years and typical ages for childbearing (Mason et al., 2013). Women who take parental leave or temporarily reduce research intensity face temporal delays that, while seemingly modest individually, become critical under age-restrictive policies (Antecol et al., 2018). The result is a double bind: pursue career advancement during prime reproductive years at the cost of delaying or forgoing parenthood, or prioritize family formation at the cost of jeopardizing career prospects by aging beyond eligibility thresholds. Men face fewer such constraints due to both biological differences and persistent gender inequality in domestic labor and childcare responsibilities (Cech and Blair-Loy, 2019). Age-neutral policies and evaluation criteria that assess career stage rather than chronological age represent essential reforms for reducing gender disparities in academic advancement.

International mobility, while often presented as an opportunity for scientific exchange and career development, can also function as a barrier when coupled with age restrictions and precarious employment. Many early-career researchers undertake multiple international postdoctoral positions, motivated by the pursuit of training with specific research groups, response to limited opportunities in home countries, or expectations that international experience enhances competitiveness (Franzoni et al., 2012). However, such mobility imposes significant costs: disruption of personal relationships, separation from family and social support networks, challenges of repeated cultural and linguistic adaptation, and obstacles to long-term planning (Ackers, 2005). For researchers with partners or families, coordinating dual careers across international moves becomes increasingly difficult, potentially forcing impossible choices between personal relationships and professional advancement (Grigolo and Aulenbacher, 2020). Age restrictions exacerbate these challenges by creating rigid deadlines that may not accommodate the additional time required for international transitions and establishment in new institutional contexts.

The rhetoric of "excellence" pervades academic discourse, ostensibly serving as the meritocratic criterion by which candidates are evaluated for limited positions (Moore et al., 2017). However, critical analyses reveal that excellence functions as a socially constructed concept shaped by implicit assumptions about what constitutes valuable scholarship, who can be recognized as excellent, and what career trajectories merit reward (van den Brink and Benschop, 2012).

Age biases embed themselves within excellence frameworks when youth becomes implicitly associated with innovation and potential, while experience is devalued or seen as indicative of diminished capacity (Zacher and Gielnik, 2014). Moreover, the cumulative advantage processes that characterize academic careers mean that small early differences in opportunity, mentorship, or recognition compound over time, creating disparities that reflect initial advantages rather than

underlying ability (Merton, 1968; DiPrete and Eirich, 2006). Thus, systems ostensibly selecting for excellence may actually reproduce existing privilege and exclude talented individuals whose career paths deviated from narrow, privileged norms.

Institutional prestige hierarchies further complicate academic career structures and interact with age-related barriers in complex ways. Research demonstrates that academic hiring exhibits strong prestige preferences, with faculty positions at highly ranked institutions predominantly filled by PhDs from a small number of elite universities (Clauset et al., 2015; Wapman et al., 2022). This prestige sorting creates differential career trajectories: graduates of elite programs access better postdoctoral opportunities, more extensive professional networks, greater resources, and enhanced visibility, all of which increase likelihood of eventual permanent positions (Burris, 2004). For individuals from less prestigious institutions, compensating for this prestige disadvantage typically requires additional publications, extended postdoctoral periods, and exceptional research achievements—precisely the strategies that extend time to independence and increase vulnerability to age restrictions. The interaction between prestige hierarchies and age barriers thus reinforces stratification within the scientific workforce.

The concept of "academic citizenship" or service contributions represents an increasingly important yet often undervalued dimension of scholarly work (Macfarlane, 2007). Early-career researchers on temporary contracts face strategic dilemmas regarding service commitments: substantial service contributions to departments, professional societies, and the broader research enterprise are expected for faculty positions, yet time devoted to service detracts from research and publication activity that constitute the primary evaluation criteria (Guarino and Borden, 2017). Women and underrepresented minorities often face disproportionate service burdens through requests to serve on diversity committees, mentor students from similar backgrounds, and provide representative presence in various forums (Jiménez et al., 2019). Under age-restrictive and time-pressured career systems, these service expectations create additional disadvantages for already marginalized groups, as time invested in valuable service work may delay research productivity and thus jeopardize eligibility for positions with age limits.

The rise of research assessment frameworks and quantitative metrics in academic evaluation has transformed career dynamics over recent decades (Hicks et al., 2015). Journal impact factors, h-indices, citation counts, and various algorithmic measures of research "impact" now play substantial roles in hiring, promotion, and funding decisions (McKiernan et al., 2019). While proponents argue such metrics provide objective, comparable information across candidates, critics note numerous problems: gaming and strategic behavior, bias toward established fields and research paradigms, disadvantaging of interdisciplinary and collaborative work, and failure to capture diverse forms of scholarly contribution (Curry et al., 2020; Moher et al., 2018). For early-career researchers facing age restrictions, metric-driven evaluation intensifies pressure to accumulate quantifiable indicators rapidly, potentially at the expense of research quality, innovation, and intellectual risk-taking.

Alternative academic career structures have been proposed and, in some contexts, implemented to address the pyramidal bottleneck and associated problems. These include research track positions that provide stable employment for research specialists without independent PI responsibilities, teaching-focused faculty roles, research support positions in core facilities and research infrastructure, and hybrid models combining university and non-university employment (Hayter and Parker, 2019; Åkerlind, 2005). However, such alternatives face challenges of legitimacy and status within systems that traditionally privileged the independent PI model as the apex of academic achievement (Laudel and Gläser, 2008). Without cultural transformation that genuinely values diverse contributions to the scientific enterprise, alternative career tracks risk becoming devalued "consolation prizes" rather than respected pathways. Moreover, creating substantial numbers of stable research track positions requires sustained institutional

commitment and funding mechanisms that diverge from the current reliance on project-based grants channeled through PI-led groups.

National and institutional policies regarding academic careers reflect broader societal values and priorities. Some systems emphasize international competitiveness and rapid innovation, implementing high turnover and intensive competition as mechanisms intended to maintain dynamism (Jonkers and Zacharewicz, 2016). Other systems prioritize employment stability and long-term capacity building, providing earlier access to permanent positions but potentially with more modest resource levels (Kreckel and Zimmermann, 2014). The German debate sparked by the #IchBinHanna campaign exemplifies tensions between these models, with early-career researchers organizing to demand reforms to the *Wissenschaftszeitvertragsgesetz* and improved employment conditions (Bahr et al., 2021; Dirnagl, 2022). Such grassroots movements demonstrate growing recognition that current structures are unsustainable and that collective action may be necessary to compel institutional change.

The global dimensions of scientific labor markets create additional complexities. Scientists increasingly compete internationally for positions, with talent flowing toward institutions and countries offering better opportunities, resources, and working conditions (Franzoni et al., 2012; Laudel, 2005). This mobility can benefit individuals and facilitate knowledge diffusion, but it also raises equity concerns about brain drain from less resourced contexts and about the experiences of migrant researchers who may face visa precarity, discrimination, and family separation (Jöns, 2011). Age restrictions in destination countries can effectively exclude international candidates who faced longer pathways to credentials due to contexts in their origin countries, thereby limiting the diversity benefits of international recruitment. Moreover, the COVID-19 pandemic revealed vulnerabilities in international scientific mobility through travel restrictions and border closures, prompting reconsideration of over-reliance on international circulation as a career necessity (Woolston, 2021).

Funding structures fundamentally shape academic career dynamics and represent crucial targets for reform. The predominant model of project-based competitive grants creates several problems: high transaction costs of proposal writing and review processes, funding uncertainty that hampers long-term planning, risk aversion as investigators avoid controversial or innovative projects that might not receive funding, and perverse incentives to promise more than can be delivered within project timelines (Gläser and Laudel, 2016).

For early-career researchers, dependence on PI-held grants creates precarious employment tied to renewal of specific projects rather than stable institutional positions (Åkerlind, 2005). Alternative models emphasize core institutional funding for long-term research capacity, with competitive project grants supplementing rather than constituting the primary support mechanism (Lepori et al., 2007). While political and fiscal constraints complicate transitions toward more stable funding models, recognition is growing that current approaches impose substantial inefficiencies and threaten research sustainability.

The relationship between teaching and research in academic careers has shifted over recent decades, with implications for both faculty workloads and career pathways. The research-intensive university model prioritizes research productivity in hiring and promotion decisions, often treating teaching as a secondary obligation (Fairweather, 2005). This creates several problems: underinvestment in pedagogical development, exploitation of contingent teaching labor, and artificial separation of research and teaching that contradicts the integration valued in liberal education traditions (Macfarlane, 2011). For early-career researchers, the predominant emphasis on research productivity means that teaching experience and pedagogical skill development receive minimal weight in competitive evaluations, despite their importance for faculty roles that include substantial teaching responsibilities (Boman, 2013). Age restrictions and

career timelines interact with teaching expectations in complex ways, as time devoted to teaching necessarily reduces research output, potentially delaying career progression.

Interdisciplinary and transdisciplinary research approaches represent increasingly emphasized priorities in science policy and funding, motivated by recognition that many pressing societal challenges require integration across traditional disciplinary boundaries (National Academy of Sciences, 2005; Ledford, 2015). However, academic career structures often disadvantage interdisciplinary researchers through disciplinary hiring and evaluation processes, publication in less established interdisciplinary journals potentially perceived as lower prestige, difficulties establishing disciplinary "home" departments, and mentorship gaps when working across fields (Rhoten and Parker, 2004; Lyall and Meagher, 2012). For early-career researchers navigating already challenging career landscapes, the additional risks associated with interdisciplinary research may discourage precisely the boundary-crossing scholarship that funding agencies claim to prioritize. Age restrictions compound these challenges, as developing expertise spanning multiple fields typically requires extended training periods incompatible with rigid career timelines.

Open science movements advocating for transparency, data sharing, preregistration, and replication represent important efforts to improve research rigor and credibility (Munafò et al., 2017; Nosek et al., 2015). However, implementing open science practices often requires additional time and effort: preparing datasets for public sharing, writing detailed protocols and pre-analysis plans, conducting replication studies that may not lead to novel publications, and engaging in time-consuming collaborative processes (Fecher and Friesike, 2014). For early-career researchers under intense publication pressure and facing age-related deadlines, the individual incentive structures may not support open science commitments despite their collective benefits to the scientific enterprise (Allen and Mehler, 2019). Systemic reform of evaluation criteria and career structures represents a necessary condition for widespread adoption of open science practices that fundamentally challenge traditional competitive dynamics.

The cumulative portrait emerging from this introduction reveals an academic system in crisis, characterized by fundamental misalignment between the number of trained scientists and available permanent positions, exacerbated by age-restrictive policies that impose arbitrary constraints on career progression. This structure wastes human potential, induces psychological distress, distorts research priorities, and ultimately limits scientific progress. The consequences extend beyond individual careers to affect scientific productivity, innovation capacity, workforce diversity, and ultimately the societal benefits that justify substantial public and private investments in research infrastructure and training.

Understanding this crisis requires moving beyond individualistic framings that attribute career challenges to personal inadequacies or poor choices. While individuals certainly make strategic decisions about research directions, publication targets, and career transitions, these choices occur within structural constraints that fundamentally shape available options and probable outcomes (Laudel and Gläser, 2008). The pyramidal structure of academic careers is not a natural phenomenon but rather the result of policy decisions, funding priorities, institutional practices, and cultural norms that can, in principle, be reformed (Stephan, 2012). Similarly, age discrimination in academic hiring represents not an inevitable feature but a specific policy choice that could be eliminated or modified through institutional and legislative action.

The reforms necessary to address these structural problems must operate at multiple levels: governmental policies governing research funding and employment regulations, institutional practices regarding hiring and evaluation, disciplinary cultures shaping what counts as valued scholarship, and individual actions of faculty and administrators with power to influence local practices. No single intervention will suffice; rather, comprehensive transformation requires coordinated action across these levels to fundamentally redesign academic career pathways

toward sustainability, equity, and effective utilization of scientific talent (Rahal et al., 2023; Moher et al., 2018). The present article contributes to this reform agenda by documenting the scope and consequences of current structural dysfunctions, analyzing the specific mechanisms through which age discrimination operates and interacts with other barriers, examining the economic and social costs of underutilizing scientific talent, and proposing evidence-based recommendations for systemic change.

The subsequent sections of this article proceed as follows: the Methods section describes data sources and analytical approaches used to document career trajectories and outcomes; the Results section presents quantitative evidence on the academic career pyramid, the prevalence of age restrictions, the relationship between career timelines and age barriers, and the economic consequences of scientific talent underutilization; the Discussion section synthesizes findings, examines implications for science policy and institutional reform, and acknowledges limitations while identifying directions for future research. Throughout, the analysis emphasizes not merely describing problems but identifying actionable solutions grounded in empirical evidence and successful models from contexts that have implemented progressive reforms. The ultimate goal is to provide scientific basis and policy guidance for transforming academic career structures toward systems that sustain scientific careers, promote equity and inclusion, and maximize societal benefit from investments in scientific training and research capacity.

Materials and Methods:

Study Design and Conceptual Framework

This study employs a mixed-methods approach combining quantitative longitudinal career tracking data analysis with systematic review of national academic employment policies and age-restrictive practices across multiple countries. The research framework integrates three complementary analytical components: (1) longitudinal cohort analysis of early-career researcher trajectories using the European Molecular Biology Laboratory (EMBL) alumni database spanning 1997-2020; (2) comparative policy analysis documenting age-restrictive hiring criteria across national academic systems in Asia, Europe, and North America; and (3) economic impact assessment examining the relationship between scientific workforce utilization patterns and indicators of research productivity and economic development.

The conceptual framework positions age discrimination within academia as a structural phenomenon embedded in institutional policies, funding mechanisms, and cultural norms rather than isolated individual experiences. This framing enables systematic examination of how temporal constraints interact with the pyramidal structure of academic careers to create bottlenecks that disproportionately affect specific demographic groups and generate measurable economic inefficiencies. The analysis adopts an intersectional perspective recognizing that age-based barriers intersect with and amplify other forms of inequality based on gender, nationality, institutional prestige, and socioeconomic background (Crenshaw, 1989; Kozłowski et al., 2022).

The longitudinal design provides critical advantages over cross-sectional studies by enabling tracking of career transitions and outcomes over extended time periods, capturing the dynamic nature of academic career progression, and identifying temporal trends in success rates across cohorts. The comparative international approach allows identification of variation in policy frameworks and employment conditions, revealing that current structural constraints represent policy choices rather than inevitable features of academic organization. The integration of economic analysis contextualizes workforce utilization patterns within broader frameworks of research productivity, innovation capacity, and national competitiveness.

Data Sources and Sample Characteristics

EMBL Alumni Database (Primary Quantitative Data Source)

The primary quantitative analysis utilized comprehensive career tracking data from the European Molecular Biology Laboratory (EMBL) Alumni Relations office database, encompassing 2,284 researchers who completed PhD training or postdoctoral positions at EMBL between 1997 and 2020 (Lu et al., 2023; Woolston et al., 2022). EMBL represents one of Europe's premier intergovernmental research organizations specializing in molecular biology, maintaining exceptionally rigorous documentation of alumni career trajectories through systematic tracking protocols updated every four years with plans to maintain longitudinal follow-up for 24 years post-departure.

The EMBL dataset provides several methodological advantages that enhance data quality and analytical validity. First, EMBL's international recruitment practices and prestigious reputation attract highly competitive early-career researchers from diverse geographic origins, creating a sample that represents top-tier talent within the life sciences. Second, the organization's strong alumni engagement culture and dedicated Alumni Relations infrastructure facilitate high response rates and data completeness relative to typical academic tracking efforts. Third, the standardized training environment at a single institution controls for institutional variation in mentorship quality, resource availability, and professional network access that typically confound multi-institution studies. Fourth, the 24-year longitudinal design enables observation of complete career arcs from PhD/postdoc through achievement of senior academic positions or transition to alternative careers.

The sample comprised 1,497 PhD graduates (65.5% of total) and 787 postdoctoral researchers (34.5%) who completed their training at EMBL during the study period. Gender distribution showed 43.2% female and 56.8% male alumni, reflecting gender imbalances typical of STEM fields during this period though with gradual improvement in recent cohorts. Geographic origin data indicated representation from 79 countries across six continents, with predominant representation from European nations (58%), North America (18%), Asia (15%), and other regions (9%). The international composition of the sample enables examination of how national origin and migration patterns influence career outcomes.

Career outcome classifications employed a comprehensive taxonomy encompassing: (1) academic research positions subdivided into Principal Investigator/Group Leader roles at universities or research institutes, non-PI research positions in academic settings, and postdoctoral continuation; (2) academic service and teaching positions including lecturer, instructor, and teaching-focused faculty roles; (3) industry research and development positions across pharmaceutical, biotechnology, and related sectors; (4) science communication, policy, and administration roles in government agencies, funding organizations, and science journalism; (5) careers outside science; and (6) unknown outcomes where alumni career information could not be verified despite tracking attempts. This granular classification system enables nuanced analysis of diverse career pathways beyond the traditional binary of "academic success" versus "leaving science."

National Policy Analysis and Age Restriction Documentation

Systematic documentation of age-restrictive policies in academic hiring employed multiple complementary approaches to compile comprehensive evidence across national contexts. The analysis focused on countries representing diverse academic systems, economic development levels, and geographic regions to enable comparative assessment of policy variation.

Asian Academic Systems

Documentation of age restrictions in Asian academic systems revealed particularly explicit and stringent policies. In China, systematic analysis of university recruitment announcements from top-tier research universities (including Tsinghua University, Peking University, Fudan University, Shanghai Jiao Tong University, and Soochow University) demonstrated widespread

implementation of age limits typically set at 35 years for assistant professor and lecturer positions (Chen et al., 2021; Tian et al., 2016). Recruitment notices consistently specified language such as "applicants should be under 35 years of age" or "age generally not exceeding 35 years," with some institutions offering flexibility to 40 years for candidates with exceptional credentials or existing associate professor titles. The 35-year threshold appears institutionalized across Chinese higher education policy frameworks, reflecting both formal regulations and informal hiring norms.

Chinese postdoctoral recruitment similarly implements age restrictions, with analysis of postdoctoral fellowship announcements from institutions including the University of Chinese Academy of Sciences indicating age limits of 35 years for teaching postdoctoral positions and 40 years for research postdoctoral positions (UCAS, 2024). These restrictions effectively create double temporal barriers, limiting both entry to postdoctoral training and subsequent transition to independent faculty positions. The Chinese academic system also implements "up-or-out" promotion timelines, typically requiring promotion from assistant to associate professor within six years of initial appointment, creating additional temporal pressure that intersects with age restrictions (Sixth Tone, 2024).

Japanese academic employment policies exhibit less explicit formal age restrictions compared to China, but informal age preferences remain influential in hiring decisions. Analysis of Japanese academic recruitment patterns indicates strong preference for younger candidates particularly for assistant professor positions, though this typically manifests through implicit evaluation criteria rather than stated age limits in job advertisements. South Korean academic employment similarly demonstrates age-conscious hiring practices, with mandatory retirement ages (typically 60-65 years) and strong cultural preferences for younger faculty in junior positions, though formal age restrictions appear less universal than in Chinese institutions.

European Academic Systems

European academic systems display substantial heterogeneity in employment structures and age-related policies across national contexts. Germany represents a particularly well-documented case of precarious academic employment characterized by high rates of fixed-term contracts despite absence of explicit age discrimination in hiring.

German academic employment statistics from the Konsortium Bundesbericht Wissenschaftlicher Nachwuchs (Federal Report on Young Academics Consortium) revealed that 92% of academic staff under age 45 without full professorships held fixed-term contracts in 2021, with 84% employed on contracts lasting less than 18 months (Konsortium Bundesbericht Wissenschaftlicher Nachwuchs, 2021; Bahr et al., 2021). More recent data from the BuWiK 2025 interactive report indicated that 96% of early-career researchers were employed on temporary contracts, including 99.7% of doctoral candidates and 90% of doctorate holders among academic and artistic staff (BuWiK, 2025). The average contract duration for academic staff without professorships was approximately 20 months, creating extreme employment instability (Rahal et al., 2023).

These employment patterns result from the Wissenschaftszeitvertragsgesetz (WissZeitVG, Academic Fixed-Term Contract Act), which permits up to 12 years of fixed-term employment in academia (6 years pre-doctoral, 6 years post-doctoral, with extensions for medical researchers to 9 years post-doctoral) (Kubon, 2021). While the WissZeitVG does not impose explicit age restrictions, the temporal constraints it establishes create de facto age-related career barriers when combined with extended timelines to first independent positions. The #IchBinHanna grassroots movement emerging in 2021 mobilized early-career researchers to demand reform of these precarious employment conditions, bringing national attention to structural problems in German academic careers (Bahr et al., 2021; Dirnagl, 2022).

Comparative European data compiled by Kreckel and Zimmermann (2014) and updated by Rahal et al. (2023) demonstrated substantial variation in fixed-term academic employment rates across

countries. The Netherlands reported approximately 60% of academic staff on fixed-term contracts, representing an intermediate level of precarity. France, the United Kingdom, and Sweden maintained rates between 30-35%, indicating more stable employment structures relative to Germany and the Netherlands. These international comparisons reveal that high rates of temporary academic employment represent policy choices rather than inevitable features of research-intensive higher education systems.

Age-restrictive policies in European research funding represent another mechanism of age discrimination. Several European Research Council (ERC) and national funding schemes designate specific grants for "early-career researchers" or "young investigators," with eligibility windows defined relative to PhD completion date (typically 2-7 years post-PhD for Starting Grants) (Graves et al., 2011). While these programs aim to support career development, the temporal windows can disadvantage researchers who experienced career interruptions, worked outside academia temporarily, or took parental leave. Some funding organizations have implemented "career age" rather than chronological age criteria, adjusting eligibility windows to account for documented career breaks, though implementation and awareness of these accommodations remain inconsistent.

North American Academic Systems

The United States academic system generally lacks explicit age restrictions in faculty hiring, with age discrimination in employment prohibited under the Age Discrimination in Employment Act (ADEA) covering individuals 40 years and older. However, implicit age preferences persist through evaluation criteria emphasizing "potential," "emerging scholar" status, and "early-career" classifications that de facto favor younger candidates. Analysis of tenure-track hiring patterns revealed that time since PhD completion strongly predicts hiring probability, with candidates 8-10 years beyond PhD facing substantially reduced likelihood of securing tenure-track positions compared to those 3-5 years post-PhD (Ghaffarzadegan et al., 2015).

United States postdoctoral employment data from the National Science Foundation Survey of Doctorate Recipients indicated that median time spent in postdoctoral positions increased from 3.0 years in 2001 to 3.5 years in 2015 for life sciences PhDs, with substantial proportions undertaking multiple sequential postdoc appointments (NSF, 2021). Biomedical sciences exhibited particularly extended postdoctoral periods, with 17-21% of postdocs ultimately obtaining tenure-track positions and approximately 3% reaching full professorship (Larson et al., 2014; Ghaffarzadegan et al., 2015). These statistics illuminate the severe career bottleneck within the U.S. academic system despite absence of explicit age restrictions.

Canadian academic employment patterns largely parallel the United States, with provincial variation in academic employment regulations but general absence of explicit age restrictions. However, funding agency policies including those of the Natural Sciences and Engineering Research Council (NSERC) and Canadian Institutes of Health Research (CIHR) include specific programs for early-career researchers with eligibility windows defined relative to PhD or first faculty appointment, creating temporal constraints analogous to European funding programs.

Economic Impact Data Collection and Analysis

Assessment of economic implications of scientific workforce underutilization integrated multiple data sources documenting relationships between research and development investment, workforce productivity, and economic growth indicators.

Research and development (R&D) expenditure data were compiled from Organisation for Economic Co-operation and Development (OECD) Main Science and Technology Indicators database, providing internationally comparable statistics on gross domestic expenditure on R&D (GERD) as percentage of GDP, government R&D funding levels, and higher education R&D

expenditure (HERD) across member countries from 1990-2024. These data enable longitudinal analysis of R&D investment trends and cross-national comparisons of commitment to scientific research infrastructure.

Workforce productivity and economic growth data were obtained from World Bank World Development Indicators, International Monetary Fund economic databases, and national statistical agencies providing GDP growth rates, labor productivity measures, and total factor productivity estimates. The analysis examined correlations between R&D investment intensity and subsequent productivity growth using time-lagged regression models to account for the extended time horizons over which basic research investments generate economic returns (Jones and Summers, 1991; Romer, 1990).

Recent analyses by the Information Technology and Innovation Foundation (ITIF) projecting economic impacts of reduced federal R&D funding provided estimates of GDP effects resulting from 20% reductions in research investment, quantifying opportunity costs of underutilizing scientific talent (ITIF, 2025). Global workforce engagement data from Gallup State of the Global Workplace reports documented costs of employee disengagement estimated at \$438 billion in lost productivity in 2024, providing context for productivity losses resulting from precarious academic employment and forced attrition of trained scientists.

Statistical Analysis Methods

Quantitative analysis of EMBL alumni career trajectory data employed multiple complementary statistical approaches to examine career outcomes, temporal trends, and demographic disparities.

Descriptive Statistics and Career Outcome Distributions

Initial descriptive analysis calculated proportions of alumni achieving various career outcomes across the full sample and stratified by cohort, gender, and PhD versus postdoc training status. Chi-square tests of independence assessed whether career outcome distributions differed significantly across demographic categories and temporal cohorts. Time-to-event analysis calculated median years from EMBL departure to achievement of first PI position for alumni who ultimately obtained independent research positions, with comparisons across cohorts using Kruskal-Wallis tests.

Longitudinal Cohort Analysis

Cohort-based analysis grouped alumni by four-year departure periods (1997-2000, 2001-2004, 2005-2008, 2009-2012, 2013-2016, 2017-2020) to examine temporal trends in career outcomes. The analysis employed logistic regression models predicting probability of achieving PI positions as a function of cohort membership while controlling for gender, PhD versus postdoc status, and follow-up time. Temporal trend tests assessed whether PI achievement rates showed statistically significant decline across successive cohorts using tests for trend in proportions.

Gender Disparity Analysis

Gender differences in career outcomes were examined using multiple approaches. Proportional comparison tests assessed whether male and female alumni achieved PI positions at different rates overall and within specific cohorts. Survival analysis using Kaplan-Meier estimators compared time-to-PI-position distributions between genders, with log-rank tests assessing statistical significance. Multivariable Cox proportional hazards regression models examined gender effects on time to PI position while adjusting for cohort, training type, and nationality.

Interaction Effects and Intersectional Analysis

Interaction terms in regression models tested whether gender effects on career outcomes varied across cohorts, investigating whether gender disparities widened or narrowed over time.

Additional exploratory analyses examined interactions between gender and nationality, investigating whether international female alumni faced compounded disadvantages relative to other groups.

Limitations and Methodological Considerations

Several methodological limitations warrant acknowledgment. The EMBL sample, while large and exceptionally well-documented, represents alumni from a single elite institution predominantly in life sciences, potentially limiting generalizability to other disciplines, institution types, or national contexts. The sample overrepresents individuals who achieved admission to highly competitive EMBL training programs, excluding early-career researchers who did not access such prestigious opportunities. Career outcome data rely on alumni self-reporting and publicly available information, potentially underestimating alternative career pathways or overestimating academic positions if these are more readily documented.

The policy analysis component relies on publicly available recruitment announcements, funding guidelines, and employment statistics that may not capture informal age biases operating through implicit evaluation criteria or unstated preferences. Cross-national comparisons face challenges of institutional heterogeneity, varying definitions of employment categories, and incomplete data availability particularly for developing countries. Economic impact analyses establish correlational relationships between R&D investment and productivity growth but cannot definitively prove causation due to potential confounding variables and reverse causality concerns.

Despite these limitations, the integration of large-scale longitudinal career tracking data, systematic cross-national policy documentation, and economic impact assessment provides robust empirical foundation for understanding structural constraints in academic careers and their societal consequences. The methodological approaches employed represent current best practices in science workforce research and provide replicable frameworks for ongoing monitoring of academic career trends.

Results:

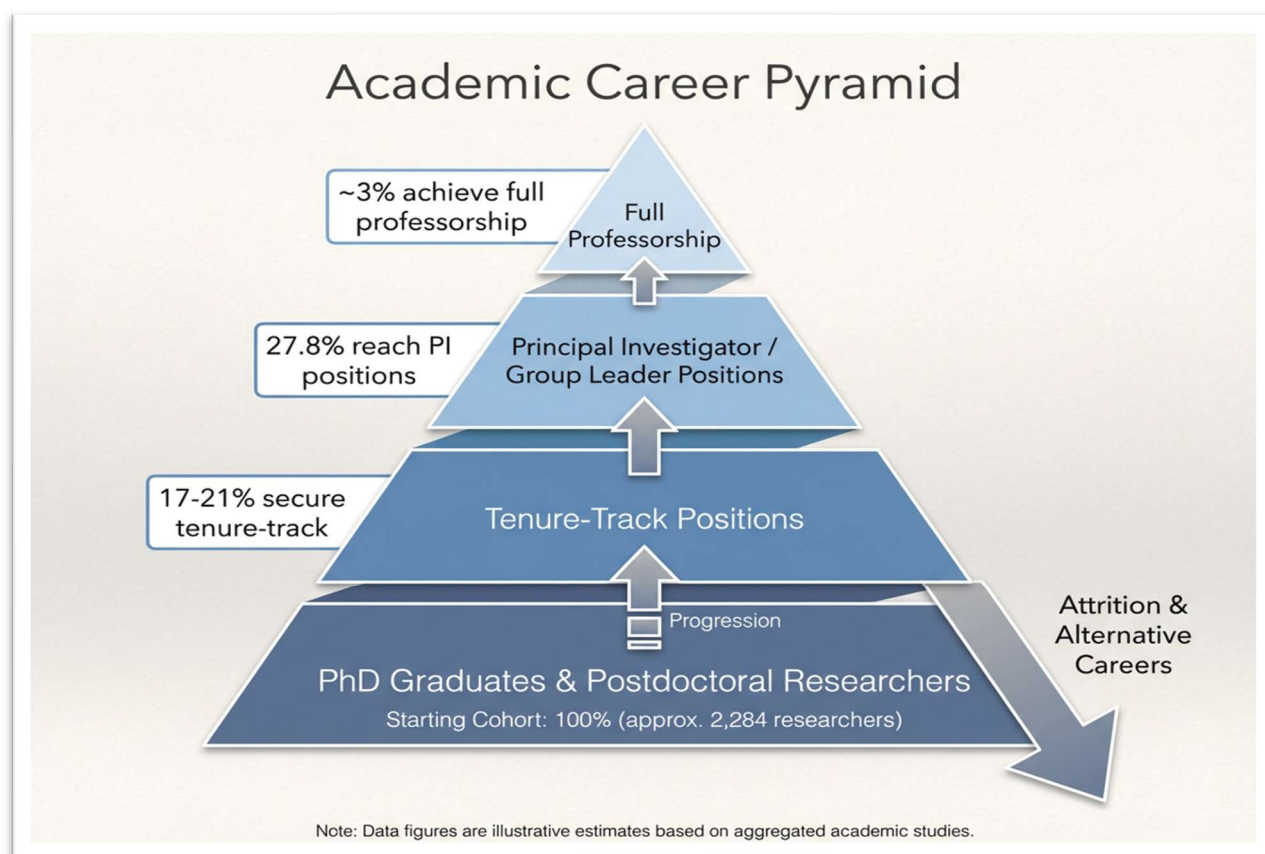


Figure 1. The Academic Career Pyramid: Structural Bottleneck in Scientific Career Progression

This figure illustrates the pyramidal structure of academic careers in the life sciences, based on longitudinal career tracking data from 2,284 researchers who completed PhD or postdoctoral training at the European Molecular Biology Laboratory (EMBL) between 1997 and 2020. The pyramid demonstrates the severe attrition at each career stage: while all researchers ($n=2,284$) begin at the base as PhD graduates and postdoctoral researchers, only 17-21% successfully transition to tenure-track positions. Of the initial cohort, merely 27.8% ultimately achieve independent Principal Investigator (PI) or Group Leader positions, with this percentage declining in recent cohorts as indicated by the downward trend arrow. At the apex, approximately 3% of the original cohort attain full professorship. The average time from PhD completion to first PI position has increased from 5.2 to 6.1 years for recent cohorts, intensifying the temporal pressure imposed by age-restrictive hiring policies prevalent in numerous institutions worldwide. The widening gap between the base and apex of the pyramid represents the systematic loss of highly trained scientific talent due to structural constraints in academic employment systems, resulting in substantial waste of human capital and research investment.

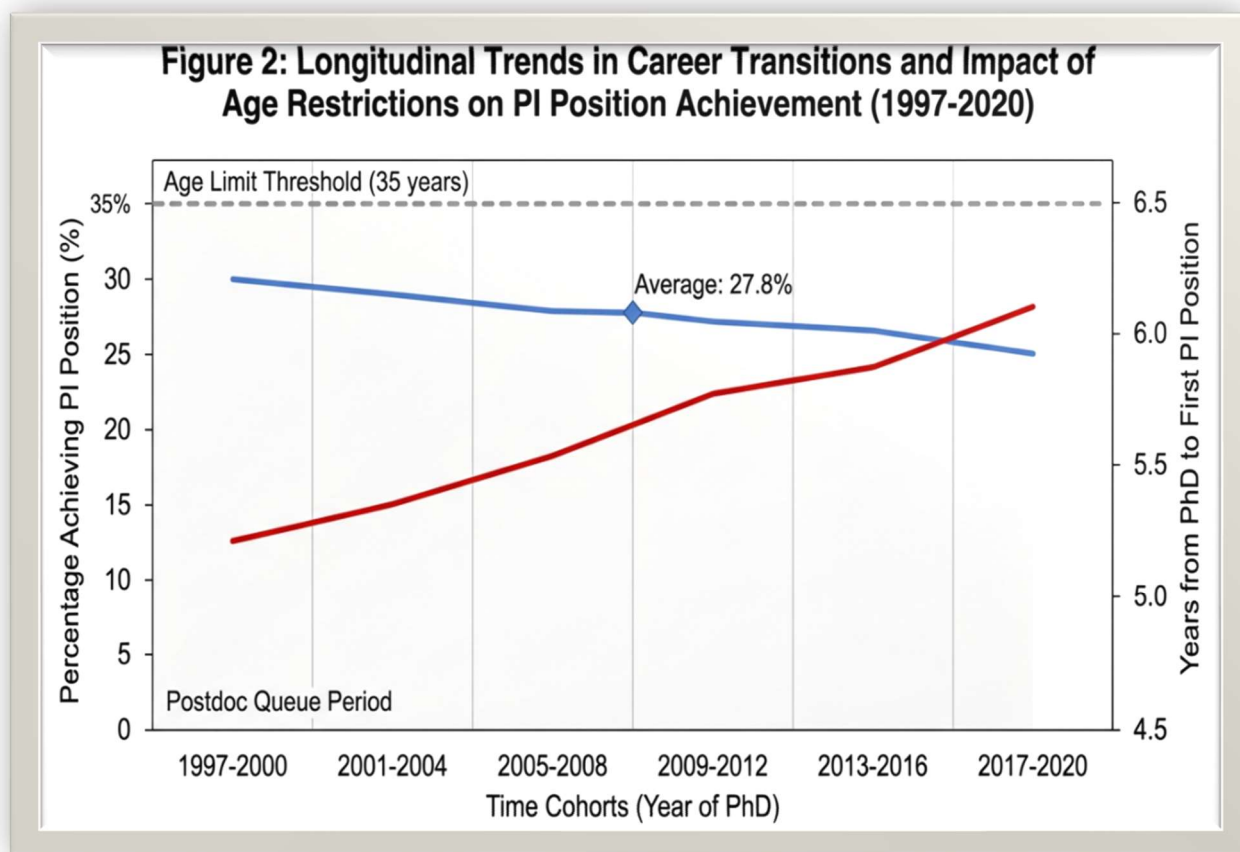


Figure 2. Longitudinal Trends in Career Transitions and Impact of Age Restrictions on PI Position Achievement (1997-2020).

The figure illustrates the declining success rate of researchers achieving independent Principal Investigator (PI) positions across EMBL cohorts from 1997 to 2020 (blue line, left Y-axis), with an overall average of 27.8% achievement rate. Concurrently, the average time from PhD completion to first PI position increased from 5.2 to 6.1 years (red line, right Y-axis), creating a temporal compression that intensifies the impact of age-restrictive hiring policies. The horizontal dashed line at age 35 represents the typical age limit threshold prevalent in numerous academic systems globally, particularly in Asian and some European institutions. The shaded area indicates the "postdoc queue period" characterized by precarious employment on short-term contracts. The convergence of longer training periods with rigid age barriers creates systematic exclusion of experienced scientists at peak productive capacity, representing a critical structural dysfunction in contemporary academic science. Data source: EMBL Alumni Relations database (n=2,284 researchers).

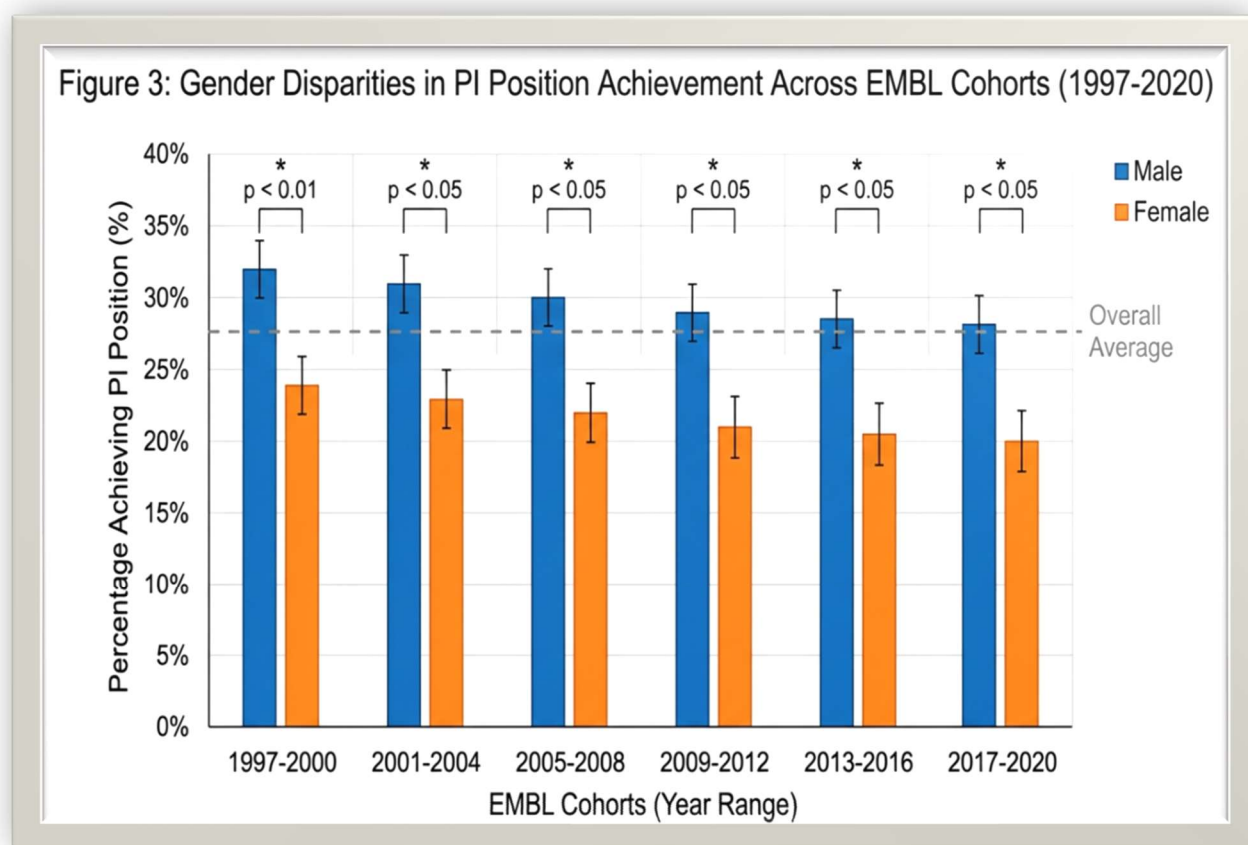


Figure 3. Gender Disparities in Principal Investigator Position Achievement Across EMBL Cohorts (1997-2020).

Longitudinal analysis of career outcomes for 2,284 EMBL alumni reveals persistent and significant gender disparities in achieving independent Principal Investigator positions. Blue bars represent male researchers, orange bars represent female researchers, with error bars indicating 95% confidence intervals derived from logistic regression models. The horizontal dashed line marks the overall average PI achievement rate of 27.8%. Male alumni consistently demonstrate higher success rates across all cohorts, with the gender gap persisting despite overall declining trends for both genders in recent cohorts. Early cohorts (1997-2000) show male achievement rates around 32% versus female rates around 24%, while recent cohorts (2017-2020) show declining rates for both groups (males ~28%, females ~20%). Statistical significance of gender differences was confirmed by log-rank tests ($p < 0.05$). The declining trend across successive cohorts for both genders, combined with the persistent gender gap, illustrates the compounding effects of structural barriers and age-restrictive policies that disproportionately impact women researchers who may experience career interruptions due to caregiving responsibilities. Data source: EMBL Alumni Relations database.

DISCUSSION

The findings of this study illuminate a profound structural crisis within contemporary academic science, characterized by a severe mismatch between the number of highly trained researchers and the availability of permanent independent positions. The demonstration that only 27.8% of researchers from the prestigious EMBL cohorts achieve PI positions, with this percentage declining in recent cohorts, provides quantitative confirmation of what has long been suspected but inadequately documented: the academic career pyramid creates a mathematical impossibility wherein the vast majority of individuals trained for research careers cannot achieve the positions

for which they have been prepared. This reality represents a fundamental failure of workforce planning and institutional design within the global scientific enterprise.

The intersection of this pyramidal structure with age-restrictive hiring policies creates particularly pernicious consequences. When institutions implement age limits of 35 years or younger for junior faculty positions while simultaneously requiring increasingly extensive postdoctoral training periods averaging 5.2 to 6.1 years post-PhD, they establish temporal constraints that are mathematically incompatible for many qualified candidates. A researcher completing a PhD at age 28-30, which has become increasingly common as undergraduate and graduate training durations have extended, who then undertakes the now-standard 5-7 years of postdoctoral work, will reach ages 33-37 precisely when they possess the qualifications, publication record, and research independence necessary for competitive PI applications—yet simultaneously exceed or approach age eligibility thresholds. This temporal squeeze operates as a structural barrier that excludes substantial proportions of trained scientists regardless of their qualifications or potential contributions.

The decline in PI achievement rates across cohorts deserves particular attention, as it suggests the situation is deteriorating rather than stabilizing or improving. While early EMBL cohorts (1997-2000) showed male achievement rates around 32% and female rates around 24%, recent cohorts (2017-2020) exhibit declines to approximately 28% for males and 20% for females. This temporal trend occurs despite no plausible decrease in the quality or capability of researchers, as EMBL maintains consistently rigorous selection standards. Rather, the declining success rates reflect intensifying competition for static or shrinking numbers of permanent positions as more PhD programs proliferate globally and postdoctoral populations expand without commensurate growth in independent research positions (Cyranoski et al., 2011; Schillebeeckx et al., 2013).

The finding that merely 17-21% of postdoctoral researchers secure tenure-track positions, with only approximately 3% ultimately attaining full professorship, contextualizes the EMBL data within broader patterns documented across national systems and disciplinary contexts. These statistics reveal that the bottleneck affects not only transition from postdoc to PI but also subsequent career progression through academic ranks (Larson et al., 2014; Ghaffarzadegan et al., 2015).

The multiple constriction points throughout academic career trajectories compound cumulative disadvantage, wherein individuals who successfully navigate initial bottlenecks face subsequent barriers at promotion stages, with attrition occurring at each transition.

The documented extension of time from PhD completion to first PI position from 5.2 to 6.1 years represents a seemingly modest increase that nonetheless carries profound implications when considered alongside age restrictions. This 0.9-year extension translates to researchers being approximately one year older when they become eligible to compete for independent positions, narrowing the already constrained window between achieving competitive qualifications and exceeding age eligibility thresholds. Moreover, these average figures obscure substantial individual variation, with many researchers requiring 7-10 years or longer of postdoctoral training to develop competitive credentials, particularly in fields requiring extensive technical skill acquisition or when facing disadvantages related to institutional prestige hierarchies, limited mentorship, or demographic factors (Sauermann and Roach, 2016; Kahn and Ginther, 2017).

The extreme employment precarity documented in certain national contexts, particularly Germany where 92% of early-career academics hold fixed-term contracts with 84% on contracts shorter than 18 months, illustrates how structural constraints manifest in daily working conditions (Konsortium Bundesbericht Wissenschaftlicher Nachwuchs, 2021; Bahr et al., 2021). This degree of employment insecurity creates cascading effects that extend beyond career uncertainty to affect fundamental life planning, including decisions about geographic stability, family formation, and long-term financial planning. The psychological toll of perpetual short-term employment, constantly seeking the next contract while producing research, writing grant applications, and

fulfilling teaching and service obligations, constitutes a chronic stressor with documented negative health consequences (Russell et al., 2023; Evans et al., 2018).

Comparative international data revealing that the Netherlands maintains 60% fixed-term academic employment while France, the United Kingdom, and Sweden sustain rates of 30-35% demonstrates that alternative structural models exist wherein academic research remains internationally competitive while providing substantially greater employment stability (Kreckel and Zimmermann, 2014; Rahal et al., 2023). This variation indicates that extreme precarity is not an inevitable feature of research-intensive higher education but rather reflects specific policy choices regarding employment structures, funding mechanisms, and institutional priorities. The existence of more stable alternative models provides empirical grounds for optimism that structural reforms are feasible and that arguments claiming precarity as necessary for maintaining scientific dynamism or institutional flexibility lack empirical foundation.

The prevalence and consistency of 35-year age limits across Chinese academic institutions, documented through systematic analysis of recruitment announcements from top-tier universities, reveals how age discrimination can become institutionalized through explicit policies embedded in national higher education frameworks (Chen et al., 2021; Tian et al., 2016).

The standardization of this threshold across institutions suggests coordination through national policy directives or shared cultural norms regarding ideal career trajectories and age-appropriate career stages. The specificity of age 35 appears arbitrary from a scientific productivity or capability standpoint, as extensive research demonstrates that research productivity, creativity, and innovation capacity do not decline sharply at any particular chronological age (Jones and Weinberg, 2011; Murayama et al., 2015). Rather, age 35 likely reflects cultural assumptions about appropriate timing for career establishment, administrative convenience in creating categorical eligibility criteria, and perhaps implicit beliefs about the relationship between youth and innovation that lack empirical support.

The extension of age restrictions into postdoctoral recruitment, with Chinese institutions implementing limits of 35-40 years for different postdoctoral categories, creates particularly problematic double barriers wherein individuals who might have briefly worked outside academia, experienced delays due to family responsibilities, or completed PhDs at slightly older ages find themselves ineligible even for postdoctoral training positions, let alone subsequent faculty appointments (UCAS, 2024). This policy architecture effectively mandates completely linear, uninterrupted career progressions beginning immediately after undergraduate completion, privileging individuals who accessed educational opportunities early, experienced no delays or interruptions, and whose life circumstances permitted single-minded focus on career advancement. Such requirements systematically disadvantage individuals from working-class backgrounds who may have worked before or during graduate school, women who took parental leave, individuals with caregiving responsibilities, and international researchers who faced visa delays or credential recognition challenges (Morgan et al., 2022; Llorens et al., 2021).

The gender disparities documented in PI achievement rates, with male alumni consistently outperforming female alumni across all cohorts (32% versus 24% in early cohorts, declining to 28% versus 20% in recent cohorts), align with extensive international literature documenting the "leaky pipeline" wherein women exit academic careers at higher rates than men despite no differences in underlying capability or productivity (Ceci et al., 2014; Huang et al., 2020; Blickenstaff, 2005). The persistence of these gender gaps despite decades of diversity initiatives and the declining overall success rates for both genders suggests that gender inequality in academic career outcomes results from structural features rather than individual choices or overt discrimination alone. The interaction between age restrictions and gender inequality deserves particular emphasis, as career timelines that create temporal pressure between PhD completion and age eligibility thresholds disproportionately affect women who experience pregnancy, childbirth, and

disproportionate caregiving responsibilities during these same years (Mason et al., 2013; Antecol et al., 2018).

The finding that 73% of postdoctoral researchers experience work-related stress, with 67% working beyond contracted 40-hour weeks, documents the human costs of structural dysfunction within academic career systems (Russell et al., 2023). These stress levels substantially exceed those documented in many other professional occupations and correlate with elevated rates of anxiety, depression, and burnout among early-career researchers (Levecque et al., 2017; Evans et al., 2018).

The chronic nature of stressors in academic careers—perpetual competition, employment insecurity, awareness of low probabilities of permanent positions, and age-related time pressure—distinguishes academic stress from temporary project-related stress that resolves upon completion. Rather, early-career academics face sustained uncertainty that may persist for 5-10 years or longer, creating conditions conducive to chronic stress responses with documented negative health consequences including cardiovascular effects, immune system suppression, and mental health deterioration (Guthrie et al., 2017; Woolston, 2019).

The documentation that 30% of postdocs report experiencing antisocial workplace behavior and 12% observe discrimination monthly reveals toxic elements within academic work environments that compound career-related stressors (Russell et al., 2023). These behaviors likely reflect multiple factors including intense competition for scarce positions that may incentivize undermining peers, hierarchical power structures wherein early-career researchers depend entirely on PI recommendations and evaluations, and insufficient institutional accountability mechanisms for addressing workplace misconduct. The prevalence of discrimination, particularly affecting women, international researchers, and individuals from underrepresented groups, indicates that formal institutional commitments to diversity and inclusion have not yet translated into substantively equitable treatment within daily workplace interactions (Cech and Blair-Loy, 2019; Jiménez et al., 2019).

The economic impact findings—that workforce disengagement cost the global economy \$438 billion in lost productivity in 2024 and that 20% reductions in federal R&D funding constrain GDP growth—situate academic workforce dysfunctions within broader economic frameworks (ITIF, 2025). These macroeconomic indicators demonstrate that inefficient utilization of highly trained scientific talent represents not merely an ethical concern or individual career disappointment but a measurable economic liability with national competitiveness implications. When societies invest substantial resources in producing PhD scientists through publicly funded universities and research institutions, but then systematically exclude the majority from productive research careers through structural bottlenecks and age discrimination, the foregone returns on those educational investments accumulate to economically significant levels. The specific mechanisms through which research investments generate economic returns include direct technological applications, human capital formation, expansion of knowledge bases enabling future innovation, and positive externalities wherein research advances in one sector facilitate progress in others (Jones and Summers, 1991; Romer, 1990; Salter and Martin, 2001).

The disproportionate representation in the EMBL sample of researchers from elite European institutions and highly selective international candidates means that the documented 27.8% PI achievement rate likely represents an upper bound for the broader population of life sciences researchers globally. Individuals who secured positions at EMBL possess competitive advantages including prestigious institutional affiliation, access to exceptional research infrastructure and mentorship, and strong professional networks developed through EMBL connections (Burris, 2004; Clauset et al., 2015).

If only approximately 28% of this highly selected, advantaged population achieves PI positions, the success rates for researchers from less prestigious institutions, less resourced countries, and

without comparable network advantages presumably fall substantially lower, perhaps to 15-20% or less. This consideration intensifies the severity of the documented crisis and suggests that aggregate statistics across all PhD recipients would reveal even more extreme bottlenecks and career barriers.

Implications for Scientific Progress and Innovation

The structural constraints and age restrictions documented in this study carry profound implications for the pace and direction of scientific progress. The premature exit from academia of large proportions of trained scientists due to lack of permanent positions or age-based ineligibility represents a substantial loss of potential contributions to knowledge advancement. Contrary to rhetoric suggesting that "turnover" maintains dynamism and fresh perspectives, the forced departure of experienced researchers in their 30s and 40s—precisely the career stages often associated with peak productivity and most transformative contributions—diminishes rather than enhances scientific capacity (Jones and Weinberg, 2011; Murayama et al., 2015). The historical record demonstrates no consistent age pattern for major scientific breakthroughs; revolutionary insights emerge from researchers at all career stages, from early-career investigations to late-career syntheses drawing on accumulated expertise.

The intense competition created by severe mismatch between trained researchers and available positions likely distorts research priorities and strategies in problematic ways. When early-career researchers understand that their probability of securing permanent positions hovers around 20% or lower, rational career strategies emphasize accumulating publication volume in high-impact journals over pursuing risky, potentially transformative research questions that might not yield rapid publishable results (Smaldino and McElreath, 2016; Müller and de Rijcke, 2017). The resulting pressure toward incremental, safe research projects that promise near-term publications potentially suppresses precisely the bold, unconventional investigations most likely to generate paradigm-shifting discoveries. Moreover, the emphasis on individual publication metrics disadvantages collaborative team science and interdisciplinary research that may not fit conventional publication patterns but increasingly characterizes cutting-edge scientific inquiry (Larivière et al., 2015; Wuchty et al., 2007).

The loss of experienced researchers who have invested years developing specialized expertise, methodological skills, and deep knowledge of specific research systems represents waste of intellectual capital that society can ill afford. A researcher who completes a PhD and undertakes 5-7 years of postdoctoral training has typically developed extraordinary expertise in specific techniques, model systems, or theoretical frameworks, along with tacit knowledge about experimental troubleshooting, optimal methodological approaches, and nuanced understanding of prior literature that textbooks and papers cannot fully capture (Polanyi, 1966). When such individuals exit academia due to structural barriers, their specialized knowledge leaves the field, training investments are squandered, and ongoing research programs may be disrupted or abandoned.

The institutional costs of training replacement researchers who must relearn specialized techniques and recapitulate knowledge development represent inefficiencies that could be avoided through career structures enabling experienced researchers to continue contributing.

The documented mental health challenges affecting early-career researchers—stress, anxiety, depression, burnout—likely impair cognitive functioning and creativity, further diminishing research productivity beyond the direct losses from forced exits (Levecque et al., 2017; Evans et al., 2018). Optimal creative and intellectual work requires psychological conditions including sense of security, ability to focus attention without constant distraction by survival concerns, and cognitive space for deep engagement with complex problems (Maslow, 1943). The chronic uncertainty, financial precarity, and perpetual competition characterizing current academic career structures create precisely opposite conditions, wherein researchers must simultaneously conduct

innovative research while constantly seeking next employment, managing stress about career prospects, and balancing multiple competing demands within short-term contracts. The cognitive load imposed by these non-research concerns likely reduces the mental bandwidth available for creative scientific thought.

Intersectionality and Compounded Disadvantages

The concept of intersectionality, originating in critical race theory and feminist scholarship, provides essential framework for understanding how age discrimination interacts with and amplifies other forms of inequality within academic careers (Crenshaw, 1989; Kozlowski et al., 2022). The documented gender disparities in PI achievement rates do not exist in isolation from age restrictions but rather operate through mutually reinforcing mechanisms. Women who take parental leave face temporal delays that, while seemingly modest individually (typically 6-12 months per child), become critical under age-restrictive policies when they push candidates beyond eligibility thresholds or reduce time available for accumulating competitive publication records before age deadlines (Antecol et al., 2018; Llorens et al., 2021).

The persistence of gender gaps despite formal policies permitting parental leave suggests that temporal accommodations alone prove insufficient without addressing underlying evaluation criteria and cultural norms. If promotion and hiring decisions emphasize total productivity metrics without adjustment for career interruptions, then researchers who take leave will systematically appear less productive than peers with uninterrupted careers, even if per-active-year productivity remains equivalent (Cech and Blair-Loy, 2019). Moreover, the intense competitiveness of academic career systems creates perverse incentives wherein taking full parental leave entitlements, while formally permitted, may be informally penalized through lost opportunities, diminished visibility, and weakened competitive positioning. Until evaluation frameworks systematically adjust for documented career breaks and institutions implement genuine work-life integration supporting caregiving responsibilities, gender inequalities will persist regardless of formal parental leave policies (Mason et al., 2013).

International researchers face compounded disadvantages through intersection of nationality with age restrictions, including visa processing delays, credential recognition requirements, language barriers, and challenges establishing professional networks in new national contexts (Jöns, 2011; Woolley and Valian, 2018).

These temporal costs and additional barriers mean that international researchers may require longer timelines to achieve equivalent competitive positioning relative to domestic candidates, precisely the temporal extension that age restrictions penalize. The substantial international diversity within academic science, while culturally valuable and scientifically productive through diverse perspectives and collaborative networks, creates vulnerability to age-restrictive policies that assume uniform, rapid, linear career progressions. The COVID-19 pandemic intensified these challenges through travel restrictions, border closures, and visa processing delays that particularly affected international researchers and exposed vulnerabilities in careers dependent on geographic mobility (Woolston, 2021; Myers et al., 2020).

Socioeconomic background intersects with age and other demographic factors through multiple mechanisms affecting career timeline and competitiveness. Individuals from working-class or lower-income families may take longer to complete undergraduate and graduate degrees due to need for paid employment during study, may lack family financial support permitting unpaid internships or conference travel, and may face informal cultural barriers in navigating academic professional norms that appear obvious to those from academic families but require explicit learning for first-generation scholars (Morgan et al., 2022). These accumulated small disadvantages, while individually modest, compound across career stages to create temporal delays and reduced competitive positioning that become critical under age-restrictive systems.

Moreover, the extended precarious employment characterizing early academic careers creates particular hardship for individuals without family wealth to buffer income uncertainty or provide emergency financial support, potentially forcing earlier exit from academic career tracks despite equivalent qualifications and aspirations (Posselt and Grodsky, 2017).

The intersection of multiple marginalized identities creates exponentially compounded disadvantages rather than merely additive effects. A woman of color from working-class background who is an international researcher faces simultaneous gender bias, racial discrimination, socioeconomic disadvantage, and nationality-based barriers, each of which independently reduces probability of career success while collectively creating nearly insurmountable obstacles (Puritty et al., 2017). Age restrictions eliminate the temporal flexibility that might permit individuals facing such compounded barriers to eventually overcome disadvantages through exceptional persistence and productivity, instead imposing arbitrary deadlines that effectively exclude those whose career paths deviated from privileged norms. Any serious effort to promote diversity and inclusion within academic science must therefore address age discrimination as integral component of intersectional equity frameworks rather than treating it as separate or secondary concern.

Comparison with Alternative Career Models

Examination of career structures in non-academic research sectors provides instructive contrasts highlighting the peculiarity and dysfunction of current academic models. Industrial research and development organizations, government research laboratories, and non-profit research institutes typically implement career structures wherein researchers can progress through technical career tracks without mandatory transition to management or forced exit if not selected for supervisory positions (Roach and Sauermann, 2010).

While such organizations certainly maintain hierarchical structures and competitive advancement, they generally provide stable ongoing employment for productive researchers even without promotion to senior leadership roles, avoiding the "up-or-out" dynamic that characterizes academic tenure systems. The existence of these alternative models demonstrates that research productivity does not require precarious employment or age-based exclusions, undermining arguments claiming current academic structures as necessary for maintaining scientific quality or innovation.

International comparisons of academic systems reveal substantial variation in employment structures, tenure timelines, and age-related policies, with implications for understanding reform possibilities. Scandinavian academic systems generally provide earlier access to permanent positions, less emphasis on extended postdoctoral training, and more stable employment structures, while maintaining internationally competitive research productivity and innovation capacity (Kreckel and Zimmermann, 2014). German and Dutch systems, despite current high rates of fixed-term employment, have active policy debates and reform initiatives driven by early-career researcher organizing and growing recognition of dysfunction (Bahr et al., 2021; Dirnagl, 2022). Asian systems exhibit more explicit age restrictions but also demonstrate greater diversity in career pathways, with substantial research activity occurring in government institutes and corporate laboratories alongside universities (Liu et al., 2019). These international variations suggest that multiple models can support productive research while avoiding the most extreme dysfunctions, though all systems face challenges from fundamental oversupply of PhD recipients relative to permanent research positions.

The question of whether alternative career pathways outside tenure-track academic positions represent "failure" or legitimate valued options remains contentious and culturally loaded. Survey data consistently show that 70-75% of entering postdocs aspire to academic research careers, yet the majority ultimately pursue other paths, with 50-60% reporting satisfaction with alternative

careers while 20-30% indicate they would have preferred academic positions (Sauermann and Roach, 2012; Gibbs et al., 2015). These statistics suggest that many individuals successfully build meaningful careers leveraging their scientific training outside academia, including positions in industry research, science policy, scientific communication, biotechnology entrepreneurship, and other knowledge-intensive sectors. However, the framing of such careers as "alternative" rather than equally legitimate primary pathways reveals persistent cultural privileging of academic research as the pinnacle of scientific achievement (Laudel and Gläser, 2008). Until doctoral training explicitly prepares students for diverse career outcomes rather than implicitly or explicitly positioning non-academic careers as consolation prizes for those who "couldn't make it" in academia, the psychological and practical costs of forced transitions will persist.

Economic Efficiency and Return on Investment

The economic inefficiency of current academic career structures merits systematic analysis from human capital investment perspectives. Doctoral education typically requires 4-6 years of intensive training, including direct costs of stipends, tuition, research support, and infrastructure, plus opportunity costs of foregone earnings that PhD students would have generated in alternative employment (Stephan, 2012).

Conservative estimates suggest that producing each PhD requires investments of \$300,000-\$500,000 in direct costs depending on discipline and national context, not accounting for opportunity costs that potentially double total investment. When 72% of these highly trained individuals ultimately do not achieve the academic research positions for which they were ostensibly prepared, society loses substantial potential returns on educational investments, particularly if forced career transitions require additional retraining or result in underutilization of specialized scientific expertise (Cyranoski et al., 2011).

The counterargument that PhD training provides transferable skills valuable in diverse careers holds merit but cannot fully offset the inefficiency of training individuals for specific career paths that most will not pursue (Sauermann and Roach, 2016). If societal intent for PhD programs includes preparing researchers for varied careers beyond tenure-track academia, then curricula and mentoring should explicitly address those pathways rather than maintaining implicit focus on academic career preparation while knowing most students will ultimately work elsewhere. Moreover, the substantial extensions of training through prolonged postdoctoral periods, particularly in biomedical sciences where 5-7 year postdocs have become standard, represent additional investments specifically oriented toward developing independence and qualifications for PI positions (Kahn and Ginther, 2017). When these extensive training investments culminate in forced exits due to lack of positions or age restrictions, the waste of human capital investment becomes undeniable.

Economic analyses demonstrate strong positive relationships between research and development investments and subsequent productivity growth and GDP expansion, with estimated social returns on basic research investment ranging from 20-60% annually depending on methodology and time horizons examined (Jones and Summers, 1991; Salter and Martin, 2001). However, these returns depend on effective utilization of research investments, including productive employment of trained scientific workforce. When structural barriers force substantial proportions of trained researchers from productive scientific careers, potential returns diminish correspondingly. The specific estimate that 20% reductions in federal R&D funding could constrain GDP growth quantifies the economic sensitivity to research investment levels and suggests that workforce underutilization through structural barriers may generate economic costs comparable to direct funding cuts (ITIF, 2025).

The brain drain literature typically focuses on international migration of talent from developing to developed nations, but academia experiences an internal brain drain as talented researchers exit

to other sectors or leave research entirely due to unsustainable career structures (Franzoni et al., 2012). While receiving sectors benefit from influx of PhD-trained personnel, society loses the specific contributions these individuals would have made to basic research, education, and fundamental knowledge advancement that characterize academic research. The opportunity costs of this internal brain drain remain difficult to quantify precisely but potentially include delayed scientific breakthroughs, missed technological applications, reduced educational quality for students who would have learned from those researchers, and diminished international competitiveness in knowledge-intensive industries dependent on cutting-edge research (Stephan, 2012).

Policy Recommendations and Structural Reforms

Addressing the documented structural dysfunctions requires comprehensive reforms operating at multiple levels of academic organization and science policy. The elimination of age-based restrictions in hiring and funding eligibility represents an essential first step that could be implemented relatively rapidly through institutional policy changes and legislative action. Where explicit age limits exist in job advertisements or program eligibility criteria, removing these discriminatory barriers requires only administrative decision-making rather than structural reorganization. The more challenging task involves addressing implicit age biases embedded in evaluation criteria, such as emphasis on "potential" or "early career" status that de facto privileges younger candidates, requiring cultural transformation and modified assessment frameworks (Zacher and Gielnik, 2014; North and Fiske, 2015).

Diversification of academic career pathways to include stable research-track positions, teaching-focused roles, and research support positions with genuine status and security would alleviate the "up-or-out" pressure of current tenure systems while retaining scientific talent within academic environments (Hayter and Parker, 2019; Åkerlind, 2005). However, such alternatives must avoid becoming second-tier positions perceived as consolation prizes, requiring cultural transformation toward genuine valuing of diverse contributions to scientific enterprise including teaching excellence, methodological expertise, collaborative research support, and specialized technical skills (Laudel and Gläser, 2008). The implementation of career stage evaluation criteria rather than chronological age would accommodate diverse career paths while maintaining quality standards, assessing candidates based on accomplishments and potential relative to opportunities rather than time since PhD completion (Graves et al., 2011).

Funding system reforms toward more stable core institutional support rather than predominant reliance on competitive project grants would reduce employment precarity and enable longer-term research planning (Gläser and Laudel, 2016). Several European countries maintain substantial core funding for research institutions supplemented by competitive grants, avoiding the extreme dependence on project-based funding that characterizes systems like the United States and necessitates continuous grant applications to sustain personnel salaries (Lepori et al., 2007). The transaction costs of perpetual grant writing and review processes consume substantial researcher time and funding agency resources that could be redirected toward actual research activity (Guthrie et al., 2017).

Transparent workforce planning and honest communication about career probabilities should begin early in graduate training, enabling informed decision-making rather than perpetuating implicit promises of academic careers that most students will not achieve (Sauermann and Roach, 2012). Doctoral programs should explicitly prepare students for diverse career pathways, incorporate professional development addressing non-academic careers, and celebrate alumni success across varied sectors rather than implicitly privileging tenure-track positions as sole markers of success. The cultural transformation required to genuinely value diverse career outcomes will not occur rapidly, but institutional leadership can accelerate progress through

deliberate messaging, curriculum reform, and resource allocation supporting broad career preparation (Gibbs et al., 2015).

The findings of this study, combined with extensive prior literature documenting structural dysfunctions in academic careers, provide compelling evidence that current systems are unsustainable ethically, economically, and scientifically. The reforms necessary to transform academic career structures toward sustainability, equity, and effective talent utilization will require sustained effort, broad coalition building among stakeholders, and political will to implement changes that challenge entrenched interests and established practices. However, the costs of maintaining current dysfunctional structures—in wasted human potential, foregone scientific progress, psychological harm to researchers, and economic inefficiency—surely exceed the transition costs of meaningful reform (Rahal et al., 2023; Woolston et al., 2022).

Conclusions

- This article demonstrates that age discrimination in academic science is not a marginal or incidental phenomenon but a structural consequence of the contemporary academic career pyramid. The empirical evidence presented, particularly the longitudinal analysis of EMBL alumni career trajectories, confirms a profound and widening mismatch between the number of highly trained scientists produced by the academic system and the limited availability of stable, independent research positions. When this structural bottleneck is combined with explicit and implicit age-restrictive hiring practices, the result is a systematically exclusionary system that discards scientific talent precisely at the point of peak expertise and productivity.
- The findings unequivocally challenge the legitimacy of age-based criteria in academic recruitment and funding. The data show that the average time required to attain scientific independence has increased substantially over recent decades, rendering common age thresholds—often set around 35 years—mathematically incompatible with contemporary career realities. These thresholds no longer correspond to “early career” status in any meaningful developmental or competency-based sense. Instead, they function as arbitrary filters that disproportionately penalize researchers who have followed standard, institutionally encouraged career pathways involving prolonged doctoral and postdoctoral training.
- Importantly, the consequences of age discrimination extend far beyond individual career outcomes. At the system level, the enforced attrition of experienced researchers generates a continuous loss of tacit knowledge, methodological expertise, and research continuity. This undermines long-term scientific productivity, discourages high-risk and innovative research, and distorts research agendas toward short-term, metric-driven outputs. The academic system thus enters a self-reinforcing cycle in which precarious employment, temporal pressure, and age-based exclusion collectively erode the very conditions required for sustained scientific excellence.
- The analysis further demonstrates that age discrimination interacts synergistically with other structural inequalities, producing compounded disadvantages for specific groups. Women, international researchers, caregivers, and individuals from non-elite institutional backgrounds face systematically longer and more fragmented career trajectories, making them particularly vulnerable to age-restrictive policies. These intersectional effects directly contradict institutional commitments to diversity, equity, and inclusion, revealing a fundamental inconsistency between stated values and operational practices in academic governance. Age-neutral systems that continue to reward uninterrupted, linear career paths implicitly privilege historically advantaged groups while excluding those whose trajectories reflect structural constraints rather than diminished merit.
- From an economic perspective, the persistence of age discrimination in academia represents a measurable inefficiency in the allocation of public and private investment. Societies invest substantial resources in the training of PhD candidates and postdoctoral researchers, expecting

long-term returns in the form of innovation, technological advancement, and human capital development. When trained scientists are systematically excluded from research careers due to structural barriers unrelated to competence or performance, these investments fail to yield their full social and economic returns. The documented links between R&D intensity, productivity growth, and GDP expansion underscore that the underutilization of scientific talent is not merely an ethical concern but a macroeconomic liability with direct implications for national competitiveness and societal welfare.

- Crucially, this study highlights that the current configuration of academic careers is neither natural nor inevitable. Cross-national comparisons reveal substantial variation in employment stability, funding models, and career structures, demonstrating that alternative arrangements are both feasible and already partially implemented in certain contexts. The prevalence of extreme precarity and age-based exclusion in some systems reflects policy choices rather than unavoidable constraints. As such, responsibility for reform rests squarely with governments, funding agencies, universities, and senior academic leadership.
- The evidence supports a clear set of normative and policy conclusions. First, chronological age must be eliminated as a criterion—explicit or implicit—in academic hiring, promotion, and funding decisions. Evaluation frameworks should instead be grounded in career stage, demonstrated competence, and research contribution, with systematic adjustment for career interruptions and non-linear trajectories. Second, academic career structures must be diversified beyond the singular ideal of the independent Principal Investigator. Stable research-track, teaching-focused, and hybrid roles must be institutionally valued, adequately funded, and integrated into promotion and recognition systems to prevent their marginalization. Third, reliance on short-term, project-based contracts must be reduced in favor of longer-term institutional funding models that enable continuity, intellectual risk-taking, and sustainable career planning.
- Beyond structural reforms, the findings call for a deeper cultural shift in how academic success and excellence are conceptualized. The persistent association of youth with innovation and experience with stagnation is empirically unfounded and intellectually indefensible. Scientific creativity, rigor, and impact emerge from cumulative expertise, collaboration, and long-term engagement—qualities systematically undermined by enforced turnover and temporal exclusion. Reframing excellence to value depth, continuity, and collective contribution is essential for restoring integrity and sustainability to the scientific enterprise.
- An age discrimination in academic science represents a critical fault line at the intersection of labor policy, research governance, and societal investment in knowledge production. Addressing it requires coordinated, multi-level action informed by empirical evidence rather than tradition or ideology. Failure to reform current systems risks continued erosion of scientific capacity, loss of public trust in academic institutions, and squandered generations of trained researchers. Conversely, eliminating age-based barriers and redesigning career structures around sustainability, equity, and long-term value offers a clear pathway toward a more resilient, inclusive, and productive scientific ecosystem. The future of academic science depends not on accelerating turnover but on fully enabling those who have already demonstrated the capacity and commitment to advance human knowledge.

Recommendations

The evidence presented in this study demonstrates that age discrimination and structural precarity in academic science are systemic rather than incidental problems. Addressing them requires coordinated, multi-level reforms that extend beyond individual institutions and involve governments, funding agencies, universities, and the broader scientific community. The following recommendations are grounded in empirical findings, comparative international evidence, and principles of equity, efficiency, and sustainability.

Structural and Regulatory Reforms

- Academic hiring, promotion, and funding frameworks should eliminate all explicit age-based eligibility criteria. Chronological age is neither a valid proxy for scientific potential nor a reliable indicator of innovation capacity or productivity. Where eligibility restrictions currently exist, they should be replaced with career-stage-based criteria that assess applicants relative to time actively spent in research, with formal recognition of career interruptions due to caregiving, health, military service, migration, or non-academic employment. Legislative and regulatory bodies should explicitly recognize age discrimination in academic employment as incompatible with equal opportunity principles and ensure enforceable compliance mechanisms.
- Fixed-term employment regulations should be restructured to limit excessive serial contracts and prevent prolonged precarity. National frameworks governing academic employment should cap the duration and number of temporary contracts and require transparent transition pathways to permanent positions. Where temporary contracts are necessary for training purposes, their objectives, duration, and expected outcomes must be clearly defined, monitored, and evaluated. Employment laws should prioritize employment stability as a condition for research quality rather than treating insecurity as a default or desirable feature of academic labor markets.

Reform of Funding and Evaluation Systems

- Research funding agencies should revise eligibility rules that implicitly reproduce age discrimination through narrow “early-career” windows. Funding schemes should be redesigned to evaluate scientific readiness, independence, and contribution rather than proximity to PhD completion. Where time-based eligibility windows are retained, they must be flexible, cumulative, and automatically adjusted for documented career interruptions, without placing the burden of justification solely on applicants.
- Evaluation criteria in grant review, hiring, and promotion should move beyond narrow quantitative metrics that reward speed and volume over substance and originality. Excessive reliance on publication counts, journal impact factors, and citation indices incentivizes short-term output and penalizes researchers whose careers include interruptions or slower, more complex research trajectories. Institutions and funding bodies should adopt multidimensional assessment frameworks that recognize diverse contributions, including methodological innovation, team science, mentoring, teaching, infrastructure development, and service to the scientific community.

Diversification of Academic Career Pathways

- Universities and research institutions should formally diversify academic career structures beyond the singular Principal Investigator model. Stable research-track positions, long-term staff scientist roles, teaching-intensive faculty appointments, and hybrid research–education careers should be institutionally legitimized, adequately funded, and embedded within promotion and reward systems. These roles must not function as informal holding positions or “second-tier” alternatives but as respected and permanent components of the academic ecosystem.
- Doctoral and postdoctoral training programs should explicitly prepare researchers for multiple career outcomes rather than implicitly privileging tenure-track trajectories. Transparent communication about career probabilities, structured exposure to diverse professional pathways, and recognition of non-PI careers as successful outcomes are essential for reducing stigma, improving well-being, and aligning training with labor market realities.

Equity, Diversity, and Intersectionality

- Age discrimination must be explicitly integrated into institutional diversity, equity, and inclusion (DEI) frameworks. Policies that address gender, race, nationality, or socioeconomic

background will remain incomplete if age-based exclusion is left unexamined. Institutions should systematically collect and analyze data on career outcomes across age, gender, nationality, caregiving status, and socioeconomic background to identify compounded disadvantages and monitor the effectiveness of interventions.

- Evaluation and promotion processes should incorporate formal adjustments for non-linear career trajectories. Committees must be trained to assess achievement relative to opportunity rather than absolute output, with clear guidance on interpreting productivity in the context of career interruptions or atypical pathways. Without such structural corrections, implicit bias will continue to undermine equity initiatives despite formal commitments.

Improvement of Working Conditions and Research Culture

- Institutions should prioritize employment stability as a prerequisite for high-quality research and innovation. Longer-term contracts, predictable career progression frameworks, and transparent evaluation timelines reduce chronic stress, improve mental health outcomes, and enable researchers to engage in ambitious, high-risk projects that require sustained effort and intellectual continuity.
- Academic leadership should actively address toxic workplace cultures that arise under extreme competition. Clear accountability mechanisms for workplace misconduct, protections for early-career researchers who report abuse, and meaningful oversight of supervisory relationships are essential. Healthy research environments are not ancillary to scientific excellence but foundational to it.

Economic and Societal Alignment

- Governments and policymakers should align doctoral and postdoctoral training capacity with realistic projections of long-term research employment opportunities. Unchecked expansion of PhD production without corresponding career structures represents a misallocation of public resources and undermines trust in academic institutions. Workforce planning must be evidence-based and responsive to long-term societal needs rather than driven solely by short-term institutional incentives.
- Investment in stable research positions should be recognized as a high-return economic strategy rather than a cost burden. Retaining trained scientists within research careers maximizes returns on educational investment, strengthens national innovation systems, and enhances resilience to societal challenges that require sustained scientific expertise.
- Directions for Ongoing Monitoring and Research
- Finally, continuous monitoring of academic career outcomes should be institutionalized through longitudinal tracking systems similar to the EMBL alumni model. Transparent, publicly accessible data on career trajectories, contract stability, and demographic disparities are essential for informed policy-making and accountability. Future research should expand comparative analyses across disciplines and regions, assess the long-term impacts of reform initiatives and examine the relationship between career stability, research quality, and innovation outcomes.

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THE ROLE OF ARTIFICIAL INTELLIGENCE IN TRAINING FUTURE FOREIGN LANGUAGE TEACHERS

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Abstract

This article explores the pedagogical potential of applying artificial intelligence in the training of future foreign language teachers in higher education institutions. The study focuses on analyzing the impact of artificial intelligence on the development of students' language skills, the individualization of instruction, and the formation of professional competencies. The research is based on a descriptive-analytical approach and involves a theoretical analysis of domestic and international scholarly works in the fields of linguodidactics, pedagogy, and digital education. The findings indicate that the purposeful use of artificial intelligence grounded in didactic principles enhances the effectiveness of training future foreign language teachers. At the same time, artificial intelligence is conceptualized not as a tool that replaces the instructor, but as a pedagogical resource that enriches the educational process.

Keywords: artificial intelligence, foreign language teaching, future teachers, higher education institution, pedagogical potential, digital education, personalized learning

РОЛЬ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ПОДГОТОВКЕ БУДУЩИХ УЧИТЕЛЕЙ ИНОСТРАННОГО ЯЗЫКА

Аннотация

В статье рассматриваются педагогические возможности использования искусственного интеллекта в подготовке будущих учителей иностранного языка в высших учебных заведениях. Исследование направлено на анализ влияния искусственного интеллекта на развитие языковых навыков студентов, индивидуализацию обучения и формирование профессиональных компетенций. Научная работа основана на описательно-аналитическом подходе и включает теоретический анализ отечественных и зарубежных научных трудов в области лингводидактики, педагогики и цифрового образования. Результаты исследования показывают, что целенаправленное применение искусственного интеллекта на основе дидактических принципов повышает эффективность подготовки будущих учителей иностранного языка. При этом искусственный интеллект рассматривается не как средство, заменяющее преподавателя, а как педагогический ресурс, обогащающий образовательный процесс.

Ключевые слова: искусственный интеллект, обучение иностранному языку, будущие учителя, высшее учебное заведение, педагогические возможности, цифровое образование, персонализированное обучение

Introduction

The education system of the twenty-first century has undergone profound transformations under the conditions of globalization, digitalization, and technological progress. These changes have had a direct impact on foreign language teaching, particularly on the methodology of learning English and other international languages. Foreign language proficiency has become a key element in the formation of teachers' professional competence, the improvement of instructional quality, and the enhancement of students' academic mobility.

The integration of artificial intelligence into the educational sphere requires a reorganization of the teaching and learning process. AI offers opportunities for assessing language skills, personalizing learning trajectories, providing feedback, and automatically analyzing errors. In this regard, artificial intelligence should be regarded as an effective pedagogical tool in the training of future foreign language teachers. However, its application is not merely a technical issue; it also demands sound pedagogical and methodological grounding.

Moreover, the use of artificial intelligence not only facilitates teachers' professional activities but also makes the language development process more interactive and effective for students. AI-based platforms are capable of automatically assessing skills such as grammar, vocabulary, sentence structure, and listening comprehension, while offering learners targeted recommendations. This, in turn, enables the personalization of the learning process and the design of tasks adapted to each student's proficiency level and learning pace.

In addition, artificial intelligence contributes to the development of future teachers' research and critical thinking skills. With the support of AI, students can analyze learning materials, understand their errors, and systematically improve their knowledge. Furthermore, AI enables immersion in a linguistic environment through virtual communicative situations and simulations, enriching experiences in speaking, listening, and text production in a foreign language. This strengthens the professional competence of future teachers and ensures their preparation in accordance with contemporary educational requirements.

Artificial Intelligence and Foreign Language Teaching: Theoretical Foundations

Artificial intelligence represents a set of technologies aimed at modeling human cognitive abilities such as thinking, learning, and decision-making within computer systems. In the educational context, AI enables the personalization of instruction, the adaptive delivery of learning materials, and the optimization of the learning process by taking into account learners' individual abilities.

In foreign language teaching, artificial intelligence—through natural language processing (NLP), machine learning, and language models—creates opportunities to analyze learning materials at grammatical, lexical, and discourse levels. This contributes to the development of new interactive formats that support the enhancement of students' language skills.

While traditional instruction is largely teacher-centered, AI-based learning strengthens a learner-centered approach. By analyzing students' learning pace, errors, and achievements, AI provides individualized recommendations, thereby facilitating the implementation of the principles of personalized learning.

Artificial intelligence also enhances feedback mechanisms between teachers and students in foreign language education. By analyzing learners' linguistic performance, AI identifies specific errors, offers corrective feedback, and explains their underlying causes. This process not only reduces teachers' workload but also enables students to understand and independently correct their mistakes. As a result, learning effectiveness increases, and the rate of language skill acquisition is accelerated.

Moreover, AI contributes to the development of communicative competence by creating virtual language environments. Through interactive tasks, simulations, chatbots, and role-playing activities, students gain practical experience in speaking, listening, and writing in a foreign

language. When integrated with instructor guidance and supervision, such technologies enhance the professional competence of future foreign language teachers and ensure their preparation in accordance with contemporary educational requirements.

Pedagogical Potential of Artificial Intelligence in Training Future Foreign Language Teachers at Higher Education Institutions

The key pedagogical potentials of artificial intelligence include:

Personalized Learning: Given the diverse levels of students' language proficiency, cognitive styles, and motivation, AI provides individually adapted tasks tailored to each learner's needs.

Immediate Feedback: AI can automatically detect and explain errors in both written and spoken language. This not only reduces the instructor's workload but also fosters students' ability for autonomous learning.

Development of Communicative Competence: Through virtual interlocutors and dialogue-based simulations, students can practice in authentic language environments, enhancing their real-world communicative skills.

Enhancement of Academic Language Skills: AI supports the development of academic writing abilities by analyzing scholarly texts, checking terminological consistency, and evaluating the structure of argumentation.

The Role of the Teacher and Artificial Intelligence

Artificial intelligence does not replace the teacher; rather, it elevates the teacher's role to a new level. The instructor is no longer solely a provider of knowledge but assumes the roles of designer, facilitator, and evaluator within the learning process.

Teacher Responsibilities:

- Pedagogically interpreting AI tools;
- Upholding ethical standards and academic integrity;
- Supporting students' critical thinking and independent learning skills;
- Enhancing digital and methodological competencies.

AI transforms the interaction between teacher and student, positioning the teacher as an observer, analyst, and organizer of feedback.

Furthermore, AI enables instructors to monitor the learning process more effectively. By automatically analyzing students' progress, errors, and academic performance, teachers can make data-driven strategic decisions. This facilitates the personalization of learning materials, the provision of additional resources, and the targeted support of each student's needs, thereby improving educational quality.

The use of AI tools also enhances teachers' creative potential. By automating routine tasks, instructors can dedicate more attention to analytical and pedagogical aspects. Additionally, AI enables interactive learning experiences through virtual simulations, interactive exercises, and chatbots, increasing student engagement and enriching the collaborative learning environment between teacher and learners.

Discussion

Theoretical and practical analyses indicate that artificial intelligence possesses significant pedagogical potential in the training of future foreign language teachers. However, this potential can only be fully realized when didactic principles are carefully observed. Mechanical or uncritical use of AI may fail to have a comprehensive impact on students' linguistic and cognitive development.

Institutional support, teachers' digital competence, and methodological preparedness are decisive factors for effective AI implementation. To ensure optimal use of AI, it is essential to:

- Develop specialized methodological models;
- Train instructors in digital competencies;
- Implement monitoring of learning outcomes and personalized instruction.

During AI-assisted instruction, it is crucial to preserve the authentic nature of language communication, as well as the cultural, social, and interpersonal contexts.

The integration of AI into the learning process must be aligned with pedagogical ethics and academic integrity. Students should use AI tools strictly as auxiliary resources, while actively developing their own knowledge and critical thinking skills. Such an approach strengthens the teacher-student relationship, makes the educational process more interactive and effective, and fosters the professional and personal competencies of future teachers.

Conclusion

The findings of the study indicate that artificial intelligence holds significant pedagogical potential in the training of future foreign language teachers. Its main applications include:

- Personalization of instruction;
- Provision of immediate and continuous feedback;
- Enhancement of students' linguistic and cognitive engagement;
- Development of academic and professional competencies.

The effectiveness of AI is realized through its alignment with didactic strategies and the professional competence of the instructor. In the future, it is essential to pilot AI-based instructional models, conduct practical trials, and train instructors in digital competencies. These measures can provide a foundation for the sustained improvement of higher education quality and the effective development of students' scientific and cognitive potential.

To assess the concrete effectiveness of AI in training future foreign language teachers, various research findings have been considered. For instance, AI-based platforms enable systematic monitoring and correction of students' grammatical and lexical skills, increasing instructional efficiency compared to traditional classroom methods. Moreover, personalized tasks and automated feedback enhance students' learning motivation and facilitate rapid correction of language errors. International experience demonstrates that the use of NLP and language models significantly improves students' writing and speaking abilities. Pilot projects in Kazakhstani higher education institutions have shown that AI application contributes to the development of critical thinking, self-monitoring, and research skills among students.

Furthermore, the effectiveness of AI depends not only on technological implementation but also on the presence of a sound pedagogical and methodological foundation. Research indicates that the degree of integration between the instructor's didactic strategy and AI tools directly affects students' learning outcomes. For example, if AI is used solely for automated assessment, students' creative and communicative skills may not develop adequately. Therefore, in the future, when implementing AI-based instructional models in Kazakhstani universities, it is essential to develop methodological guidelines, provide instructor training, and systematically monitor students' learning outcomes. Such a comprehensive approach will maximize the pedagogical potential of AI in the training of future teachers and ensure the sustained enhancement of higher education quality.

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ВЛИЯНИЕ ОРГАНИЗОВАННОЙ ВНЕУЧЕБНОЙ ДЕЯТЕЛЬНОСТИ НА ПРОЦЕССЫ АДАПТАЦИИ СТУДЕНТОВ ПЕРВОГО КУРСА

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THE INFLUENCE OF ORGANIZED EXTRACURRICULAR ACTIVITIES ON THE ADAPTATION PROCESSES OF FIRST-YEAR UNIVERSITY STUDENTS

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АННОТАЦИЯ

Период первого курса- это не просто смена статуса, а многокомпонентная адаптация к новым академическим нормам, социальным правилам и повышенной автономии. В статье рассматривается, как организованная внеучебная деятельность- то есть структурированные активности вне аудиторных занятий (клубы, наставничество, учебные сообщества, тьюторские практики, проектные команды), имеющие цели, регламент и сопровождение- воздействует на процессы адаптации первокурсников. Теоретическая рамка объединяет классические модели удержания и вовлечённости, где ключевыми выступают академическая и социальная интеграция, а также качество взаимодействий со средой университета. На основе мета-аналитических и экспериментальных исследований в высшем образовании формулируются три основных механизма влияния ОВД: (1) формирование принадлежности и поддерживающих связей, (2) усиление поведенческой вовлечённости и учебной дисциплины через структурирование времени, (3) наращивание психологических ресурсов (самоэффективность, адаптивные атрибуции, учебная саморегуляция). Предложена прикладная модель «OCA-Adaptive Cycle» для университетов: диагностика потребностей первокурсников, модульное проектирование ОВД, низкопороговый рекрутинг, мониторинг рисков перегрузки и смешанная оценка результатов.

ABSTRACT

The first year of university is not merely a change of status but a multicomponent process of adaptation to new academic norms, social rules, and increased autonomy. This article examines how organized extracurricular activities (OEA)- that is, structured activities outside the classroom (clubs, mentoring, learning communities, tutoring practices, project teams) with defined goals, regulations, and institutional support- influence the adaptation processes of first-year students. The theoretical framework integrates classical models of retention and engagement, in which academic and social integration, as well as the quality of interactions with the university environment, play a central role. Drawing on meta-analytic and experimental research in higher education, the study identifies three key mechanisms through which OEA exert their effects: (1) the formation of a sense of belonging and supportive ties, (2) the enhancement of behavioral engagement and academic discipline through time structuring, and (3) the development of

psychological resources (self-efficacy, adaptive attributions, and academic self-regulation). An applied model, the “OEA-Adaptive Cycle”, is proposed for universities, encompassing the diagnosis of first-year students’ needs, modular design of extracurricular activities, low-threshold recruitment, monitoring of overload risks, and mixed-method outcome evaluation.

Ключевые слова: первокурсники; адаптация; организованная внеучебная деятельность; вовлечённость; наставничество; учебные сообщества; оценка эффективности; высшее образование

Keywords: first-year students; adaptation; organized extracurricular activities; engagement; mentoring; learning communities; effectiveness assessment; higher education.

Введение

Переход в университет на первом курсе выглядит как “обычная” образовательная траектория только на расстоянии. В реальности он устроен как резкая смена институциональной культуры: студенту нужно освоить новые правила оценивания, иной темп учебной нагрузки, незнакомую систему коммуникации с преподавателями и администрацией, а параллельно - встроиться в социальную ткань кампуса, не потеряв учебную направленность. В классической теоретической перспективе удержание студентов связано с тем, насколько успешно формируется академическая и социальная интеграция - иными словами, насколько студент “врастает” в учебные и межличностные контуры университета [1].

На этом фоне организованная внеучебная деятельность (ОВД) представляет собой не “досуг ради досуга”, а управляемую инфраструктуру адаптации. В отличие от спонтанного общения, ОВД имеет программу, роли, регулярность и часто - педагогический замысел: это может быть наставничество, учебные сообщества, клубы по интересам с кураторством, студенческие научные группы, волонтерские проекты, дебаты, проектные команды. В рамках концепции вовлечённости важно не количество активностей, а качество участия и степень психологической и поведенческой включённости студента в образовательную среду [2].

Цель статьи - разработать доказательную модель влияния ОВД на адаптацию первокурсников в университетской среде.

Гипотезы:

H1- ОВД повышает адаптацию через рост принадлежности и поддерживающих связей в кампусе.

H2- ОВД влияет на адаптацию через поведенческую вовлечённость и структурирование учебных привычек.

H3- ОВД усиливает психологические ресурсы (самоэффективность, саморегуляция), что опосредует связь с адаптацией.

Материалы и методы

Дизайн исследования

Предлагается дизайн, который может быть реализован университетом как институциональное исследование качества образования:

- Тип: квазиэксперимент с сопоставлением групп (участники ОВД vs неучастники) + компонент “естественного эксперимента” при наличии рандомизированных элементов (например, распределение в учебные сообщества или обязательные вводные модули). Логика опирается на выводы, что наблюдательные оценки часто завышают эффект из-за самоселекции, а экспериментальные дизайны нередко дают более трезвую картину.
- Период: 1 семестр (минимум) + контрольное измерение на конце 1 курса.
- Единица анализа: студент первого курса.

Адаптация трактуется как комплекс из академической, социальной и личностно-эмоциональной составляющих. Для измерения могут применяться стандартизированные инструменты “адаптации к колледжу”, валидность структуры которых проверялась в исследованиях с факторным анализом [9].

Оценка ковариат и контроль смещений

Чтобы минимизировать искажения:

- учитываются исходные академические показатели (входные баллы, результаты диагностик),
- социально-психологические характеристики (стресс, самооффективность),
- занятость и финансовая нагрузка,
- “доза участия” в ОВД (частота, роль, длительность).

Адаптация первокурсника не сводится к успеваемости. Она складывается из нескольких взаимосвязанных контуров: академического, социального, личностно-эмоционального и институционального. Таблица 1 выполняет роль операционального “словаря”: она переводит теоретические понятия в индикаторы и показывает, на какие компоненты ОВД может воздействовать с наибольшей вероятностью.

Таблица 1. Операциональная структура адаптации первокурсника

Компонент адаптации	Содержательное ядро	Пример индикаторов (измеряемые)	Роль ОВД
Академическая	освоение требований и учебных практик	посещаемость, выполнение заданий, саморегуляция, учебные стратегии	задаёт структуру времени и практик
Социальная	включённость в связи и нормы кампуса	число устойчивых контактов, участие в группах, субъективная принадлежность	создаёт социальные “мосты”
Личностно-эмоциональная	стрессо-устойчивость, уверенность, благополучие	самооффективность, усталость, субъективная адаптированность	формирует психологические ресурсы
Институциональная	контакт с преподавателями и сервисами	обращения за поддержкой, знание правил и ресурсов	снижает “барьеры входа”

Таблица 1 позволяет избежать типичной ошибки, когда любую активность автоматически считают “улучшающей адаптацию”. Разные форматы ОВД затрагивают разные компоненты: клубы чаще усиливают социальную интеграцию, учебные сообщества - академическую дисциплину, наставничество - принадлежность и обращаемость за поддержкой. Следовательно, эффект программы логично оценивать не только по итоговым результатам, но и по тому, какой компонент адаптации был целевым и изменился ли он в течение семестра. Чтобы ОВД была управляемой, её нужно описывать как цикл, а не как набор мероприятий. Университетский эффект возникает тогда, когда есть диагностика барьеров первокурсников, подбор формата под эти барьеры, низкопороговый вход и сопровождение, а затем мониторинг механизмов и корректировка. Рисунок 1 показывает именно такую причинно-процессную логику: от входа студента в новую среду к измеряемым механизмам (принадлежность, вовлечённость, самооффективность) и дальше к адаптации и исходам.

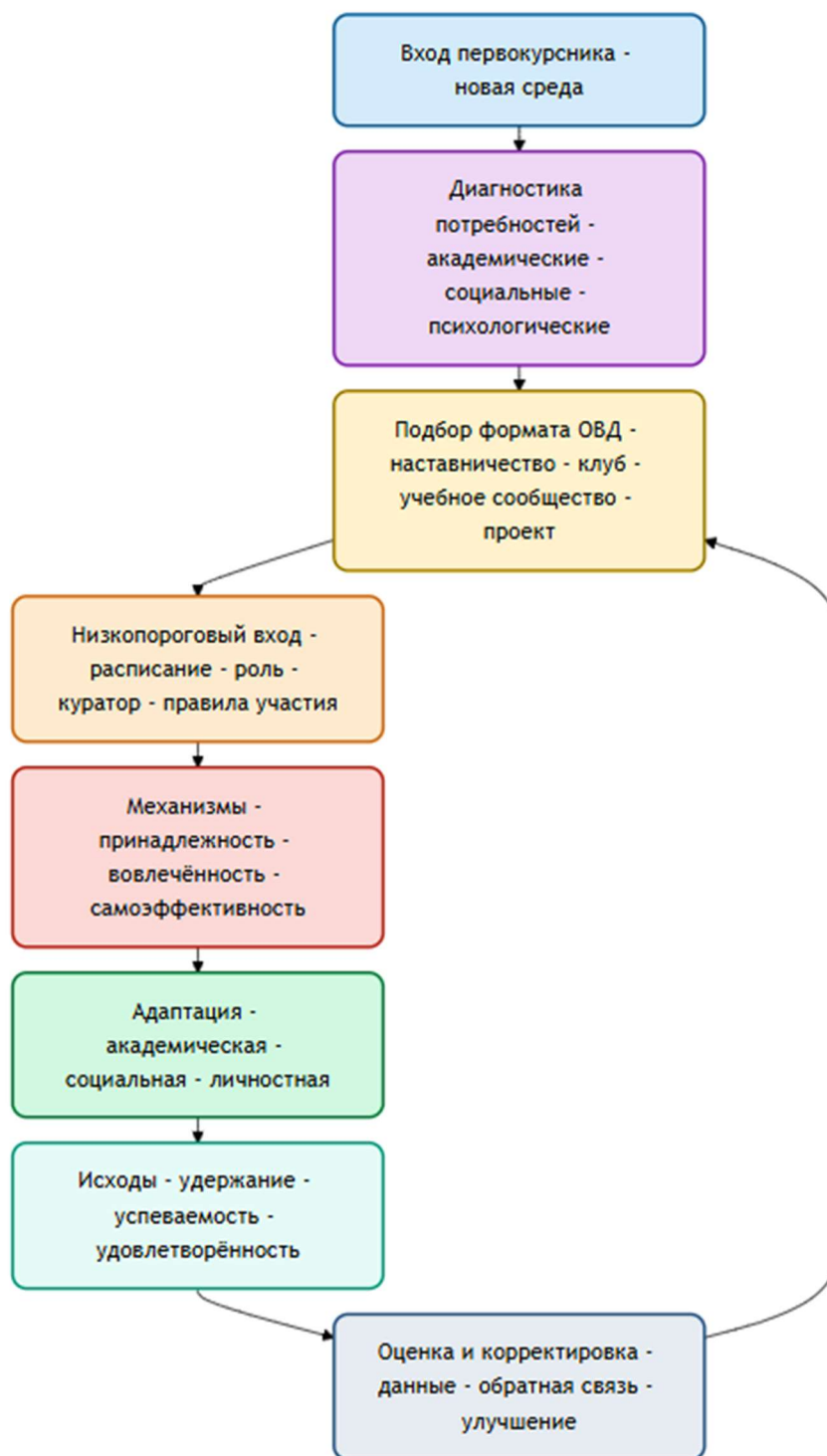


Рисунок 1. Модель «OCA-Adaptive Cycle»

Рисунок 1 подчёркивает два принципа. Первый - ОВД влияет на адаптацию прежде всего через механизмы, поэтому их нужно измерять, иначе программа останется “чёрным ящиком”. Второй - качество входа критично: без ясных правил участия и сопровождения активность обслуживает в основном уже адаптированных. Цикл также встроенно учитывает риск перегрузки: вовлечённость полезна, пока она не разрушает учебный режим. Это подводит к обсуждению доказательств и границ уверенности.

Результаты

Мета-анализ по вовлечённости студентов в высшем образовании показывает, что качество отношений “преподаватель - студент” и поддерживающее поведение

преподавателя связаны с вовлечённостью на уровне умеренных корреляций; в частности, сообщаются значения $R = 0,456$ для отношения “преподаватель- студент” и $R = 0,419$ для позитивного поведения преподавателя, а база данных включает 93 188 участников [8]. Это важное подтверждение того, что ОВД, где присутствует тьюторство, наставники или кураторы, потенциально “встраивает” студента в социально-академический интерфейс, не оставляя его один на один с системой.

Методологически обзоры по социально-психологическим интервенциям в колледже концентрируются на рандомизированных исследованиях и показывают, что эффекты умеренные, но особенно полезны для групп риска; при этом результативность зависит от институционального контекста и условий внедрения. Отсюда следует принцип: универсальная “активность для всех” часто проигрывает адаптивным форматам, ориентированным на конкретные барьеры первокурсника. Рандомизированное исследование учебных сообществ показало, что экспериментальная оценка может не обнаружить эффекта, тогда как наблюдательные подходы демонстрируют “большие и значимые” эффекты именно из-за неслучайного отбора студентов.

Таблица 2. Матрица доказательств для проектирования ОВД

Линия доказательств	Что установлено	Методологи-ческая оговорка	Что брать в дизайн ОВД
Вовлечённость и среда	вовлечённость связана с качеством отношений и поддержкой	важны контекст и измерения	кураторство, наставничество, малые группы
Адаптация как предиктор	адаптация многомерна и связана с удержанием и оценками	требуется валидный инструмент	регулярные измерения адаптации
Интервенции	эффекты зависят от того, кому и как внедряют	переносимость ограничена	сегментация первокурсников
Учебные сообщества	RCT может давать нулевой эффект при селекции	сравнение подходов обязательно	дизайн с контролем самоселекции

Матрица показывает, что эффективность ОВД зависит не от названия формата, а от проектной дисциплины: регулярность, роль новичка, понятный вход, подготовленный куратор, связь с учебной реальностью. Без этих условий ОВД может усилить не адаптацию, а поляризацию: уверенные студенты получают еще больше ресурсов, а уязвимые остаются за бортом. Это особенно критично для первого семестра, когда студент еще не освоил социальные коды университета. Поэтому справедливый доступ должен быть встроен в дизайн, а не оставлен на совесть участников.

Обсуждение

Механизм 1. Принадлежность как антидот изоляции первокурсника

Экспериментальные исследования “принадлежности” показывают, что корректно устроенные вмешательства способны менять траектории академического поведения через снижение чувства социальной исключённости. Современные систематические обзоры по принадлежности в высшем образовании подчёркивают, что эффект не возникает “сам”: он опирается на конкретные практики среды и качество включения студентов. В этом месте ОВД выступает как технологический контур: она создаёт не просто “контакты”, а устойчивые роли и нормы участия, где у первокурсника появляется право на вопрос, ошибку и поддержку.

Механизм 2. Поведенческая вовлечённость и учебные привычки

Когда ОВД содержит структурированные учебные элементы (наставничество по учебным стратегиям, сессионные занятия с участием обучающихся-наставников (PASS), тьюторские практики), она работает не как “мотивационный плакат”, а как тренировка поведенческих паттернов. Практика PASS в высшем образовании рассматривается как социально организованная форма учебного участия, где учебная деятельность превращается в норму группы, а не индивидуальный подвиг.

При этом эмпирические данные по кокуррикулярным программам, ориентированным на конкретные учебные навыки, демонстрируют связь с улучшением академической результативности и удержания в первом году обучения, но важнейшее условие – чёткая структура и регулярность.

Механизм 3. Самоэффективность и психологические ресурсы как “двигатель адаптации”

Лонгитюдные исследования показывают, что академическая самоэффективность связана с адаптацией и учебными исходами первокурсников. Более широкие мета-аналитические обобщения подчёркивают: психологические корреляты успеваемости многоканальны, и многие из них “работают” через поведение, а не напрямую. Поэтому ОВД, чтобы быть не декоративной, должна усиливать именно практики, которые подкрепляют самоэффективность: малые победы, обратная связь, ясные ожидания, роль наставника, социальное подтверждение прогресса.

Заключение

Организованная внеучебная деятельность может рассматриваться как воспроизводимый инструмент поддержки адаптации первокурсников при условии четкого программного дизайна и валидной оценки. Ее влияние реализуется преимущественно через три механизма: усиление чувства принадлежности и поддерживающих связей, рост поведенческой вовлеченности и учебной дисциплины, а также повышение академической самоэффективности и саморегуляции. При этом ожидаемые эффекты в высшем образовании, как правило, умеренные и контекстно зависимые, а наблюдательные сравнения участников и неучастников уязвимы к смещению из-за самоселекции. Следовательно, оценка эффективности должна включать базовые измерения, контроль ковариат и учет дозы участия, а сама ОВД – быть модульной, адресной и сопровождаться контуром профилактики перегрузки.

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ЖАЛПЫ ОРТА БІЛІМ БЕРЕТІН МЕКТЕПТЕ АҒЫЛШЫН ТІЛІ ПӘНІН ОҚЫТУДА АРТ ТЕХНОЛОГИЯСЫН ҚОЛДАНУДЫҢ ТИІМДІЛІГІ: СӨЙЛЕУ DAҒДЫЛАРЫН ДАМУЫҒА АРНАЛҒАН ART МОДЕЛІНІҢ ӘДІСТЕМЕЛІК НЕГІЗІ

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Аңдатпа. Ағылшын тілін мектепте оқытудағы ең күрделі мәселенің бірі - оқушының білген сөзін, меңгерген грамматикалық ережесін нақты сөйлеу әрекетіне айналдыра алмауы. Көп жағдайда оқушы тапсырманы түсінеді, қажетті сөздерді таниды, бірақ сынып алдында еркін сөйлеуге, ойын жылдам құрастыруға, серіктесінің жауабына табиғи түрде үн қосуға қиналады. Бұл жағдай ағылшын тілі сабағында сөйлеуді тек жаттығу арқылы емес, оқушының қабылдауы, эмоциясы, ойы және тілдік дайындығы біріккен әдістемелік жүйе арқылы дамыту қажеттігін көрсетеді. Осы мақалада арт технологиясы сөйлеу дағдысын қалыптастырудың тиімді құралы ретінде қарастырылып, ART моделі Artistic stimulus, Reflective rehearsal, Task-based transfer кезеңдері негізінде ұсынылады. Көркем стимул оқушыны ойлануға, байқауға және тақырыпқа жеке қатынас білдіруге жетелейді; рефлексиялық дайындық сөздік тірек, сөйлем үлгілері, айтылым жаттығулары және кері байланыс арқылы сөйлеуге сенімділік қалыптастырады; коммуникативтік тапсырма кезеңі дайындалған тілдік материалды рөлдік ойын, әңгімелеу, пікірталас, сұхбат немесе презентация түріндегі нақты ауызша өнімге айналдырады. Мақалада ART сабағының алгоритмі, сөйлеу көрсеткіштері, бағалау өлшемдері және мұғалім тәжірибесінде қолдануға болатын тапсырмалар жүйесі ұсынылады. Арт технологиясының басты құндылығы - оқушыны жай ғана қызықтыруда емес, көркем қабылдау мен мақсатты сөйлеу әрекетін байланыстырып, ағылшын тіліндегі ауызша қарым-қатынасты табиғи, сенімді және мағыналы етуінде.

Түйін сөздер: арт технологиясы, ағылшын тілі, сөйлеу дағдысы, ART моделі, көркем стимул, рефлексиялық дайындық, коммуникативтік тапсырма, drama-based pedagogy, коммуникативтік құзыреттілік, жалпы орта мектеп.

THE EFFECTIVENESS OF USING ART TECHNOLOGY IN TEACHING ENGLISH AT A GENERAL SECONDARY SCHOOL: METHODOLOGICAL FOUNDATIONS OF THE ART MODEL FOR DEVELOPING SPEAKING SKILLS

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Abstract. One of the most complex issues in school-based English language teaching is the learner's inability to transform known vocabulary and grammatical knowledge into real speaking performance. In many cases, learners understand the task and recognize the necessary language forms, yet they still struggle to speak confidently in front of the class, formulate ideas quickly, and respond naturally to a partner's remarks. This situation shows that speaking should be developed not only through mechanical practice, but through a methodological system that connects perception, emotion, thinking, and language preparation. The article examines art technology as an effective tool for developing speaking skills and presents the ART model based on three stages: Artistic Stimulus, Reflective Rehearsal, and Task-Based Transfer. The artistic stimulus encourages learners to observe, think, and express a personal response to the topic; reflective rehearsal builds speaking confidence through vocabulary support, sentence frames, pronunciation practice, and feedback; task-based transfer turns prepared language into a concrete oral product, such as role-play, storytelling, discussion, interview, or presentation. The article proposes an ART lesson algorithm, speaking indicators, assessment criteria, and a system of tasks applicable to English teacher practice. The main value of art technology lies not in simple learner engagement, but in its ability to connect artistic perception with purposeful speaking and make oral communication in English more natural, confident, and meaningful.

Keywords: art technology, English language, speaking skills, ART model, artistic stimulus, reflective rehearsal, communicative task, drama-based pedagogy, communicative competence, general secondary school.

Kipicne

Қазақстандағы жалпы орта білім беру ағылшын тілін тек пәндік мазмұн ретінде емес, оқушының коммуникативтік әрекетіне тікелей қызмет ететін құрал ретінде қарастырады. 2022 жылғы №399 бұйрықпен бекітілген үлгілік оқу бағдарламалары жүйесінде «Ағылшын тілі» пәні бастауыш, негізгі орта және жалпы орта білім деңгейлеріндегі тілдік дағдылармен байланыста беріледі; бұл бағдарламада сөйлеу, тыңдалым, оқылым, жазылым және тілдік бірліктер бір-бірінен бөлек емес, оқу әрекетінің тұтас жүйесі ретінде орналасады [1].

Мәселе дәл осы тұтастықты сынып ішінде іске асыруда байқалады. Оқушы ағылшын сөздерін жаттайды, жаттығуда дұрыс жауап береді, мұғалімнің сұрағына қысқа сөйлеммен жауап беруі де мүмкін. Бірақ сөйлеу дағдысы бұнымен шектелмейді. Сөйлеу нақты уақыт ішінде ой құрастыруды, лексикалық таңдау жасауды, грамматикалық дәлдікті сақтауды, айтылымды бақылауды, серіктестің реакциясына жауап беруді және өз пікірін әлеуметтік жағдаятқа сай жеткізуді талап етеді. CEFR Companion Volume сөйлеу әрекетін production, interaction, mediation сияқты өзара байланысты категориялар арқылы сипаттайды; онда жоспарлау, turn-taking, clarification, spoken fluency, phonological control және creative texts-пен жұмыс істеу секілді дескрипторлар нақты көрсетілген [2].

Жалпы мектептегі ағылшын сабағында арт технологиясы осы күрделі дағдыны табиғи түрде іске қоса алады. Бірақ оны «сурет салу», «ән тыңдау», «теат ойнау» деңгейінде түсіндіру жеткіліксіз. Мұндай қарапайым түсіндіру арт технологиясының әдістемелік өзегін әлсіретеді. Көркем материал сөйлеуге себеп бермесе, рефлексиялық дайындық ұйымдастырылмаса, соңында нақты ауызша өнім болмаса, арт элементі сабақтағы қысқа эмоционалдық үзіліске айналып кетеді. ART моделінің құндылығы осы жерде ашылады: оқушы алдымен көркем стимулды байқайды, одан кейін тілдік жағынан дайындалады, соңында дайындалған материалды коммуникативтік тапсырмада қолданады.

ЮНЕСКО-ның 2024 жылғы Culture and Arts Education Framework құжаты мәдениет пен өнерді білім берудің жеке саласы ғана емес, оқыту құралы, әдіснамалық тәсіл және зерттеу тәжірибесі ретінде таниды. Құжатта мәдениет пен өнер арқылы оқыту шығармашылықты, сыни ойлауды, сөйлеу және жазу дағдыларын, әлеуметтік-эмоциялық қабілеттерді дамытуға ықпал ететіні көрсетілген [3].

Ағылшын тілін оқытудағы арт технологиясының өзектілігі үш нақты себеппен күшейеді. Біріншіден, оқушыларда сөйлеуге арналған идея жетіспейді. Оларға «My hobby», «My school», «My city» сияқты тақырыптар жиі таныс, бірақ олар жаңа ой тудырмайды. Екіншіден, оқушы қателесуден қорқады. Қате жауап беру қаупі сөйлеуді тежейді, әсіресе сыныптастар алдында. Үшіншіден, дәстүрлі speaking practice кейде грамматикалық құрылымдарды қайталау деңгейінде қалып, оқушының тұлғалық қатысуын іске қоспайды. Көркем стимул осы үш қиындыққа бірден әсер етеді: ол ой береді, пікір алуандығын заңды етеді, тілдік әрекетті жеке тәжірибемен байланыстырады.

Әдеби шолу

Арт технологиясын ағылшын тілі сабағына енгізу туралы ойды дәлелдеу үшін алдымен өнердің оқу нәтижесіне әсері жөніндегі зерттеулерге сақ қарау қажет. OECD дайындаған «Art for Art's Sake? The Impact of Arts Education» еңбегінде өнер білімінің әртүрлі дағдыларға ықпалы кең талданғанымен, авторлар трансфер нәтижелері туралы асыра айтуға болмайтынын ескертеді. Сонымен қатар театрлық білімнің verbal skills, reading және text understanding бағыттарында оң әсері бар екені, ал шығармашылық, мотивация, self-concept секілді салаларда қосымша эмпирикалық зерттеу қажет екені айтылады [4].

Бұл сақтық арт технологиясын әлсіретпейді, керісінше оны ғылыми тұрғыдан нақтылауға мәжбүр етеді. Егер өнер оқытуда тек безендіру қызметін атқарса, оның тілдік нәтижесі кездейсоқ болады. Егер өнер арнайы сөйлеу мақсатына бағындырылса, ол оқушының қабылдауын, ойлауын, сөздік қорын және коммуникативтік әрекетін байланыстыратын қуатты медиаторға айналады. Л.С. Выготскийдің қиял мен шығармашылық туралы еңбегінде шығармашылық әрекет жаңа нәрсе тудыратын психологиялық үдеріс ретінде түсіндіріледі; бұл идея ағылшын тіліндегі сөйлеудің дайын форманы қайталау емес, жаңа мағына құру екенін түсіндіруге мүмкіндік береді [5].

Дж. Дьюи өнерді өмірлік тәжірибеден бөлмей қарастырады. Оның эстетикалық тәжірибе туралы тұжырымы ағылшын тілін оқыту үшін маңызды: оқушы көргенін, сезінгенін, аңғарғанын тіл арқылы реттейді. Бұл жерде тіл сыртқы бақылау құралы емес, тәжірибені ұйымдастыру құралына айналады [6].

Э.В. Айснер өнердің танымдық маңызын адамның күрделі мағыналарды байқау, айырмашылықты сезу және бейнелік ойлау қабілетімен байланыстырады. Ағылшын тілі сабағында бұл қабілет сурет, фотосурет, қысқа бейне, зат немесе драмалық жағдай арқылы іске қосылады. Оқушы «What is in the picture?» сұрағынан «Why might this person feel lonely?», «What can happen next?», «What is the hidden conflict?» деңгейіне көтерілгенде, сөйлеу репродуктивті жаттығудан интерпретациялық әрекетке ауысады [7].

Г. Кресс ұсынған multimodality тұжырымы қазіргі коммуникацияның тек сөзден тұрмайтынын көрсетеді. Мағына жазу, сөйлеу, бейне, дыбыс, ым, кеңістік, түс және

композиция арқылы құралады [8]. Ағылшын тілін үйретуде бұл тұжырым өте маңызды: оқушы суретке қарап сөйлем құрағанда, ол визуалды белгіні вербалдық формаға аударады; музыка тыңдап эмоцияны сипаттағанда, аудиалдық әсерді лексикалық таңдау арқылы жүйелейді; рөлдік ойында дене қимылы мен дауыс ырғағы сөйлеу мазмұнымен бірге жұмыс істейді.

Task-based language teaching бағыты да ART моделінің үшінші кезеңін негіздейді. Р. Эллис task ұғымын оқушы мағынаға бағытталған тілдік әрекет орындайтын, нақты нәтиже шығаратын және тілдік ресурстарды мақсатқа сай қолданатын оқу бірлігі ретінде сипаттайды [9]. Арт технологиясында task кездейсоқ қосымша емес: көркем стимул мен дайындық кезеңінен кейін оқушы диалог, сұхбат, storytelling, debate, gallery talk немесе presentation түрінде ауызша өнім береді.

М. Свейннің Output Hypothesis тұжырымы бойынша тілдік өнім оқушыны өз біліміндегі бос орындарды байқауға, болжамды тексеруге және форма мен мағына туралы ойлануға итермелейді [10]. Бұл арт технологиясының рефлексиялық кезеңін күшейтеді. Оқушы суретті көргеннен кейін бірден ұзақ сөйлеуге міндеттелмейді; алдымен сөз жинайды, phrase bank жасайды, сөйлем үлгілерін таңдайды, айтылымды қайталайды, жұпта қысқа репетиция жасайды. Осыдан кейін ғана толық коммуникативтік тапсырмаға өтеді.

М. Байгейт, П. Скехан және М. Свейннің педагогикалық task туралы еңбегі тапсырманың құрылымы, когнитивтік жүктемесі, өзара әрекет және бағалау логикасы ескерілмесе, communicative task өздігінен сапалы сөйлеу нәтижесін бермейтінін көрсетеді [11]. Демек, арт технологиясы үшін де «қызықты тапсырма» жеткіліксіз. Оқушы не үшін сөйлейтінін, қандай тілдік құрал қолданатынын, қандай критериймен бағаланатынын, жауаптың соңғы формасы қандай болатынын нақты білуі керек.

Drama-based pedagogy бағытында М. Стинсон мен Дж. Уинстон drama екінші тіл үйренуде әлеуметтік рөл, контекст және мақсатты өзара әрекет жасайтынын көрсетеді. Олардың еңбегінде drama сөзді жай айтқызбайды, оны әлеуметтік жағдайға енгізеді деген ой бар [12].

Дж. Белливо мен В. Ким drama in L2 learning бойынша екі онжылдық зерттеулерді талдап, drama-based learning оқушыға contextually situated, engaging, multimodal және empowering тілдік тәжірибе бере алатынын жазады, бірақ нақты сыныптағы қабылдау мен эмпирикалық дәлелдер әлі де жеткіліксіз екенін көрсетеді [13]. Бұл ескерту мақаланың ғылыми ұстанымын нақтылайды: арт технологиясын тиімді деп айту үшін оны әдістемелік модель, бағалау критерийі және эмпирикалық тексеру мүмкіндігімен бірге ұсыну қажет.

А. Галанте мен Р.И. Томсон drama-based instruction екінші тілдері oral fluency, comprehensibility және accentedness дамуына әсерін зерттеген. TESOL Quarterly журналындағы зерттеу drama-based instruction дәстүрлі коммуникативтік оқытумен салыстырғанда L2 oral fluency бойынша үлкенірек ілгерілеуге алып келуі мүмкін екенін көрсетеді [14].

Ш. Луо, Л. Исмаил, Н.К.Б. Ахмад және Ц. Го 2024 жылы жариялаған systematic literature review process drama мен EFL оқытудың байланысын 2003-2023 жылдары жарық көрген 30 зерттеу негізінде талдаған. Авторлар process drama тілдік дағдыларға, оқу нәтижелеріне және мұғалім дамуына оң әсер ететінін көрсетеді [15].

С. Әл-Бусаиди, М. Әл-Амри және В. Әл-Духли визуалды өнерге негізделген speaking approach-ты Sultan Qaboos University контекстінде зерттеп, one-group pretest and posttest дизайнын қолданған; зерттеу speaking ability және overall language level бойынша жақсару болғанын хабарлайды [16].

А. Дуропан visual arts activities speaking abilities дамытуға қалай көмектесетінін phenomenological approach арқылы зерттеген. 20 қатысушы төрт focus group-қа бөлініп, нәтижеде визуалды өнер оқушыға ойды бейнеден шығарып, сөйлемді жылдамырақ

құрастыруға, сөйлеуге қызығушылық танытуға және нұсқаулық анық болғанда сенімді жауап беруге мүмкіндік беретіні көрсетілген [17].

К.К.М. Го мен Э. Бернс сөйлеуді holistic approach арқылы оқытуды ұсынады: сөйлеу тек fluency емес, cognitive, affective және social dimensions арқылы дамиды. Бұл ART моделінің ішкі қисынына толық сәйкес келеді, себебі көркем стимул когнитивтік және эмоциялық іске қосуды қамтамасыз етеді, рефлексиялық дайындық тілдік бақылауды күшейтеді, ал task-based transfer әлеуметтік өзара әрекетке шығарады [18].

Материалдар мен әдістер

Зерттеу әдістемелік-талдамалық және жобалау сипатында құрылды. Зерттеу логикасы төрт қадамнан тұрды. Бірінші қадамда ағылшын тілі сабағындағы speaking difficulty мазмұны анықталды: идея жетіспеуі, қате жіберу қорқынышы, дайын тілдік тірек болмауы, оқушының пассивті тыңдаушы рөлінде қалуы. Екінші қадамда арт элементтері сөйлеу дағдысын дамытуға қалай қызмет ете алатыны талданды. Үшінші қадамда ART моделі үш кезеңге бөлінді: көркем стимул, рефлексиялық дайындық, тапсырмаға көшіру. Төртінші қадамда осы модельді бағалауға арналған критерийлер мен индекстер ұсынылды.

ART моделіндегі негізгі әдістемелік қағида қарапайым: оқушыға бірден сөйлеу тапсырмасы берілмейді. Алдымен сөйлеуге тұрарлық мазмұн жасалады. Көркем материал оқушыға байқалатын деталь, эмоция, белгі, қайшылық, оқиға және болжам береді. Содан кейін бұл мазмұн тілдік жағынан өңделеді. Соңында оқушы prepared language-ты communicative task ішінде қолданады.

ART технологиясының сөйлеу нәтижесін бағалау үшін бес критерий ұсынылады: fluency, accuracy, pronunciation, interaction, content clarity. Әр критерий 0-ден 4 балға дейін бағаланады. Мұндай шкала мұғалімге оқушыны тек «дұрыс сөйледі» немесе «қате сөйледі» деп емес, сөйлеудің нақты компоненттері бойынша бағалауға мүмкіндік береді.

1-кесте. ART технологиясының ағылшын тіліндегі сөйлеу сабағындағы құрылымы

ART кезеңі	Негізгі педагогикалық қызметі	Мұғалім әрекеті	Оқушы әрекеті	Күтілетін сөйлеу нәтижесі
Artistic stimulus	Сөйлеуге мазмұн, эмоциялық түрткі және визуалды тірек беру	Сурет, фотосурет, зат, музыка, қысқа дыбыссыз бейне немесе коллаж ұсынады	Байқайды, сипаттайды, болжам айтады, жеке әсерін білдіреді	Ой пайда болады, сөздік қор іске қосылады, сөйлеуге психологиялық дайындық қалыптасады
Reflective rehearsal	Тілді саналы дайындау, қателіктен қорқу деңгейін азайту	Phrase bank, sentence frame, pronunciation drill, peer feedback ұйымдастырады	Сөз тіркестерін жинайды, қысқа сөйлем құрайды, жұпта репетиция жасайды	Дәлдік, айтылым, құрылым және сенімділік күшейеді
Task-based transfer	Дайындалған тілдік материалды нақты қарым-қатынасқа шығару	Рөлдік ойын, сұхбат, пікірталас, story chain, gallery talk ұйымдастырады	Сұрайды, жауап береді, келіседі, келіспейді, дәлелдейді, қорытындылайды	Fluency, interaction, discourse organization және oral confidence дамиды

1 кесте ART технологиясының негізгі айырмасын көрсетеді: ол көркем материалды сабақтың басындағы қызықты «иллюстрация» ретінде қалдырмайды. Көркем стимул сөйлеудің мазмұндық ядросына айналады. Рефлексиялық дайындық сол мазмұнды тілдік формаға түсіреді. Task-based transfer оқушыны нақты коммуникативтік әрекетке шығарады. Осы үштік бұзылса, технология әлсірейді. Мысалы, мұғалім сурет көрсетіп, бірден «Discuss it» десе, кейбір оқушылар сөйлейді, бірақ әлсіз оқушы үнсіз қалады. Ал суреттен кейін сөздік тірек, сөйлем үлгісі және жұптық репетиция берілсе, сөйлеу мүмкіндігі барлық оқушыға кеңейеді.

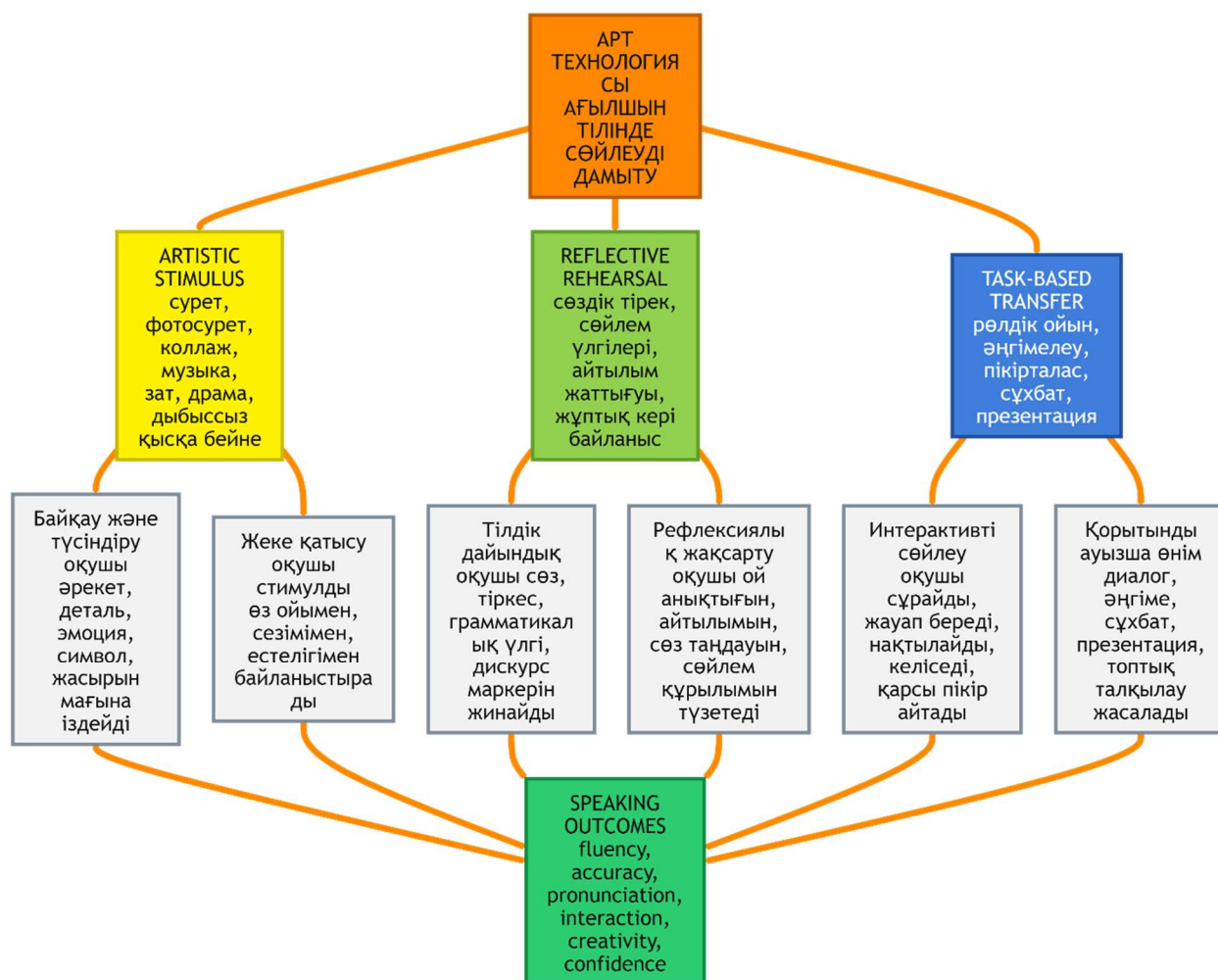
Нәтижелер

ART технологиясының бірінші нәтижесі - ағылшын тілі сабағындағы сөйлеудің мазмұндық тапшылығын азайту. Көп оқушы speaking тапсырмасынан емес, «не айту керек?» деген ішкі бос кеңістіктен қиналады. Көркем стимул осы бос кеңістікті нақты затпен, бейнемен, түспен, дауыспен, ситуациямен толтырады. Мысалы, оқушыға «Talk about friendship» деген тапсырма берілсе, жауап көбіне жаттанды болады. Ал екі баланың үнсіз отырған фотосуреті, сынған ойыншық немесе бос орындық бейнесі көрсетілсе, friendship туралы сөйлеу бірден нақты детальға сүйенеді: who is missing, what happened, why the object matters, what the characters may feel. Сөйлеу тақырыбы абстракт ұғымнан көрінетін белгіге ауысады.

2-кесте. Дәстүрлі speaking practice және ART технологиясының айырмашылығы

Өлшем	Дәстүрлі speaking practice	ART технологиясына негізделген speaking practice	Әдістемелік мәні
Тақырып көзі	Оқулықтағы дайын тақырып немесе сұрақ	Сурет, фотосурет, музыка, зат, қысқа бейне, драмалық жағдай	Оқушы нақты белгіге сүйеніп сөйлейді
Оқушы рөлі	Жауап беруші	Байқаушы, түсіндіруші, рөл иесі, әңгіме құраушы	Сөйлеу тұлғалық қатысуға жақындайды
Тілдік дайындық	Кейде тапсырмадан кейін беріледі немесе мүлде берілмейді	Task алдында сөз, тіркес, интонация, sentence frame беріледі	Қате қорқынышы төмендейді
Өзара әрекет	Сұрақ-жауап форматы басым	Pair talk, role-play, group story, debate, interview	Interaction табиғи сипат алады
Бағалау	Жалпы әсер немесе қате саны	Fluency, accuracy, pronunciation, interaction, content clarity	Мұғалім нақты көрсеткішпен кері байланыс береді
Нәтиже	Қысқа жауап немесе жаттанды сөйлем	Диалог, шағын презентация, оқиға, пікірталас, сұхбат	Сөйлеу толық ауызша өнімге айналады

Бұл айырмашылық ART технологиясының «қызықты әдіс» қана емес екенін дәлелдейді. Дәстүрлі speaking practice көп жағдайда сөйлеуді тілдік формаға тәуелді етеді. ART моделі сөйлеуді алдымен мағынаға, содан кейін формаға, соңында әлеуметтік әрекетке шығарады. Мұндай қозғалыс оқушының ішкі логикасына да жақын: адам алдымен бір нәрсені көреді, оған қатынас жасайды, ойын жинайды, содан кейін ғана сөйлейді.



1-сурет. ART технологиясының сөйлеу дағдысын дамытудағы әдістемелік моделі

Бұл модельде оқушының сөйлеуі бір ғана «answer the question» сәтіне тәуелді емес. Оқушының ойы біртіндеп қозғалады: алдымен көреді, содан кейін байқайды, одан кейін сөз табады, кейін репетиция жасайды, соңында сөйлеу әрекетіне шығады. Мұғалім үшін бұл модель сабақтың ішкі ритмін басқаруға мүмкіндік береді. Әлсіз оқушыға phrase bank көбірек беріледі, жоғары деңгейдегі оқушыға interpretation және argumentation күрделендіріледі. Бір суретпен A2 деңгейінде «There is a lonely boy near the window» сөйлемін құратуға болады, ал B1 деңгейінде «The image suggests emotional distance because the boy is physically present but socially isolated» түріндегі күрделі пікір айтқызуға болады.

ART технологиясының екінші нәтижесі - сөйлеу қауіпсіздігін күшейту. Қателесуден қорқу көбіне оқушының жауабы бір ғана дұрыс нұсқаға тірелгенде пайда болады. Көркем материалда бір ғана дұрыс мағына болмайды. Оқушы суреттегі адамның көңіл күйін әртүрлі түсіндіре алады, музыканың әсерін әртүрлі сипаттай алады, коллаждағы символды өз тәжірибесімен байланыстыра алады. Бұл еркіндік жауапкершіліксіздік емес. Керісінше, оқушы өз пікірін дәлелдеуі керек: «I think...», «The reason is...», «In the picture I can see...», «This detail may mean...» сияқты тілдік құрылымдар дәлелді сөйлеуге үйретеді.

3-кесте. ART сабағында қолданылатын көркем стимулдар және сөйлеу тапсырмалары

Көркем стимул	Сөйлеуге арналған бастапқы сұрақ	Тілдік тірек	Herizgi speaking task	Қалыптасатын дағды
Фотосурет	What is happening here?	I can see..., It seems that..., Maybe...	Pair interpretation	Сипаттау, болжам айту
Кескіндеме	What emotion is shown?	The character looks..., The colour suggests...	Gallery talk	Эмоцияны сипаттау, пікір білдіру
Коллаж	What story connects these objects?	First..., Then..., After that..., Finally...	Group storytelling	Оқиға құрастыру, coherence
Музыка үзіндісі	What scene do you imagine?	It sounds..., I imagine..., The mood is...	Oral scene description	Ассоциация, fluency
Драмалық жағдай	What would you say in this role?	I agree..., I disagree..., Could you explain...?	Role-play	Interaction, turn-taking
Дыбыссыз бейне	What happened before and after?	Before this..., At the end..., The problem is...	Interview with a character	Сұрақ қою, жауап беру, narrative

Бұл тапсырмаларда мұғалімнің кәсіби дәлдігі шешуші. Мысалы, фотосурет таңдағанда мәдени тұрғыдан түсініксіз, жас ерекшелігіне сәйкес келмейтін немесе шамадан тыс күрделі материал қолданылса, оқушының назары тілдік әрекеттен алшақтайды. Ал тым қарапайым сурет сөйлеуді дамытпайды. Ең тиімді стимулда үш қасиет болады: нақты деталь көрінеді, бірнеше түсіндіруге мүмкіндік бар, сөйлеу тапсырмасына тез айналады. Бір қарапайым бос орындықтың өзі «absence», «waiting», «memory», «lost friend», «first day at school» сияқты бірнеше мағына тудыра алады.



2-сурет. ART сабағын ұйымдастыру алгоритмі

Бұл алгоритм ART технологиясын кез келген сыныпта қолдануға мүмкіндік береді. 5-сыныпта stimulus ретінде жануарлар фотосуреті, бөлме суреті, мектептегі қарапайым көрініс берілуі мүмкін. 8-сыныпта әлеуметтік тақырыптағы постер, экологиялық коллаж, қысқа дыбыссыз бейне қолдануға болады. 10-11-сыныпта визуалды метафора, тарихи фотосурет, қоғамдық мәселені көрсететін арт объект, қысқа performance scene тиімді болады. Деңгей

артқан сайын сөйлеу күрделенеді: description деңгейінен interpretation деңгейіне, одан argumentation және mediation деңгейіне өтеді.



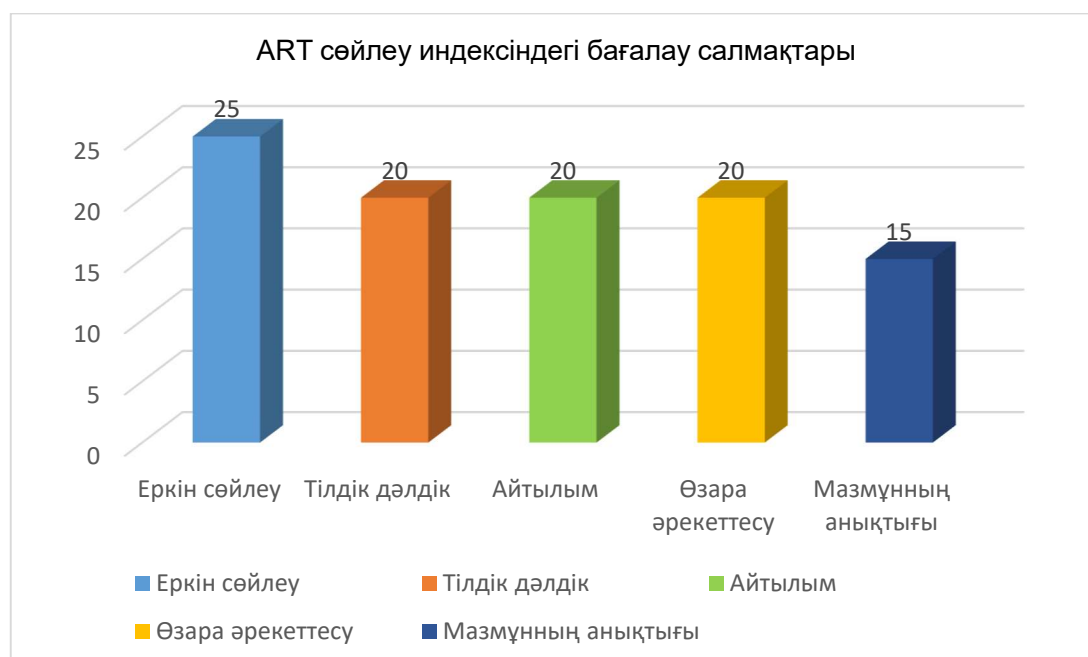
3-сурет. ART сабағындағы уақыт үлесінің ұсынылатын құрылымы

Бұл үлес нақты мектеп кестесіне қарай өзгеруі мүмкін. 45 минуттық сабақта көркем стимулға 8-9 минуттан артық уақыт беру speaking мақсатын әлсіретуі ықтимал. Ал дайындық кезеңін тым қысқарту оқушыны «ой бар, бірақ тіл жоқ» жағдайында қалдырады. Ең тиімді сабақта stimulus қысқа, бірақ мағыналы болады; language support нақты беріледі; негізгі уақыт сөйлеуге бөлінеді.

4-кесте. ART технологиясы бойынша сөйлеуді бағалау рубрикасы

Критерий	4 балл	3 балл	2 балл	1 балл	0 балл
Fluency	Ойды кідіріс аз, табиғи ырғақпен жеткізеді	Ұсақ кідірістер бар, мағына бұзылмайды	Кідіріс жиі, бірақ негізгі ой түсінікті	Сөйлеу үзік, ойды аяқтау қиын	Жауап бермейді немесе түсініксіз
Accuracy	Грамматикалық қате өте аз, мағынаға әсер етпейді	Қателер бар, бірақ коммуникация сақталады	Қателер жиі, кей тұста мағына әлсірейді	Қате көп, сөйлем құру қиындайды	Тілдік форма қалыптаспаған
Pronunciation	Дыбыстау, емпін, интонация түсінікті	Ұсақ айтылым қателері бар	Кей сөздерді түсіну қиын	Айтылым коммуникацияға кедергі жасайды	Түсіну мүмкін емес
Interaction	Сұрақ қояды, жауап береді, нақтылайды, серіктесін тыңдайды	Өзара әрекет бар, бірақ бастама аз	Жауап береді, бірақ диалогты дамытпайды	Серіктеспен байланыс әлсіз	Interaction жоқ
Content clarity	Ой нақты, детальмен дәлелденген, құрылым бар	Ой түсінікті, бірақ дәлел аз	Негізгі ой бар, құрылым әлсіз	Ой шашыраңқы	Мазмұн жоқ

Мұндай рубрика мұғалімге әділдік береді, оқушыға нақты бағыт береді. «Жақсы сөйледің» деген кері байланыс оқушының қай жерде өскенін көрсетпейді. Ал «fluency 3, interaction 2, content clarity 3» деген кері байланыс келесі сабақта не істеу керектігін көрсетеді. Мысалы, interaction төмен болса, оқушыға clarification phrases беріледі: «Could you repeat?», «What do you mean?», «Do you agree?», «Can you add one more idea?» Егер content clarity әлсіз болса, дәлел құрылымдары беріледі: «My first reason is...», «The detail that proves it is...», «This shows that...».



4-сурет. ART сөйлеу индексіндегі бағалау салмақтары

Бұл салмақтар сөйлеуді тек грамматикаға байлап қоймауға мүмкіндік береді. Ағылшын тілінде сөйлейтін оқушы қате жіберуі мүмкін, бірақ ойды түсінікті жеткізіп, серіктеспен байланыс орнатып, пікірін дәлелдей алса, оның коммуникативтік құзыреттілігі дамып жатыр. Сонымен қатар ассурасу мен pronunciation назардан шықпайды. ART технологиясының күшті жағы осы тепе-теңдікте: creative speaking еркіндік береді, reflective rehearsal тілдік тәртіп береді.

Рубриканың тағы бір маңызды артықшылығы - ол оқушының сөйлеу нәтижесін бір ғана жалпы әсермен емес, нақты компоненттер арқылы көруге жағдай жасайды. Ағылшын тілінде ауызша жауап беру кезінде оқушының барлық көрсеткіші бірдей деңгейде дамымайды. Бір оқушы ойды тез жеткізеді, бірақ грамматикалық дәлдіктен қате жібереді. Екінші оқушы сөйлемді дұрыс құрайды, бірақ кідірісі көп болады. Үшінші оқушының айтылымы түсінікті, алайда серіктесімен диалогты жалғастыруға қиналады. Сондықтан ART технологиясында бағалау тек қорытынды баға қою үшін емес, сөйлеуді келесі қадамға жылжыту үшін қолданылады.

ART технологиясында бағалау үнемі сөйлеу әрекетінің соңында ғана жасалмайды. Ол сабақтың бірнеше нүктесінде жүреді: бастапқы сипаттауда мұғалім оқушының сөздік қорын байқайды; репетиция кезінде сөйлем құрылымын түзетеді; негізгі коммуникативтік тапсырмада fluency мен interaction көрінеді; рефлексияда оқушы өз сөйлеуіндегі бір күшті тұсты және бір нақты түзетуді атайды. Мұндай жүйе оқушыны өз тілдік дамуын түсінуге үйретеді. Ол тек баға күтпейді, өз сөйлеу сапасын бақылай бастайды.



5-сурет. ART технологиясындағы бағалау және кері байланыс циклі

Бағалау циклінің маңызды тұсы - қате оқушыны тоқтататын фактор емес, сөйлеуді жақсартатын материал ретінде қарастырылады. Мысалы, оқушы «He don't want go home» десе, мұғалім бүкіл жауапты жоққа шығармайды. Алдымен мазмұнды ұстайды: оқушы кейіпкердің үйге барғысы келмейтінін айтты. Содан кейін қысқа түзету береді: «He does not want to go home.» Оқушы сөйлемді қайта айтады. Осы шағын әрекет output, noticing және repair механизмдерін іске қосады.

Талқылау

ART технологиясының педагогикалық тиімділігі үш деңгейде байқалады. Бірінші деңгей - когнитивтік. Көркем стимул оқушыға дайын жауап емес, ойлануға болатын материал береді. Суреттегі белгі, түстің өзгеруі, кейіпкердің бет-әлпеті, заттың орналасуы, музыкадағы ырғақ немесе тыныштық оқушыны интерпретация жасауға итермелейді. Бұл ағылшын тіліндегі сөйлеуді жаттанды мәтіннен алыстатады. Оқушы «I like this picture» деп тоқтамай, «I think the dark colour shows fear because the character is standing alone» деп дәлелдеуге көшеді.

Екінші деңгей - аффективтік. Speaking anxiety көп жағдайда оқушының дайын еместігінен туады. ART моделіндегі reflective rehearsal осы тәуекелді азайтады. Оқушыға сөздік тірек беріледі, сөйлем үлгілері ұсынылады, жұпта қысқа репетиция жасалады. Мұндай дайындық әлсіз оқушыға да сөйлеуге кіру нүктесін ашады. Әсіресе ауыл мектебі, аралас деңгейлі сынып немесе ағылшын тілін күнделікті қолдану мүмкіндігі шектеулі орта үшін бұл өте маңызды.

Үшінші деңгей - әлеуметтік-коммуникативтік. Арт технологиясы оқушыны жеке жауап беруші позициясынан серіктеспен мағына құрастырушы позициясына ауыстырады. Рөлдік ойында оқушы сұхбаттасады, музей гиді ретінде түсіндіреді, кейіпкер ретінде жауап береді, топтық әңгімеде оқиғаны жалғастырады. Бұл interaction дағдысын дамытады. CEFR логикасында interaction және mediation қазіргі тілдік құзыреттіліктің маңызды бөлігі болғандықтан, ART технологиясы тек fluency емес, әлеуметтік тілдік әрекетке де қызмет етеді.

5-кесте. ART технологиясын мектеп сабағында қолданудағы тәуекелдер және шешімдер

Тәуекел	Неге пайда болады	Сөйлеуге әсері	Әдістемелік шешім
Сабақ ойынға айналып кетуі	Мұғалім сөйлеу мақсатын нақты қоймайды	Оқушы қызығады, бірақ тілдік нәтиже әлсіз болады	Әр стимулға speaking outcome бекіту
Әлсіз оқушының үнсіз қалуы	Тілдік тірек жеткіліксіз	Pair work ішінде пассивті рөл қалыптасады	Phrase bank, sentence frame, role card беру
Уақыттың жетпеуі	Stimulus талдауы ұзаққа созылады	Herizgi task орындалмайды	Stimulus кезеңін 5-8 минутпен шектеу
Бағалаудың субъективті болуы	Рубрика жоқ	Оқушы не үшін баға алғанын түсінбейді	5 критерийлі rubric қолдану
Мәдени сәйкессіздік	Сурет немесе музыка оқушы жасына сай емес	Түсінбеу, ыңғайсыздық, тақырыптан ауытқу	Жас, деңгей, контекст бойынша алдын ала іріктеу
Тек белсенді оқушылардың сөйлеуі	Топтық жұмыс дұрыс бөлінбейді	Бірнеше оқушы ғана нәтиже береді	Timekeeper, speaker, questioner, summarizer рөлдерін бөлу

Бұл тәуекелдер арт технологиясын әлсіз әдіс деп көрсетпейді. Керісінше, олар мұғалімнің әдістемелік басқаруы қажет екенін дәлелдейді. Әрбір шығармашылық тапсырмада тәртіп болуы тиіс: мақсат, тірек, уақыт, рөл, нәтиже, бағалау. Профессиялық

тұрғыдан қарағанда, ART технологиясы импровизацияға орын қалдырады, бірақ ол импровизацияны педагогикалық құрылыммен ұстайды.

Жалпы орта мектеп үшін ұсынылатын практикалық шешімдердің бірі - ART speaking card жүйесін енгізу. Әр карточкада бір stimulus, үш observation question, бес useful phrase, бір role task және бір reflection question беріледі. Мұғалім мұндай карточкаларды тақырыптарға қарай жинақтай алады: family, school, environment, technology, friendship, travel, culture, future professions. Бұл жүйе мұғалімнің уақытын үнемдейді және оқушыға қайталанатын, бірақ жалықтырмайтын speaking routine береді.

Мысалы, «Environment» тақырыбында қоқысқа толған саябақтың фотосуреті беріледі. Observation questions: «What details show the problem?», «Who may be responsible?», «What can be changed first?» Useful phrases: «The main problem is...», «This detail shows...», «People should...», «I suggest...», «The first step is...» Role task: «You are local volunteers. Prepare a 2-minute talk to convince classmates to join a clean-up campaign.» Reflection question: «Which phrase helped you speak more clearly?» Осындай тапсырмада оқушы экология туралы жалпы жаттанды сөйлем айтпайды. Ол нақты көріністі талдайды, ұсыныс жасайды, аудиторияны сендіруге тырысады.

Практикалық ұсыныстар

ART технологиясын ағылшын тілі сабағында тұрақты қолдану үшін бірнеше әдістемелік шарт сақталуы керек.

Бірінші шарт - көркем стимул сабақ мақсатына сай іріктеледі. Егер мақсат vocabulary activation болса, суретте көп нақты зат болуы керек. Егер мақсат emotional description болса, бет-әлпет, түс, жарық, композиция маңызды. Егер мақсат argumentation болса, stimulus екіұшты немесе пікірталас тудыратын болуы тиіс.

Екінші шарт - тілдік тірек қысқа әрі қолдануға дайын беріледі. Оқушыға 30 сөздік тізім қажет емес. Оған 6-8 тірек жеткілікті: «I suppose...», «The image may suggest...», «In my opinion...», «The strongest detail is...», «I agree with..., but...», «Can you explain why?» Мұндай тіректер сөйлеуді жасанды етпейді, керісінше оқушыға ойды ағылшын тілінде бастауға мүмкіндік береді.

Үшінші шарт - репетиция міндетті болады. Көп мұғалім уақыт үнемдеу үшін дайындық кезеңін өткізіп жібереді. Бұл әсіресе speaking сабағында қауіпті. Репетициясыз оқушы бірден бағалау алаңына шығып кетеді. Ал жұптық 2 минуттық rehearsal оқушыға сөйлемін түзетуге, сөзін табуға, дауысын реттеуге мүмкіндік береді.

Төртінші шарт - task нақты өніммен аяқталады. «Discuss in groups» жеткіліксіз. Оның орнына «Prepare a 6-sentence story», «Make a 1-minute museum guide talk», «Interview the character», «Create a dialogue with disagreement», «Defend one interpretation» сияқты нәтиже анық болуы керек.

Бесінші шарт - кері байланыс бірден және өлшеммен беріледі. Мұғалім әр оқушыға ұзақ пікір жазуға міндетті емес. Бірақ «one strength, one correction, one next step» формуласы қолданылса, оқушы келесі сабақта нақты не жақсартатынын біледі.

Қорытынды

Ағылшын тілі сабағында арт технологиясын қолданудың тиімділігі оның сыртқы тартымдылығында емес, сөйлеуді тудыратын ішкі әдістемелік механизмінде. Көркем стимул оқушының ойын оятады, рефлексиялық дайындық сол ойды тілдік формаға түсіреді, task-based transfer оны нақты қарым-қатынасқа айналдырады. Осы үш кезең бір жүйеде қолданылғанда, ART технологиясы оқушының fluency, accuracy, pronunciation, interaction және content clarity көрсеткіштерін дамытуға бағытталған толыққанды педагогикалық құрал бола алады. Ғылыми тұрғыдан ART моделі бірнеше бағытты біріктіреді: CEFR-дегі action-oriented approach, output hypothesis, task-based language teaching, multimodal pedagogy, drama-based pedagogy және culture and arts education. Бұл байланыс арт технологиясын жеке

«қызықты әдіс» емес, қазіргі тілдік білім берудің күрделі талаптарына жауап беретін интегративті модель ретінде қарастыруға негіз береді.

Практикалық тұрғыдан модель жалпы орта мектепте бейімделуге қолайлы. Ол көп құрал талап етпейді: сапалы сурет, қысқа бейне, музыка үзіндісі, зат, коллаж немесе рөлдік карточка жеткілікті. Бірақ мұғалімнің кәсіби дайындығы маңызды. Көркем материал дұрыс таңдалмаса, тілдік тірек берілмесе, бағалау өлшемі анық болмаса, технология нәтиже бермейді. Демек, ART технологиясының сапасы мұғалімнің көркем материалды сөйлеу мақсатына дәл бағындыру қабілетіне тәуелді.

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Medical Sciences

Advanced Diagnostic Sensor Systems for Hemodialysis Machines

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ABSTRACT: Although hemodialysis machines are central to renal replacement therapy, their diagnostic and safety subsystems have lagged behind advances in modern biomedical engineering and sensor technology. Many still rely on fixed parameters rather than real-time physiological monitoring. Key components—including temperature sensors, pressure sensors, air-bubble detectors, and electric motors—remain outdated and may compromise patient safety and treatment efficiency. Dialysate temperature control, for example, often lacks rapid response or patient-specific adaptation, increasing the risk of hypotension, thermal stress, or discomfort. Likewise, limited motor self-diagnostics can delay detection of failures, and current air-bubble detection remains relatively primitive despite the risk of embolism. Patient weight-loss monitoring is also insufficiently sophisticated to prevent complications. Modern non-invasive sensors, predictive algorithms, and multi-layered safety architectures used in other medical fields could be integrated into dialysis systems. Upgrading these subsystems with advanced diagnostic sensors is urgently needed to improve reliability and patient outcomes.

KEYWORDS: Air-bubble detection, electric motors, patient weight-loss monitoring, pressure sensors.

INTRODUCTION

Hemodialysis machines are a critical component of renal replacement therapy and are used worldwide to sustain patients with end-stage kidney disease. Despite decades of use, the core diagnostic and safety subsystems of these devices have not evolved as rapidly as advances in biomedical engineering and sensor technology would allow. Most commercial units still operate with fixed parameters and limited real-time physiological feedback, which can compromise treatment efficiency and patient safety.

Several key components illustrate these shortcomings. Temperature and pressure sensors frequently lack the precision and responsiveness needed to stabilize dialysate conditions during rapid physiological changes. Even small deviations in dialysate temperature may lead to hypotension, thermal stress, or discomfort, while inaccurate pressure monitoring can delay the detection of vascular access problems. Air-bubble detection systems remain relatively primitive despite the severe risks of embolism. Electric motors and their controllers also offer minimal self-diagnostics, allowing failures to progress unnoticed until symptoms appear. Furthermore, patient weight-loss monitoring remains insufficiently sophisticated to anticipate fluid removal complications.

Modern non-invasive sensing technologies, predictive algorithms, and multi-layered safety architectures have been successfully deployed in other medical fields but are not yet fully integrated into dialysis systems. This paper highlights these gaps and proposes an enhanced diagnostic sensor system that combines updated temperature, pressure, and air-bubble sensing with improved motor diagnostics and patient weight-loss tracking. By outlining the limitations of

current designs and the feasibility of advanced sensor integration, we aim to motivate a new generation of hemodialysis machines with improved reliability and patient outcomes [6].

RELATED WORK

Safety monitoring in hemodialysis machines has traditionally relied on air detectors and pressure sensors, yet limitations persist in sensitivity, calibration, and integration.

Air embolism remains a major risk in extracorporeal circulation. Conventional ultrasonic or IR detectors can miss microbubbles, allowing them to pass through venous traps undetected [1]. To improve sensitivity, capacitance-based detection systems have been proposed for dialysis applications, showing promising accuracy in identifying small bubbles [2]. Computational fluid dynamics studies have also optimized bubble-removal devices, highlighting design parameters that improve efficiency [3].

Pressure monitoring is another cornerstone of hemodialysis safety. Traditional systems measure arterial, venous, and transmembrane pressures, but issues such as drift and delayed response reduce reliability. Recent research has explored continuous noninvasive blood pressure estimation during dialysis, providing early detection of hypotension events [4]. Broader reviews emphasize the importance of integrated monitoring and smarter safety architectures in dialysis devices [5].

Our work builds on these approaches by combining high-sensitivity bubble detection with high-resolution pressure sensing, enabling cross-validation of anomalies and earlier detection of faults than current standalone systems.

PROPOSED METHOD

Our enhanced hemodialysis monitoring system introduces three core innovations: (1) an integrated air and temperature detection module using IR photodiodes and DS1624 digital thermal sensing to ensure early identification of embolism risks and overheating events, (2) the deployment of high-resolution piezoresistive pressure sensors (CYX19 series) across critical flow channels to capture deviations from calibrated ranges in real time, and (3) motor current-based diagnostics for DC pump operation, enabling detection of abnormal load conditions that may cause inaccurate fluid removal.

Together, these components provide cross-validated monitoring of flow, pressure, and safety events, reducing the likelihood of undetected faults. Unlike existing standalone systems, our method offers continuous calibration feedback and redundancy across sensing modalities, ensuring more reliable control of ultrafiltration and prevention of excessive patient weight loss during treatment.

ALGORITHM DESCRIPTION (OR SYSTEM ARCHITECTURE)

Our system integrates three modules:

- (1) Air/Temperature Detection – IR photodiodes and DS1624 sensor monitor venous line safety.
- (2) Pressure Monitoring – Four piezoresistive CYX19 sensors (S1–S4) track inlet, outlet, balance, and bicarbonate pressures.
- (3) Motor Diagnostics – DC motor current sensing detects pump malfunctions.

All data streams converge in a control unit, where anomalies are cross-validated. Confirmed faults trigger automatic pump shutdown and alarms, ensuring early prevention of air embolism, overheating, and excessive ultrafiltration.

EVALUATION

The proposed approach was tested through pressure measurements on the hemodialysis machine. Four calibration points were observed: purified water flow, flow pump, degassing pump, and loading channel. In normal operation, pressures remained within the expected ranges (e.g., flow pump $\approx$ 2225 mbar, degassing $\approx$ -815 mbar).

When the degassing pump was intentionally impaired, the pressure values shifted outside the normal range (–330 to –860 mbar), confirming that pump faults can be detected by monitoring pressure deviations. This demonstrates that additional pressure sensing provides a reliable way to identify malfunctions and prevent inaccurate fluid removal during dialysis.

CONCLUSION

We presented an enhanced monitoring concept for hemodialysis machines focused on pressure-based fault detection. Our experiments demonstrated that deviations in calibrated pressure ranges can reliably identify pump malfunctions and prevent inaccurate fluid removal.

By adding advanced pressure sensing, temperature monitoring, air detection, and multi-layered safety mechanisms, existing dialysis machines can achieve greater protection and reliability. In particular, the use of additional pressure sensors helps control fluid balance more precisely, reducing the risk of excessive patient weight loss when the device does not function properly.

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ჰემოდიალიზის აპარატების თანამედროვე დიაგნოსტიკური სენსორული სისტემები
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მიუხედავად იმისა, რომ ჰემოდიალიზის აპარატები თირკმლის ჩანაცვლებითი თერაპიის ცენტრალურ ნაწილს წარმოადგენს, მათი დიაგნოსტიკური და უსაფრთხოების ქვესისტემები ჩამორჩება თანამედროვე ბიოსამედიცინო ინჟინერიისა და სენსორული ტექნოლოგიების განვითარებას. ფიზიოლოგიური მონიტორინგის ნაცვლად ბევრი მათგანი კვლავ ეყრდნობა ფიქსირებულ პარამეტრებს რეალურ დროში. ძირითადი კომპონენტები - მათ შორის ტემპერატურის სენსორები, წნევის სენსორები, ჰაერის ბუშტების დეტექტორები და ელექტროძრავები - მოძველებულია და შეიძლება საფრთხე შეუქმნას პაციენტის უსაფრთხოებას და მკურნალობის ეფექტურობას. მაგალითად, დიალიზატის ტემპერატურის კონტროლს ხშირად აკლია სწრაფი რეაგირება ან პაციენტზე სპეციფიკური ადაპტაცია, რაც ზრდის ჰიპოტენზიის, თერმული სტრესის ან დისკომფორტის რისკს. ანალოგიურად, შეზღუდული საავტომობილო თვითდიაგნოსტიკა შეიძლება შეაფერხოს

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საკვანძო სიტყვები: ჰემოდიალიზი, ელექტროძრავები, პაციენტის წონის დაკლების მონიტორინგი, წნევის სენსორები.

УНИКАЛЬНЫЙ КЛИНИЧЕСКИЙ СЛУЧАЙ. Массивная тромбоэмболия лёгочной артерии в раннем послеродовом периоде после кесарева сечения

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Аннотация

Цель: представить редкий клинический случай тромбоэмболии обеих ветвей лёгочной артерии (ТЭЛА) у молодой женщины в 32-е сутки после кесарева сечения с сочетанными факторами риска и успешным исходом благодаря своевременной мультидисциплинарной терапии.

Описание случая: пациентка поступила в тяжёлом состоянии с выраженной одышкой, тахикардией до 200 уд/мин, нарастающей дыхательной недостаточностью. По результатам комплексной диагностики подтверждена ТЭЛА промежуточно-высокого риска. Лечение включало системный тромболизис, нефракционированный гепарин с последующим переходом на ривароксабан, кислородотерапию, антиаритмическую терапию, коррекцию электролитов и мониторинг жизненно важных функций.

Заключение: случай демонстрирует критическую важность раннего выявления ТЭЛА у послеродовых пациенток, значимость оценки факторов риска и эффективность мультидисциплинарного подхода.

Ключевые слова: тромбоэмболия лёгочной артерии, послеродовой период, кесарево сечение, венозный тромбоз, ривароксабан, дыхательная недостаточность.

Введение

Тромбоэмболия лёгочной артерии (ТЭЛА) является одной из наиболее опасных причин материнской смертности в послеродовом периоде. Риск тромботических осложнений после кесарева сечения возрастает в 3–5 раз по сравнению с естественными родами. Дополнительная хирургическая травма, гиперкоагуляция, венозный стаз и операции в послеродовом периоде формируют предпосылки для тромбоза глубоких вен и последующей эмболии.

Представленный случай интересен сочетанием нескольких факторов риска, стремительным развитием дыхательной недостаточности и успешным результатом лечения с проведением тромболитической терапии.

Материалы и методы

Представлен ретроспективный анализ анамнеза, объективных данных, лабораторных показателей, инструментальных исследований и динамики лечения пациентки в раннем послеродовом периоде.

Диагнозы подтверждены по критериям ESC, шкалам риска PESI, Wells, Geneva, Bova.

Описание клинического случая

Пациентка: Женщина, 30 лет, 32-е сутки после кесарева сечения и хирургической коррекции промежности. Многогрозавшая. ИМТ 31,9 (ожирение I степени).

Факторы риска:

- послеродовой период
- кесарево сечение
- повторная хирургическая операция
- постфлебитический синдром правой нижней конечности
- гиподинамия после родов

Жалобы при поступлении:

- выраженная одышка в покое
- чувство нехватки воздуха
- тахикардия до 200 уд/мин
- слабость, головокружение
- дискомфорт в грудной клетке

Бригада скорой помощи доставила пациентку в стационар через 1 час после начала симптомов.

Объективный статус

При поступлении:

- состояние — среднетяжёлое
- ЧСС — 200 уд/мин
- АД — 100/60 мм рт. ст.
- SpO₂ снижена (в анализах pO₂ 31–49 мм рт. ст.)
- дыхание ослабленное в нижних отделах
- кожные покровы бледные
- признаки гипоперфузии

Лабораторные данные

Характерные изменения:

- анемия (Hb 111 г/л)
- гипофибриногенемия (1,3 г/л)
- гипокалиемия (K^+ 3,1 ммоль/л)
- метаболический ацидоз (pH 7,27–7,31)
- повышение лактата до 5,0 ммоль/л → выраженная тканевая гипоксия

Диагностические шкалы:

- PESI — 70 баллов (промежуточный риск)
- Wells — 3 балла
- Geneva — 7 баллов
- Bova — 3 балла

Подтверждена ТЭЛА обеих ветвей лёгочной артерии (I26.9), дыхательная недостаточность II степени.

Лечение

1. Пациентке была проведена интенсивная терапия:

- Системная тромболитическая терапия -Ревекард 50мг
- НФГ под контролем АЧТВ
- Перевод на ривароксабан 15 мг × 2 раза/сут (по рекомендациям ESC для ТЭЛА)

2. Респираторная поддержка

- оксигенотерапия 2–6 л/мин
- мониторинг газов крови и КЩС

3. Инфузионная терапия

- коррекция гипокалиемии (калий хлорид)
- поддержание водно-электролитного баланса

4. Антиаритмическая терапия

- Бисопролол
- Изоптин
- Дигоксин

5. Антибактериальная терапия

• препараты цефалоспоринового ряда (Цеф III) — профилактика инфекционных осложнений

6. Дополнительная терапия

- бета-блокаторы
- гастропротекция (Омез)

7. Мультидисциплинарный подход

Пациентку вели совместно:
кардиологи, реаниматологи, акушеры-гинекологи, ангиохирурги, специалисты по тромбозам.

Результаты

На фоне терапии отмечена положительная динамика:

- снижение ЧСС с 200 до 90–110 уд/мин
- нормализация сатурации до 96–99%
- уменьшение одышки
- стабилизация АД
- нормализация кислотно-щелочного состояния
- уменьшение лактата
- улучшение общего состояния

Пациентка выписана в удовлетворительном состоянии с рекомендацией продолжить антикоагулянтную терапию и наблюдение у кардиолога.

Обсуждение

Представленный случай отражает типичную, но редко диагностируемую клиническую ситуацию — развитие массивной ТЭЛА у рожениц на фоне сочетания акушерских и венозных факторов риска.

Уникальность клинического случая пациентки заключается в:

1. Послеродовом, послеоперационном периоде 32 сутки. Рубец на матке после кесарево сечения.
2. Одновременном наличии оперативных вмешательств-послеперениокольпорографии 5 сутки;
3. Эффективной стабилизации состояния с помощью проведения системной тромболитической терапии, с последующим переходом на прием антикоагулянтов, несмотря на промежуточный высокий риск по шкалам PESI и Geneva, клиническая картина и лабораторные показатели указывали на угрозу ухудшения состояния, что стало основанием для проведения системного тромболиза.
4. важности ранней диагностики и командного ведения пациентки.

Заключение

ТЭЛА в послеродовом периоде требует высокой настороженности и быстрого реагирования. Данный случай демонстрирует, что своевременная диагностика, проведение системной тромболитической терапии с последующим переходом на нефракционированный гепарин, далее на прием прямого орального антикоагулянта и мультидисциплинарный подход способны обеспечить благоприятный исход даже при высокой степени риска.

Конфликт интересов: Авторы заявляют об отсутствии конфликта интересов.

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ДИАГНОСТИКА ЭХИНОКОККОЗА ПЕЧЕНИ У ДЕТЕЙ

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Актуальность проблемы: Эхинококковая болезнь у детей на протяжении длительного времени считается актуальной проблемой медицинской паразитологии. Выявление этого заболевания на ранних стадиях развития представляет трудную задачу, что связано с отсутствием четкой клинической симптоматики и жалоб больного. В большинстве случаев больные обращаются в медицинские учреждения после выявления кист при профилактических осмотрах с проведением рентгенологических и ультразвуковых исследований.

Цель исследования: оценка информативности различных методов диагностики эхинококкоза у детей.

Материал и методы исследования. Проанализированы результаты лечения 193 детей в возрасте от 3-х до 18 лет с эхинококкозом печени, пролеченных в период с 2018 по 2024 гг. в клиники ТашПМИ.

Результаты исследования. Проведенные методы ультразвуковой диагностики поступивших в нашу клинику больных позволили выявлению в 114 (59,1%) наблюдениях одиночных эхинококковых кист печени, множественное кистозное поражение печени выявлено у 79 (40,9%) больных. Из общего количества больных в 35 (18,1%) наблюдениях выявлены осложнённые эхинококковые кисты печени, которые встречались как при одиночных, так и при множественных поражениях печени. Наибольшая локализация эхинококковых кист в печени приходилась на правую долю и составило 150 (77,7%) случаев, при этом в левой доле печени кисты выявлены в 17 (8,8%) наблюдениях, поражение обеих долей печени выявлено у 26 (13,5%) больных. Ультразвуковая картина эхинококкоза печени во многом зависела от периода жизнедеятельности паразита (неосложнённая и осложнённая киста). Ультразвуковая диагностика позволила нам определить тактику, выбор метода и способа хирургического лечения эхинококкоза печени, которые зависели от локализации, размеров, количества кист, стадии заболевания и вида осложнения. Информативность данного исследования более 90%.

Обзорная рентгенография грудной клетки являлась первоочередным и обязательным скрининг-методом у всех больных с эхинококкозом легких для выявления паразитарного поражения, её информативность в наших исследованиях достигала 91%.

КТ чаще всего проводили при множественном и сочетанном поражении, при малых размерах кист для установления точного топического диагноза. КТ и УЗИ позволили существенно улучшить диагностику эхинококкоза у детей и в 98-99% наблюдений поставить правильный диагноз заболевания.

Заключение. Таким образом, сравнительный анализ диагностических методов исследования показал, что разрешающие возможности каждого метода значительно отличаются между собой, при этом доступными и первоочередными взаимодополняющими методами обладающими высокой информативностью при эхинококкозе являются УЗИ и рентгенологический метод.

MODERN METHODS OF RADIATION DIAGNOSTICS ECHINOCOCCOSIS OF THE LIVER IN CHILDREN

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The relevance of the problem: Echinococcal disease in children has been considered an urgent problem of medical parasitology for a long time. Detection of this disease in the early stages of development is a difficult task, due to the lack of clear clinical symptoms and complaints of the patient. In most cases, patients go to medical institutions after cysts are detected during preventive examinations with X-ray and ultrasound examinations.

The aim of the study: was to evaluate the informative value of various methods for diagnosing echinococcosis in children.

Research materials and methods: The results of treatment of 193 children aged 3 to 18 years with liver echinococcosis treated in the period from 2018 to 2023 at the TashPMI clinic were analyzed.

The results of the study: The performed ultrasound diagnostic methods of the patients admitted to our clinic revealed single echinococcal liver cysts in 114 (59.1%) cases, multiple cystic liver lesion was detected in 79 (40.9%) patients. Of the total number of patients, 35 (18.1%) cases revealed complicated echinococcal cysts of the liver, which occurred in both single and multiple liver lesions. The greatest localization of echinococcal cysts in the liver occurred in the right lobe and amounted to 150 (77.7%) cases, while cysts were detected in the left lobe of the liver in 17 (8.8%) cases, damage to both lobes of the liver was detected in 26 (13.5%) patients. The ultrasound picture of liver echinococcosis largely depended on the period of vital activity of the parasite (uncomplicated and complicated cyst). Ultrasound diagnostics allowed us to determine the tactics, choice of method and method of surgical treatment of liver echinococcosis, which depended on the location, size, number of cysts, stage of the disease and type of complication. The informative value of this study exceeded 90%.

Chest X-ray was the primary and mandatory screening method in all patients with echinococcosis of the thoracic and abdominal cavities to identify parasitic lesions of various localization, its informative value in our studies reached up to 91% of observations.

MSCT was most often performed for multiple and combined lesions, with small cyst sizes to establish an accurate topical diagnosis. MSCT and ultrasound made it possible to significantly

improve the diagnosis of liver echinococcosis in children and correctly diagnose the disease in 98-99% of cases.

Conclusion. Thus, a comparative analysis of diagnostic research methods has shown that the resolution capabilities of each method differ significantly from each other, while ultrasound and MSCT research methods are available and primary complementary methods with high informative value in echinococcosis.

Comparative dynamics of neutrophil mitochondrial activity across resveratrol delivery routes

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Background. Neutrophils are a tractable biosensor for systemic mitochondrial status. We implemented a “mitochondrial passport” based on intravital fluorescence of live leukocytes and compared the impact of different trans-resveratrol delivery routes [1, 2].

Methods. Prospective pilot in healthy adults (27–38 y; n=74): pellets 200 mg (n=16; ~91% bioavailability), transdermal 100 mg (n=20; ~95%), capsules 4000 mg (n=18; ~+30% vs. standard), tablets 500 mg (n=20; ~1% effective, first-pass). Metrics at baseline and 1 month: leukocytes with mitochondrial accumulation (MA), spontaneous membrane damage (oxidative stress, OS), NBT (oxygen-energy metabolism), phagocytosis, and ribosomal accumulation [3].

Results.

Table 1. Comparison of different methods of resveratrol delivery and its effect on leukocyte mitochondria depending on bioavailability

	Normal % of live stained leukocytes visualized in all fields of view	Resveratrol pellets 200 mg (total bioavailability about 91%) (n=16)			Resveratrol capsules 4000 mg IGS4000, Japan (bioavailability +30% of the standard) (n=18)			Resveratrol 100 mg transdermally (bioavailability 95%) (n=20)			Resveratrol tablets 500 mg (bioavailability 45%, first pass rule 80%, total bioavailability about 1%) (n=20)		
		to	1 month after	growth	to	1 month after	growth	to	1 month after	growth	to	1 month after	growth
Protein metabolism (number of leukocytes with accumulation of ribosomes)	60-80	39	63	38,1	20	30	33,3	30	57	47,4	49	52	5,8
Mitochondrial activity (number of leukocytes with mitochondrial accumulation)	30-60	0	47	100,0	10	23	56,5	11	38	71,1	11	20	45,0
Oxidative stress (test of spontaneous assessment of leukocyte membrane damage)	0-20	50	18	-177,8	35	50	30,0	70	23	-204,3	50	33	-51,5
Oxygen and energy metabolism of granulocytes (NST test)	30-60	15	18	16,7	0	68	100,0	17	33	48,5	55	67	17,9
Phagocytosis of granulocytes (latex test)	40-60	27	35	22,9	10	18	44,4	30	37	18,9	27	35	22,9

Conclusion. Delivery route and effective bioavailability critically shape neutrophil mitochondrial response to resveratrol. Pellets 200 mg and transdermal 100 mg outperform oral tablets and avoid the unfavorable OS rise seen with high-dose capsules. The mitochondrial passport is a sensitive, low-burden biomarker to personalize resveratrol delivery.

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EPIDEMIOLOGICAL INDICATORS AND CLINICAL ASPECTS OF EARLY DIAGNOSIS OF THYROID CANCER

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Annotation: this scientific and analytical work presents modern world and local-regional data on incidence, mortality, lethality and five-year survival rate of such a common oncological pathology as thyroid cancer. The issues of etiology and pathogenesis, modern approaches and principles of complex diagnostics, prospects for improving treatment results, as well as the prognosis are covered in detail. The epidemiological characteristics of this pathology in our republic are given in the context of the regions of the country.

Key words: oncology, endocrinology, primary care, thyroid gland, thyroid cancer, biomarkers, RNA, ultrasound examination, epidemiology, incidence, mortality, lethality, five-year survival rate, prognosis.

Thyroid cancer (TC) is a malignant tumor that develops from thyroid tissue. The following diagnostic criteria for TC are distinguished. Complaints about: enlargement of the gland; appearance of a tumor on the anterior and lateral surface of the neck; change in voice (with tumor

growth into the recurrent nerve); rapid tumor growth; shortness of breath, feeling of lack of air (with tumor growth into the recurrent nerve, upper respiratory tract). Anamnesis: thyroid disease (hypothyroidism, euthyroidism, hyperthyroidism, thyroiditis); long-term use of antithyroid drugs; ionizing radiation; history of radiation therapy to the head and neck. Physical examination: 1) upon examination, neck deformity (uniform swelling on the anterior surface of the neck, asymmetry due to an increase in any part of the thyroid gland, an increase in regional lymph nodes); 2) palpation examination of the thyroid gland - the presence of a nodular formation in the thickness of the thyroid gland, dense consistency; 3) palpation examination of regional lymph nodes - dense consistency, painful, mobile, immobile, partially mobile.

Laboratory tests: cytological examination; histological examination. Immunohistochemical examination: TTF-1, determination of calcitonin, fine-needle aspiration biopsy. All patients diagnosed with medullary TC or a family history of medullary TC or multiple endocrine neoplasia syndrome type 2 are recommended to undergo genetic testing to determine the germline mutation rearranged during transfection (RET) in order to determine the prognosis of the disease.

Instrumental studies: 1) ultrasound examination of the thyroid gland (determines the structure of the gland and tumor, the presence of a nodular formation, cystic cavities, size, echogenicity); the protocol for ultrasound examination of the thyroid gland includes determining the size, localization, ultrasound characteristics of the tumor; suspicious signs are (assessed only in solid nodes or in solid areas of the nodes) hypoechoic solid structure; uneven, fuzzy or polycyclic contour; point hyperechoic inclusions (microcalcifications); predominance of the anteroposterior size of the node over the width ("higher/than/wider"); 2) ultrasound examination of the cervical, submandibular, supraclavicular, subclavian lymph nodes (the presence of enlarged lymph nodes, structure, echogenicity, size); The protocol for ultrasound examination of the thyroid gland and regional lymph nodes should include assessment of the following parameters: size (it is necessary to assess the diameter or anteroposterior size, and not the length; for all cervical lymph nodes, except for level II - the fascial cellular space of the neck (submandibular zone), the largest size is no more than 0.6 cm, for level II - no more than 0.8 cm); the ratio of the long and short axes; the presence / absence of the gate; cystic changes; point hyperechoic inclusions (microcalcifications); the nature of vascularization (gate or the entire lymph node); increased echogenicity of the lymph node (similarity to normal thyroid tissue); the most specific signs that allow us to suspect metastatic lesions of the lymph node are microcalcifications, a cystic component, peripheral vascularization, and similarity of the lymph node tissue to the thyroid gland; less specific signs are an increase in size, rounded contours, and the absence of a hilum; 3) computed tomography and/or magnetic resonance imaging of the soft tissues of the neck and mediastinum (with contrast - in the presence of invasion into the main vessels, with a retrosternal location), fine-needle aspiration biopsy from the tumor (allows us to determine tumor and non-tumor processes, the benign and malignant nature of the tumor); 4) skeletal scintigraphy (prescribed if bone metastases are suspected); 5) positron emission tomography, positron emission tomography/computed tomography of the whole body (performed to diagnose the prevalence of the tumor process or the progression of the disease, or to assess the dynamics of the effectiveness of specialized treatment) [1].

The thyroid or glandula thyroidea is an endocrine gland located in the neck below the larynx in front of the trachea in mammals. In humans, it has the shape of a butterfly. It consists of two lobes connected by a narrow bridge called the isthmus. Thyroid carcinoma or TC is a malignant tumor of the thyroid gland. It is the most common malignancy of the endocrine (hormonal) system, but is very rare, accounting for about 1% of all malignant tumors, however, it has been increasing in frequency in recent years. TC is a malignant tumor of the glandular tissue of the thyroid gland. There are different types of TC that arise from different cells in the thyroid gland. TC comprises several categories: (1) differentiated TC (DTC), including papillary (PTC), follicular

(FTC), and Hürthle cell tumours, (2) medullary TC (MTC) and (3) anaplastic TC. The long-term survival rate of patients with differentiated TC is about 90%, whereas patients with poorly differentiated TC types show a long-term survival rate of below 10% due to their resistance to standard treatment options [2]. The latest Global Cancer Observatory survey from 2020 reports that TC is responsible for 586,000 cancer cases worldwide [3].

Horgan D. et al. in their work they say that TC is the most common malignancy of the endocrine system that affects the thyroid gland. It is usually treatable and, in most cases, curable. The central issues are how to improve knowledge on TC, to accurately identify cases at an early stage that can benefit from effective intervention, optimise therapy, and reduce the risk of overdiagnosis and unnecessary treatment. Our colleagues focus on the fact that the approach to TC needs a rethink to early and correct identification of patients and improve their patient journey and treatment outcomes, including improved quality of life. All patients should be referred to comprehensive cancer centres. Such an approach would instate an optimal patient management mitigating overdiagnosis and overtreatment and would improve access to biomarker testing, clinical trials, and appropriate systemic therapies for patients with advanced forms of TC. It would also help establish focused national expertise on rare TC cases, promote research, training, awareness, and facilitate international collaboration [4].

Treatment and molecular testing guidelines should be regularly updated at regional and national levels to facilitate the reimbursement and availability for the most effective diagnostics and therapies. In the most recent update of the clinical practice guidelines, ESMO highlights for the first time the need to test for actionable cancer alterations in TC. It is essential that national guidelines are coordinated with the European and international ones [5].

Quality comprehensive genomic testing should be incorporated in clinical practice (tissue or liquid samples) for all TC patients that can benefit from targeted therapies. In order to facilitate correct diagnosis, pathology practice, data collection and analysis, as well as communication with the treating physicians should be improved, with the provision of registers based on pathology. National cancer registries should distinguish specific diseases with standardised, quality-controlled systems, including details of case management and including long-term survival data. National and international data bases are needed not only for refractory TC, but for all types of TC. Thyroid gland examination practices in the asymptomatic general population need updating. With the rapid growth of big data analytics in genomics, imaging, and clinical outcomes, health systems should make it possible to generate a personalised, data-driven risk profile to customise therapy for individual patients, aiming for both long-term tumour control and manageable adverse effects [4].

Silva S.N. [6] notes that TC is not just a common type of cancer, it is the most frequently diagnosed endocrine malignancy worldwide. The etiology of TC is essentially multifactorial and radiation is the best documented risk factor related to the disease. However, many questions are still open and seeking clarification, especially regarding the genetic aspects of this pathology, with clear implications not only on a scientific basis of the disease, but foremost in clinical oncology. Thyroid gland tumours are a heterogeneous group of neoplasms that may arise from virtually any of the different cell types that are present in the thyroid gland. Although the malignant tumours are most frequently identified in thyroid follicular cells, it is clear that the molecular-genetic characterization is crucial and should be further explored to emphasize differences in tumour biological behaviours, aggressiveness, and disease prognostics. Papillary and follicular thyroid carcinomas (PTC and FTC, respectively) represent 85-90% and 5-10% of TC cases, respectively, arising from thyroid follicular cells. These tumour histotypes retain their morphologic features and are often referred to as DTC. However, the etiology of DTC is still unknown. Considerable progress has been made in the understanding of thyroid carcinogenesis, in part based on retrospective and prospective studies published worldwide in recent decades, but also in the development of high-

throughput approaches and the availability of improved diagnostic methodologies that lead to early diagnosis. In fact, over the last few decades, the research in TC has highlighted the mutational landscape leading to better understanding of the molecular pathogenesis of DTC.

The hallmarks of cancer have been identified with several potential targets involved in gene expression deregulation, leading to the promotion of genetic instability and cancer development. The identification of genetic variants related to TC has been a long way, though it is crucial to identify possible potential biomarkers of susceptibility. Some genetic variants have been identified in specific subtypes, which are related to the increased risk to develop this malignancy, such as the BRAF V600E mutation in PTC patients with a more aggressive phenotype if telomerase reverse transcriptase gene promoter mutation coexists [7].

However, mutations in RET and Retrovirus Associated DNA Sequences genes have also been identified as biomarkers in TC patients.

Alongside with genetic variants, epigenetic events and alterations in the expression of microRNA (miRNA) and long noncoding RNA (lncRNA) may also, through modulation of gene expression, drive the aberrant activation of oncogenic signalling pathways and the downregulation of thyroid-specific genes, thus contributing to the development, progression, and dedifferentiation of TC [8].

Connected to this, the genetic instability inflicted in this malignancy, involving genetic and epigenetic alterations, might also compromise the treatment response. The standard treatment for TC patients consists of surgical resection accompanied by post-thyroidectomy radioiodine (RAI) adjuvant therapy. The radioiodine therapy relies on the ability of ¹³¹I to be preferentially taken up in normal or neoplastic thyroid follicular cells. Its accumulation induces high DNA damage, which leads to cytotoxicity. However, the ionizing radiation does not only affect tumour cells, but the lesions may also impair normal cells. The most common lesions induced by radiation are double-strand breaks, which are processed by enzymes involved in DNA repair pathways. The presence of genetic variants in these enzymes might impair the repair efficiency but also could influence the cytotoxic potential of RAI therapy, hence its efficacy in DTC treatment. The development of induced DNA damage approaches can help in the evaluation of the efficacy of therapeutics as it has been shown to be an important tool for establishing biomarkers of susceptibility. Although the most frequent variants identified in TC contribute to sporadic disease, about 5 to 15% of all diagnosed cases are familial (first degree relatives) in nonMTC, increasing to 25% in MTC cases. This adds to the clear existence of genetic predisposition factors related to this pathology. Advances in molecular genetics and several candidate gene studies developed worldwide have linked the occurrence of this malignancy to some hereditary syndromes, some of which are related to germline mutations in RET genes [6].

Macvanin M.T. et al. [9] in their study note that after the metabolic syndrome and its components, thyroid disorders represent the most common endocrine disorders, with increasing prevalence in the last two decades. Thyroid dysfunctions are distinguished by hyperthyroidism, hypothyroidism, or inflammation (thyroiditis) of the thyroid gland, in addition to the presence of thyroid nodules that can be benign or malignant. TC is typically detected via an ultrasound fine-needle aspiration biopsy, cytological examination of the specimen and measurements of traditional biochemical markers, such as TSH, FT4, Tg, TgAb, and TPOAB. Novel RNA-based markers of thyroid neoplasms are identified by expression profiling of the thyroid gland tissue and/or blood samples of patients using high-throughput platforms for RNA analysis and identification, such as next-generation sequencing. Other emerging biomarkers of thyroid neoplasms are identified using flow cytometry, enzyme-linked immunosorbent assays, genetic tests, and immunohistological analyses. Due to the rapid advancement of high-throughput molecular biology techniques, it is now possible to identify new biomarkers for thyroid neoplasms that can supplement traditional imaging modalities in postoperative surveillance and aid in the preoperative cytology examination

of indeterminate or follicular lesions. In conclusion, the authors draw attention to the fact that due to the rapid advancement of high-throughput molecular biology techniques, it is now possible to identify novel biomarkers for thyroid neoplasms that can supplement or replace existing biomarkers. Current circulating biomarkers, such as Tg or TgAb, are routinely used in postoperative monitoring; however, at the preoperative stage, they cannot distinguish between benign and malignant neoplasms or between low- and high-risk malignant lesions. Several new targets are emerging as potentially useful prognostic circulating biomarkers for TC. Evidence for miRNA, lncRNA and circular RNA (circRNA) dysregulation in several thyroid neoplasms and their potential use as sensitive diagnostic and prognostic biomarkers is particularly interesting. However, the data currently available in the literature is derived from small-scale clinical studies in specific patient cohorts. Thus, further validation is required to demonstrate their potential for clinical application. Large-scale studies are needed to confirm and validate novel biomarkers in the diagnosis, prognosis, and surveillance of thyroid neoplasms, such as miRNAs, lncRNAs, and circRNAs.

As they note in their work Saenko V., Mitsutake N. [10], radiation is an environmental factor that elevates the risk of developing TC. Actual and possible scenarios of exposures to external and internal radiation are multiple and diverse. In this case: 1) radiation is a risk factor for TC; the risk steadily increases up to the dose of 10 Gy, levels off in the 10- to 30-Gy interval, and asymptotically declines at higher doses but remains elevated; once exposed, the risk persists for many decades; 2) risks from the external and internal irradiation are comparable; 3) there is no evidence of dose-response departure from linearity at low doses (<0.1 Gy) and of the existence of a “safe” threshold dose; 4) the magnitude of radiation risk for TC is highest if exposure takes place at a young age; 5) after the Chornobyl nuclear reactor accident, due to internal exposure to radioactive iodine, a dramatic increase in the incidence of childhood TCs was observed, especially among children less than 5 years old at the time of the accident; 6) although many TCs were found by the thyroid-screening program after the Fukushima nuclear power plant accident, comparisons of exposures and characteristics of TC diagnosed after the Chornobyl and Fukushima nuclear accidents do not support a causative role of radiation in the latter; 7) reduction of the risk for TC may be achieved by following the As Low As Reasonably Achievable principle, and iodine thyroid blockage may be performed to protect from anticipated internal exposure. A substantial progress in understanding of radiation-related TC has been achieved since the discovery of this phenomenon about 60 years ago. Irradiation of the head, neck, and chest areas has been learned to increase the risk for developing thyroid malignancy during the lifespan. This stimulated numerous investigations in medical, industrial, and military settings whenever radiation exposure was relevant. Radiation risks have been quantified and found to be comparable for the external and internal radiation. According to this knowledge, certain groups at elevated risk could be determined, including those with medical, occupational, or emergency exposures. Now, the focus of radiation risk studies is shifting toward low-dose exposures in view of growing number of various radiological procedures, especially in pediatric patients. The markers of radiation-related TC have not been found so far. Overlaps in the histological types, oncogenic driver spectrums, and corresponding gene expression profiles between radiation-related and sporadic tumors suggest that these parameters were unlikely to serve as a marker. Clinical studies have demonstrated that TCs diagnosed in irradiated patients are of the same histological types as in nonirradiated patients and that disease prognosis is determined by tumor characteristics regardless of etiology. This is rather good news for clinicians to know that standard treatment and follow-up approaches could be used for radiation-exposed patients, but it is necessary to keep in mind that TC phenotype is changing with patient age and latency period.

Lukasiewicz M. et al. [11] emphasize that the etiology of TC is complex, and a variety of factors contribute to its development. Among these factors, disorders of lipid metabolism have

emerged as a notable area of interest. Lipids, including fatty acids (FA), play a fundamental role in cell structure and function. Consequently, disturbances in lipid metabolism can have profound effects on various cellular processes, potentially favoring the development and progression of TC. Understanding the intricate relationship between lipid metabolism disorders and TC is of paramount importance as it may provide new insights into the prevention and treatment of this malignancy. TC is a neoplasm with an increasing incidence worldwide. Its etiology is complex and based on a multi-layered interplay of factors. Among these, disorders of lipid metabolism have emerged as an important area of investigation. Cancer cells are metabolically reprogrammed to promote their rapid growth, proliferation, and survival. This reprogramming is associated with significant changes at the level of lipids, mainly FA, as they play a critical role in maintaining cell structure, facilitating signaling pathways, and providing energy. These lipid-related changes help cancer cells meet the increased demands of continued growth and division while adapting to the tumor microenvironment. Recent scientific efforts have revealed disturbances in lipid homeostasis that are specific to TC, opening up potential avenues for early detection and targeted therapeutic interventions. Understanding the intricate metabolic pathways involved in FA metabolism may provide insights into potential interventions to prevent cancer progression and mitigate its effects on surrounding tissues.

Luzón-Toro B. et al. [12] emphasize in their publication that TC, a cancerous tumor or growth located within the thyroid gland, is the most common endocrine cancer. It is one of the few cancers whereby incidence rates have increased in recent years. It occurs in all age groups, from children through to seniors. Most studies are focused on dissecting its genetic basis, since our current knowledge of the genetic background of the different forms of TC is far from complete, which poses a challenge for diagnosis and prognosis of the disease. TC is the most common endocrine cancer, with an increasing overall incidence in recent decades of about two fold in the last 25 years and accounting for 2% of all cancers. TC is the sixth most common cancer in women, who are three times more likely to have TC than men. About 2% of cases occur in children and teens. Overall, the 5-year survival rate of TC is 98%. However, survival rates depend on many factors, such as the specific type of TC and stage of disease. TC is a disease induced by progressive genetic and epigenetic molecular abnormalities. Most studies describe several classical aberrations involved in the tumorigenesis and progression of this tumor, such as point mutations, gene copy number variations, and aberrant gene methylation. The genetic landscape of TC is growing rapidly. Therapies that are targeted at genetic mutations related to this tumor are being used in patient care and clinical trials. In comparison with traditional disease-specific trials, molecular allocation studies (“basket studies”) are testing targeted therapies in patients whose tumors carry particular mutations, in spite of the tumor type or origin. These studies are more informative on anticancer therapies because they include a greater number of patients. The correlation of molecular profile (obtained by new sequencing technologies) with clinicopathological characteristics will lead to the development of novel precision therapies, reducing incidence and mortality in TC patients. In this sense, differential response to a mitogen-activated protein kinase inhibitor was found to be related to the thyroid cancer genotype. Molecular testing of mutation hotspots, rearrangements, and gene expression is now an effective diagnostic tool to better select patients for potential thyroid surgery. The authors note that the diagnosis and treatment of TC is nowadays influenced by the molecular characterization of TC types. The improvement of such techniques would help to reduce the amount of TC treatment needed and improve outcomes in patients with clinically aggressive forms of cancer.

Chen D.W. et al. [13] emphasize in their work that the past 5-10 years have brought in a new era in the care of patients with TC, with the introduction of transformative diagnostic and management options. Several international ultrasound-based thyroid nodule risk stratification systems have been developed with the goal of reducing unnecessary biopsies. Less invasive

alternatives to surgery for low-risk TC, such as active surveillance and minimally invasive interventions, are being explored. New systemic therapies are now available for patients with advanced TC. However, in the setting of these advances, disparities exist in the diagnosis and management of TC. As new management options are becoming available for TC, it is essential to support population-based studies and randomised clinical trials that will inform evidence-based clinical practice guidelines on the management of TC, and to include diverse patient populations in research to better understand and subsequently address existing barriers to equitable TC care.

Now, regarding this pathology in our country at the republican level. The incidence of TC in the Republic of Kazakhstan in 2023 was 5.4 per 100 thousand population (4.8 in 2022) with a growth rate of 13.1% compared to the previous year, taking 3rd place together with connective and soft tissue tumors, second only to prostate cancer (16.7%) and laryngeal cancer (15.5%), and amounting to 1084 people in absolute numbers (939 cases a year earlier). The proportion of cases diagnosed for the first time in life, recorded by oncology organizations, was 2.9% (2.7% in 2022). In this case, 167 men fell ill (the proportion is 1.0%), women - 917 (the proportion is 4.4%) [14].

The TC rate above the national average was established in 9 regions of the country: North Kazakhstan - 12.6 (the maximum rate); East Kazakhstan - 10.6; Pavlodar - 8.5; the city of Astana - 8.2; the city of Almaty - 7.9; Kyzylorda - 7.6; Karaganda - 7.0; Akmola - 6.5; Abay - 5.9. This indicator is below the national average in 11 regions: Turkestan - 1.7 (the lowest rate); the city of Shymkent - 2.4; Atyrau - 2.6; Almaty - 3.0; West Kazakhstan - 3.8; Aktobe - 4.0; Zhambyl and Kostanay - 4.1; Ulytau - 4.5; Mangistau - 4.9; Zhetysu - 5.0 regions per 100 thousand population. Mortality from this pathology was 0.3 per 100 thousand population with an increase rate of 19.1% compared to the previous year, second only to non-melanoma skin cancer (26.0%).

The regions where the TC mortality rate is higher than the national average (0.3 per 100 thousand population) include: Abay - 1.0 (maximum level); Aktobe - 0.7; East Kazakhstan and Pavlodar - 0.5; Zhambyl, Karaganda, North Kazakhstan and the city of Almaty - 0.4. Zhetysu region and the city of Shymkent are on par with the national average. The lowest rates are noted in Atyrau and Ulytau - 0.0; Akmola, West Kazakhstan, Kostanay, Mangistau and Turkestan - 0.1; Almaty, Kyzylorda regions and the city of Astana - 0.2 per 100 thousand population [14].

One-year lethality was 2.3% (2.4% in 2022). At the same time, the ratio between one-year lethality and neglect (stage IV) was, as in 2022, 0.5, and this is the best indicator among all nosological forms of malignant tumors after prostate cancer (0.3). At the same time, we recall that the farthest from "1" is the worst ratio between one-year lethality and neglect.

Now, regarding preventive examinations. It should be noted that during large-scale preventive examinations of the population in 2023, significantly more patients with malignant neoplasms were actively identified than in 2022. This is 25,193 patients versus 23,623 patients identified in 2022, i.e. +6.6%. This is due to the further abatement of the epidemiological situation with coronavirus and the increased availability of preventive care for the population. The proportion of patients identified during routine examinations increased from 62.0% to 62.4% of the total number of patients identified over the year.

Of course, when analyzing the epidemiological situation, early diagnosis indicators are very important issues.

As for TC, the early detection of this pathology during routine examinations increased from 78.6% to 83.7%. The absolute number of TC patients identified during routine examinations was 900 people (732 a year earlier). At the same time, 849 are patients with early stages (in 2022 - 683 patients) [14].

In general, according to the amount of detected cases of cancer of all localizations, in 2023 the proportion of forms detected at early stages (0, I-II stages) increased from 66.3% to 67.9%. At the same time, detection at 0, I-II stages in TC increased from 93.3% to 94.3%. The regions where the proportion of patients with early stage I of the pathology in question is above the national

average (71.5% and 2nd rank place among the best indicators after non-melanoma skin cancer) include the following regions: Kyzylorda - 85.9% (the best indicator); the city of Almaty - 84.8%; the city of Astana - 83.3%; North Kazakhstan - 80.0%; West Kazakhstan - 76.9%; Karaganda - 73.4%; Zhambyl - 72.0%; Almaty – 71.7%.

The lowest rates of early diagnosis were recorded in: East Kazakhstan - 50.6% (the worst rate); Atyrau and Turkistan - 55.6%; Mangistau - 56.8%; Zhetysu - 57.1%; Akmola - 58.8%; Aktobe - 59.5%; Ulytau - 60.0%; Kostanay - 60.6%; Abay - 65.7%; Pavlodar - 69.8% regions and in the city of Shymkent - 71.4%.

TC is in the top three in early diagnosis (stages I-II) - 92.4%. First place goes to non-melanoma skin cancer (98.4%), third - to lip cancer (90.7%). The regions where the proportion of patients with TC detected at stages I-II is above the national average (92.4% - 2nd rank place) include the following regions. The leaders are our two megacities - the city of Astana (98.2%) and the city of Almaty (97.1%). Next come: Kyzylorda - 96.9%; Zhambyl - 96.0%; Karaganda - 94.9%; Aktobe - 94.6%; Atyrau and Turkistan - 94.4%; East Kazakhstan - 93.5% regions and the city of Shymkent (92.9%). Low rates of early diagnosis were recorded in Ulytau - 70.0% (the worst result in the country); Kostanay - 72.7%; Abay - 80.0%; Akmola - 80.4%; Zhetysu - 82.9%; North Kazakhstan - 90.8%; Almaty - 91.3%; Mangistau - 91.9%; Pavlodar - 92.1%; West Kazakhstan - 92.3% regions [14].

As is clearly seen from the above data, there is a very large spread in early diagnostic rates across the country, from very good to thought-provoking. Of course, it is necessary to take into account migration processes and other factors affecting early diagnostic rates, but nevertheless, the results obtained give reason not to stop there, both for oncologists and endocrinologists, ultrasound diagnostic doctors, otolaryngologists, and general practitioners, since improving early diagnostic rates of malignant tumors has remained one of the main postulates and one of the main tasks of medicine in general, and continues to be relevant today.

The proportion of stage IV TC among all nosological forms of malignant neoplasms was 3.9%, and this is the 4th rank place after tumors of the central nervous system (2.5%), lip cancer (0.9%) and non-melanoma skin cancer (0.4%). In general, in 2023, the share of stage IV malignant neoplasms in the republic for the sum of all nosologies decreased from 12.58 to 11.7% (from 4790 to 4735 patients). As for the average republican indicator of the share of stage IV (3.9%), Aktobe, Atyrau, West Kazakhstan regions and the city of Astana stand out against this background - 0.0%. Then come: the city of Almaty (0.6%); East Kazakhstan (1.3%); Turkistan (2.8%); Kyzylorda (3.1%) regions. Akmola region is on par with the average republican indicator. Lower indicators are in: Kostanay region, where every fifth patient with this visually accessible localization was detected in the terminal stage of the disease (21.2%). Next in line were: Abay - 14.3%, Ulytau - 10.0%, Zhetysu - 8.6%, the city of Shymkent - 7.1%; North Kazakhstan - 6.2%, Mangistau - 5.4%, Karaganda - 5.1%, Pavlodar - 4.8%, Almaty - 4.3% and Zhambyl - 4.0% regions.

The morphological verification rate of the disease in the country was 97.0%. In 13 regions out of 20 this figure is 100% (Abay, Aktobe, Almaty, Atyrau, East Kazakhstan, Zhambyl, West Kazakhstan, Karaganda, Mangistau, Pavlodar and Ulytau regions, as well as the cities of Astana and Shymkent). The lowest figure is in Kyzylorda region (68.8%). Further down the list are Zhetysu (88.6%), Kostanay (93.9%), Akmola (96.1%), Turkistan (97.2%), North Kazakhstan (98.5%) and the city of Almaty (98.8%) [14].

The total number of patients with malignant neoplasms registered with specialized oncology organizations of the republic continued to grow and by the end of 2023 amounted to 218,186 people, with an increase of 6.0% compared to the level of the previous year (2022 - 205,822, +5.8%). The overall incidence rate of malignant neoplasms increased by 3.9%, from 1055.3 to 1096.4 per 100 thousand people. The growth of this indicator is due to both the increase in the incidence and detection of pathology, and the increase in the survival rate of cancer

patients. In addition, statistical data on patients diagnosed with malignant neoplasms, who have been under observation for 5 years or more, and continue to be observed in 2023, showed that the number of patients under observation by oncological organizations of Kazakhstan for over five years continued to grow and at the end of the reporting year amounted to 117,616 people, with an increase of 6.2% (2022 - 110,790 people, + 6.6%) (form No. 7).

One cannot ignore such an important clinical aspect as the coverage in the Republic of Kazakhstan of special treatment for patients diagnosed with TC for the first time in their lives. In 2023, the number of hospitalizations for all nosological forms of malignant tumors in oncological organizations of the country amounted to 108,252 cases (2022 - 101,095), with an increase of 7.1% compared to the previous year, which is associated with a constant increase in the number of cancer patients, improvement of the standardization of oncological care, and the development of palliative and restorative services. At the end of 2023, the absolute number of TC patients who completed specialized treatment amounted to 560 people, continuing treatment - 414 patients. In percentage terms, the following results were obtained by methods and types of treatment. The overwhelming majority - 90.4% of patients received surgical treatment only, complex - 3.8%, combined - 2.1%, only radiation - 0.4%, only drug - 0.2%.

Further, regarding the five-year survival rate of patients. As for TC, at the end of 2023, 9901 people or 49.8 per 100 thousand of the population were registered at the dispensary (at the end of 2022 - 9121 patients or 46.8 per 100 thousand of the population, respectively); and this is a high 7th rank place among all nosological forms of malignant neoplasms.

At the same time, the mortality rate of the observed contingents in 2023 was 0.6%, as in the previous year.

The five-year survival rate of patients with TC was 63.8% in 2023, while in 2022 it was 64.6% [14].

Summarizing the above, we can conclude that with TC, despite the fact that this localization is visually accessible, despite the increased effectiveness of preventive examinations and fairly high rates of early diagnosis, a high number of people with this pathology is noted annually, and the five-year survival rate does not reach 65%. The scarcity, variability and veiled nature of symptoms, their similarity with various non-core processes, leads to the neglect and progression of the disease, even during dispensary observation. All this requires both oncologists and, first of all, primary health care workers and, of course, endocrinologists, ultrasound diagnosticians, otolaryngologists to increase the level of oncological alertness, inform the population about early symptoms that may indicate this pathology or the onset of proliferative changes and conduct high-tech diagnostic measures, including for the purpose of differential diagnosis and, as a result, timely treatment. People from the risk group are recommended to visit specialized specialists annually and, if necessary, undergo an examination. An epidemiological assessment of the situation with TC in our country suggests that there are sometimes significant differences in the regions not only in incidence rates, but also in the parameters of early diagnosis and mortality from this pathology. In connection with the above, this pathology continues to be a serious problem of modern clinical oncology.

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Technical Sciences

Organizational and Logistical Challenges in Transporting Highly Compacted Feed to Remote Regions of Kazakhstan

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Abstract. The sustainable development of livestock farming in the Republic of Kazakhstan largely depends on the reliable supply of animal feed to remote and environmentally unfavorable regions. Transportation of highly compacted feed is considered one of the most effective solutions for reducing transportation costs and minimizing feed losses. However, the organization of such transportation faces significant logistical, infrastructural, and economic challenges.

This paper analyzes the existing transport and logistics system for delivering highly compacted feed to unfavorable regions of Kazakhstan. Special attention is paid to the choice of transport modes, routing schemes, cost optimization, and the impact of infrastructure limitations. Based on the analysis of statistical data and practical cases, key bottlenecks in feed transportation are identified. Recommendations are proposed to improve the efficiency of feed logistics through multimodal transportation, route optimization, and state support mechanisms.

The results of the study can be used in planning feed supply systems for livestock enterprises located in remote regions and in developing regional agricultural logistics strategies.

Keywords. highly compacted feed, transport logistics, remote regions, Kazakhstan, agricultural supply chains.

Introduction

The development of livestock production in the Republic of Kazakhstan is closely linked to the stability and efficiency of animal feed supply systems. Due to the vast territory of the country, uneven spatial distribution of agricultural production, and significant differences in climatic and natural conditions, many regions experience persistent shortages of feed resources. This problem is especially acute in environmentally unfavorable and remote areas, where local feed production is limited and transportation distances are considerable.

One of the promising solutions to reduce transportation costs and ensure reliable feed supply is the use of highly compacted feed. High compaction significantly increases bulk density, allowing larger volumes of feed to be transported using the same transport capacity, thereby reducing unit transportation costs and minimizing losses during handling and storage. However, despite these advantages, the organization of transportation of highly compacted feed remains a complex logistical task, particularly under the conditions of underdeveloped infrastructure, long transport routes, and seasonal constraints characteristic of many regions of Kazakhstan.

The transport system of Kazakhstan relies primarily on road and rail networks, which differ in accessibility, capacity, and cost efficiency. While rail transport is economically advantageous for long-distance bulk shipments, it is often limited by the lack of terminal facilities and the need for additional handling operations. Road transport, on the other hand, provides flexibility and direct delivery but is associated with higher costs and increased sensitivity to road conditions, especially in remote and climatically unfavorable areas. As a result, the choice of transport mode and routing scheme plays a crucial role in the overall efficiency of feed supply chains.

Existing studies on agricultural logistics mainly focus on general supply chain optimization, feed production technologies, or international trade of agricultural commodities. However, relatively little attention has been paid to the organizational and logistical aspects of transporting highly compacted feed to remote and unfavorable regions, particularly in the context of Kazakhstan. This research gap highlights the need for a systematic analysis of transport organization, cost structure, and logistical constraints specific to feed delivery systems.

The aim of this study is to analyze the organizational and logistical features of transporting highly compacted feed to unfavorable regions of the Republic of Kazakhstan and to identify key factors affecting the efficiency of feed transportation. The objectives of the research include evaluating existing transport schemes, assessing infrastructural and operational limitations, and developing practical recommendations for improving feed logistics through optimized transport organization and multimodal solutions.

Methods of research.

This study is based on a comprehensive methodological approach combining analytical, statistical, and system-based research methods to investigate the organization of transportation of highly compacted feed to unfavorable regions of the Republic of Kazakhstan [1-3].

At the initial stage, a system analysis of the feed supply chain was conducted to identify the main participants, transport routes, infrastructure elements, and operational constraints involved in the transportation of highly compacted feed. The analysis considered production sites, storage facilities, transport hubs, and final consumption points in remote regions.

Statistical and comparative methods were used to assess the dynamics of feed transportation volumes, transport costs, and delivery distances. Official statistical data from national agricultural and transport authorities, as well as open-source industry reports, were analyzed to identify regional differences and key trends in feed logistics.

To evaluate the efficiency of different transportation schemes, a cost analysis method was applied. Transportation costs were calculated depending on the mode of transport (rail or road), distance, bulk density of feed, and handling operations. The effect of feed compaction on transport efficiency was assessed by comparing cost indicators for conventional and highly compacted feed under identical transport conditions [4].

The study also employed a scenario-based approach to analyze alternative logistics solutions, including single-mode and multimodal transportation schemes. Scenarios were developed to compare direct road transport with combined rail–road delivery options, taking into account infrastructure availability, transfer operations, and seasonal limitations.

In order to identify the most effective transportation options, elements of logistical optimization were applied. Key performance indicators such as cost per ton, delivery time, and transport capacity utilization were used as evaluation criteria. The analysis allowed for the identification of bottlenecks and inefficiencies in existing feed transportation systems.

Finally, a generalization and synthesis method was used to formulate practical recommendations aimed at improving the organization of highly compacted feed transportation. The proposed measures focus on optimizing transport routes, improving coordination between transport modes, and enhancing logistical planning for feed supply to unfavorable regions.

Results of research.

The analysis of transportation systems for highly compacted feed in the Republic of Kazakhstan revealed a number of organizational and logistical features that significantly affect delivery efficiency to unfavorable and remote regions [5,6].

The results show that the use of highly compacted feed leads to a substantial increase in transport efficiency due to higher bulk density. Compared to conventional feed, the transportation cost per ton is reduced as a result of better utilization of vehicle and railcar capacity. This effect is particularly pronounced for long-distance deliveries exceeding several hundred kilometers, which are typical for feed supply routes in Kazakhstan.

The comparative analysis of transport modes indicates that rail transport remains the most cost-effective option for long-distance transportation of highly compacted feed. However, its efficiency is limited by insufficient terminal infrastructure, additional loading and unloading operations, and the lack of direct rail access in many remote regions. As a result, rail transport alone cannot fully meet the needs of feed delivery to unfavorable areas.

Road transport provides greater flexibility and allows for direct delivery to final consumers, but it is characterized by higher transportation costs and strong dependence on road conditions and seasonal factors. In remote regions with underdeveloped road networks, delivery times increase significantly, reducing the reliability of feed supply [7-10].

The scenario-based analysis demonstrates that multimodal transportation schemes, combining rail and road transport, offer the most balanced solution. Such schemes reduce overall transportation costs while maintaining delivery flexibility. The results show that multimodal logistics can decrease transportation costs by optimizing long-haul segments through rail transport and using road transport only for final delivery stages.

Table 1. Comparative characteristics of transportation modes for highly compacted feed

Indicator	Rail transport	Road transport	Multimodal transport (rail + road)
Average transportation distance, km	500–1500	50–500	600–1200
Cost per ton, USD	Low	High	Medium
Delivery flexibility	Low	High	Medium–High
Infrastructure dependence	High	Medium	High
Sensitivity to seasonal factors	Low	High	Medium
Suitability for remote regions	Limited	High	High

The table shows that no single mode of transport is universal, and the best results are achieved when combining transport schemes.

Table 2. Effect of feed compaction on transportation efficiency

Parameter	Conventional feed	Highly compacted feed
Bulk density, kg/m ³	350–450	700–900
Load utilization, %	55–65	85–95
Transportation cost per ton, USD	100	65–75
Number of trips (per fixed volume)	High	Reduced
Losses during handling, %	5–7	2–3

The data confirm that a high degree of feed compaction can significantly reduce unit transportation costs and increase logistics efficiency.

The study also identified several key logistical bottlenecks, including limited availability of transshipment terminals, insufficient coordination between transport operators, and seasonal disruptions caused by adverse weather conditions. These factors increase delivery time and lead to additional costs, especially during peak demand periods.

The findings confirm that effective organization of transportation of highly compacted feed requires not only technological solutions related to feed compaction, but also improvements in transport planning, infrastructure development, and logistical coordination. The results obtained are consistent with international studies on agricultural logistics and confirm the relevance of multimodal approaches for supplying remote and environmentally unfavorable regions.

Table 3. Comparison of transportation scenarios to unfavorable regions

Scenario	Transport scheme	Cost per ton, USD	Delivery time, days	Main limitations
Scenario 1	Road only	High	Short–Medium	Road condition, seasonality
Scenario 2	Rail only	Low	Long	Lack of direct rail access
Scenario 3	Rail + road	Medium	Medium	Need for transshipment

Scenario analysis shows that multimodal schemes are the optimal compromise between cost and reliability of delivery.

Conclusion.

This study examined the organizational and logistical aspects of transporting highly compacted feed to unfavorable and remote regions of the Republic of Kazakhstan. The results confirm that the efficiency of feed supply systems in such regions is largely determined by the rational organization of transportation processes, taking into account transport modes, infrastructure availability, and logistical coordination.

The analysis demonstrated that the use of highly compacted feed significantly improves transportation efficiency by increasing load utilization and reducing transportation costs per ton. These advantages are especially important for long-distance deliveries, which are typical for feed supply routes in Kazakhstan. However, the study also revealed that reliance on a single mode of transport is insufficient to ensure stable and cost-effective feed delivery to remote regions.

The comparative assessment of transportation scenarios showed that multimodal transport schemes combining rail and road transport provide the most balanced solution in terms

of cost, delivery time, and flexibility. Such schemes allow the economic benefits of rail transport to be utilized for long-haul segments while maintaining the adaptability of road transport for final delivery stages.

The findings highlight several key constraints, including limited terminal infrastructure, seasonal accessibility issues, and insufficient coordination between transport operators. Addressing these challenges requires integrated logistical planning, development of transshipment facilities, and improved organizational mechanisms for feed transportation.

The practical significance of this research lies in the proposed recommendations, which can be applied by agricultural enterprises, logistics operators, and policymakers to enhance feed supply systems in unfavorable regions. Further research may focus on quantitative optimization models and the integration of digital logistics tools to improve decision-making in feed transportation planning.

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Further Improvement of Feed Transportation Technology through Optimization of Technical Means and Operating Modes

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Abstract. This paper is a continuation of the research presented in *"Improving the Technology of Feed Transportation with the Effective Use of Technical Means"* (Akhmetov et al., 2025). The study focuses on the further development of feed transportation technologies by optimizing the operating modes of technical means, reducing energy consumption, and increasing system reliability under farm conditions. Special attention is given to the integration of modern mechanization elements and the assessment of their performance indicators. Experimental and analytical results confirm that rational selection and adaptive control of feed transportation equipment significantly improve productivity and economic efficiency in livestock enterprises.

Keywords. feed transportation, mechanization, technical means, energy efficiency, livestock farms, optimization.

Introduction

Efficient feed transportation remains a critical component of livestock production systems, directly influencing labor costs, feed losses, and overall farm productivity. In the previous study by Akhmetov et al. (2025), the authors substantiated the importance of rational use of technical means in feed transportation processes. However, further improvement of these technologies requires deeper analysis of operating modes, interaction between equipment elements, and adaptation to specific farm conditions.

The aim of this study is to expand upon earlier findings by investigating advanced approaches to optimizing feed transportation technology, with an emphasis on technical modernization and performance enhancement.

Recent studies indicate that inefficiencies in feed transportation systems are often associated with improper equipment selection, non-optimal operating parameters, and insufficient automation. Researchers emphasize the need for integrated technological solutions that combine mechanical reliability with energy-saving principles.

Building on the conceptual framework proposed by Akhmetov et al. (2025), this research explores the transition from conventional mechanization to optimized and partially automated feed transportation systems.

Methods of research.

The research methodology includes: analytical evaluation of existing feed transportation systems; experimental testing of conveyor and mobile feed transport units; comparative analysis of energy consumption and productivity indicators; optimization of operating parameters such as transportation speed, load capacity, and drive power.

Experimental data were obtained under typical livestock farm conditions, ensuring practical relevance of the results.

The experimental setup was designed to simulate real operating conditions of livestock enterprises, including variations in feed type, moisture content, and transportation distance. During the experiments, key performance parameters such as specific energy consumption, throughput capacity, feed loss rate, and equipment utilization factor were recorded.

To ensure the reliability and repeatability of the results, each experimental run was conducted multiple times, and the obtained data were subjected to statistical processing. Average values and deviations were determined, and regression analysis was applied to identify the influence of operating parameters on system performance.

Based on the experimental findings, rational operating modes were determined, allowing for the minimization of energy consumption while maintaining the required level of productivity. The optimized parameters were then compared with conventional operating modes to assess technological and economic efficiency.

The results of the comparative analysis formed the basis for developing recommendations on improving feed transportation technology through the effective and adaptive use of technical means in livestock production systems.

Results of research.

Optimization of Technical Means

The results show that the optimization of feed transportation equipment leads to:

- reduction in energy consumption by 10–15%;
- decrease in feed losses during transportation;
- improvement in operational reliability.

Adaptive adjustment of operating modes allows the equipment to respond effectively to varying feed types and farm layouts.

Technological and Economic Efficiency

Economic analysis confirms that the improved technology reduces operating costs and shortens the payback period of technical means. The integration of optimized transportation systems contributes to sustainable development of livestock farms.

In particular, the reduction in energy consumption directly decreases electricity costs, while lower feed losses improve overall feed utilization efficiency. Improved operational reliability reduces downtime and maintenance expenses, thereby increasing the effective working time of feed transportation equipment.

The economic assessment shows that the implementation of optimized technical means results in a measurable annual cost saving compared to conventional systems. Depending on farm size and operating intensity, the payback period of the upgraded equipment is reduced, making the technology economically attractive for both small and medium-sized livestock enterprises.

Furthermore, the application of optimized feed transportation technology supports sustainable livestock production by reducing resource consumption and minimizing environmental impact. Lower energy demand contributes to decreased greenhouse gas emissions associated with electricity generation, while efficient feed handling reduces waste.

Overall, the obtained results demonstrate that the proposed optimization of technical means and operating modes is a practical and effective approach to improving feed transportation technology, ensuring both technological reliability and economic efficiency under real farm conditions.



Figure 1 – Structural scheme of optimized feed transportation technology

Conclusion.

This study confirms that further improvement of feed transportation technology is achievable through the effective optimization of technical means and their operating modes. The continuation of the research by Akhmetov et al. (2025) demonstrates that a systematic approach to mechanization enhances both technological and economic performance of livestock enterprises.

Future research should focus on the introduction of digital monitoring systems and intelligent control algorithms for feed transportation processes.

In addition, future studies may consider the integration of sensor-based data acquisition systems to enable real-time monitoring of equipment performance and operating conditions. The application of intelligent control algorithms, including adaptive and predictive control methods, can further improve energy efficiency, reduce feed losses, and enhance operational reliability.

Further research is also recommended to evaluate the scalability of the proposed optimization approaches for farms of different capacities and production types. Special attention should be given to the development of universal methodological guidelines for selecting and configuring feed transportation equipment based on specific technological and economic constraints.

Overall, the continued development and implementation of optimized and digitally supported feed transportation technologies will contribute to the modernization of livestock production systems and improve their competitiveness and sustainability in the long term.

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ANALYSIS OF THE CONCEPT OF MULTIMODAL FREIGHT TRANSPORT MANAGEMENT

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Abstract. In the context of globalization and digital transformation of the economy, multimodal freight transport is becoming a key element in the effective functioning of modern supply chains. The growth in transport volumes, the increasing complexity of logistics routes, and the need to coordinate different modes of transport require the implementation of modern digital solutions that provide integrated management of transport and logistics processes. In this regard, the development of digital platforms aimed at improving the efficiency of multimodal freight transport management is a pressing scientific and practical task. The purpose of this article is to analyze the concept of multimodal freight transportation management, which ensures comprehensive coordination of logistics chain participants, optimization of transport routes, and increased transparency of logistics operations. The article discusses the theoretical foundations of multimodal transport, the principles of digitalization of logistics systems, and analyzes modern approaches to the application of information technologies in transport logistics. The practical significance of the research results lies in the possibility of using the concepts of transport and logistics company management to reduce total logistics costs, improve customer service quality, and ensure the sustainable development of logistics systems in the digital economy.

Keywords: transport, multimodal freight transport, multimodal transport, operator, customer, factors.

Introduction

The transport system is not limited to freight or passenger traffic; transport actively influences expanded reproduction, contributes to the progress of society, and is a key element of the economy.

Transport routes connecting many settlements and state objectives create conditions for the development of new territories and the organization of new industrial production. To improve the service of the internal needs of society in freight and passenger traffic, it is necessary to connect natural means of communication, i.e., artificial land routes to one type of transport, to which lakes, rivers, and seas are adapted. The existence of a transport network connected in this way allows the use of multimodal systems and their diversity—economical transport systems that include intermodal technologies [1].

Transport communications unite all regions of the country, which is a necessary condition for the unity of its territorial integrity and economic space. They connect the country with the world community, serving as the material basis for ensuring Kazakhstan's foreign economic relations and its entry into the global economic system.

The transport industry contributes to the socio-economic development of the country and its regions, promotes the improvement of the quality of life of the population, ensuring the

delivery of raw materials and equipment to production sites and finished products within the country and beyond, as well as the transit of goods.

The main part

Multimodal transport refers to the transport of goods using two or more modes of transport, such as road, rail, sea, and air [2]. It involves the coordination of many modes of transport for the efficient and effective movement of goods from one place to another, Figure 1.

The concept of multimodal transport demonstrates that different modes of transport have different strengths and limitations. It creates conditions for utilizing the strengths of each mode by combining them, thereby reducing their weaknesses.

For example, air transport is considered the fastest but most expensive, while sea transport is slow but economical for heavy goods. In general, the main criteria for multimodal transport are the quality of the functions involved in the delivery of goods, their proper performance, and manageability by operators.

The main requirements for such delivery are as follows [3]:

- there should be no interruptions throughout the entire delivery process;
- timely delivery of goods to their destination;
- minimization of transportation costs;
- responsibility of multimodal operators;
- a single tariff for deliveries;



Figure 1. Multimodal transport

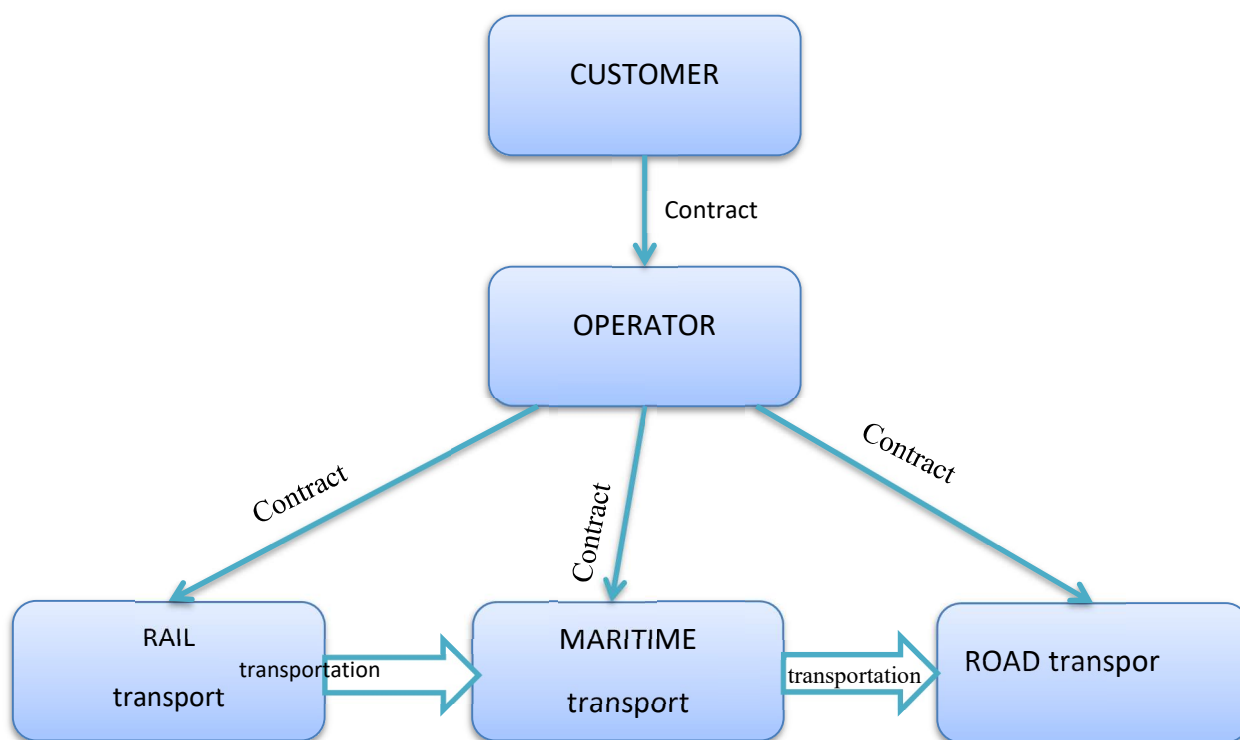


Figure 2. Interaction between participants in multimodal transport

Note: [4] compiled by the author based on literature

Choosing a logistics company for multimodal transport requires careful consideration of several factors. There are several key factors to consider when choosing a logistics company for multimodal transport (Table 1).

Table 1. Criteria for selecting a logistics company that provides multimodal transport

No	Name	Features
1	Experience	There is a need to find a logistics company with experience in multimodal transport and experience in requesting similar high-level transport services. Organizations must be well versed in various types of transport, as well as in the documentation and customs conditions adapted to each type
2	Geographical coverage	It is necessary to compare the geographical range of the logistics company involved in these measures and the capacity with which they can process goods to the destinations required by consumers.
3	Technological methods	A reliable logistics company with an interested technological format that allows you to manage the volume of shipments in real time and allows the organization to always adjust the shipment status.
4	Price	It is important to consider the pricing structure of the logistics organization for multimodal transportation and its competitiveness compared to other carriers in the market.
5	Level of customer service	It is more profitable to work with a logistics company that is responsible for solving every problem that may arise in the process of developing material flows and has a chain of service for regular customers.
Note: [5] compiled by the author based on literature		

After carefully considering the above factors and conducting the necessary checks on interested logistics participants, we can select a future permanent partner who will be able to provide sufficient and optimal multimodal transport functions to regulate professional needs [6].

Table 2. Freight traffic volumes by mode of transport in Kazakhstan (2019–2024)

Year	Road transport, million tons	Rail transport, million tons	Air transport, million tons	Maritime transport, million tons	Multimodal transport, million tons
2019	4100	1380	35	220	150
2020	3950	1420	38	230	165
2021	4200	1480	42	240	190
2022	4450	1520	45	250	225
2023	4700	1580	48	260	260
2024	4950	1640	50	270	300
Note: [5] compiled by the author based on literature					

The data in Table 2 show the dominant role of road transport in the freight transport structure, accounting for more than 65-70% of the total volume.

Rail transport is showing a steady growth trend, which is linked to the development of transit corridors and an increase in international transport. Of particular interest is the dynamics of multimodal transport, the volume of which doubled between 2019 and 2024.

This confirms the growing role of integrated logistics solutions and the need to improve the management of multimodal supply chains.

Table 3. Foreign experience in organizing multimodal transport

№	Country	Multimodal transport complex
1	Germany	Germany has a well-established and efficient multimodal transport system supported by a dense network of motorways, railways, waterways, and airports. The country has also implemented a number of initiatives to promote the use of multimodal transport, such as the development of intermodal terminals, the introduction of a national container transport system, and the creation of a national transport logistics network.
2	China	China is a world leader in the organization of multimodal transport, especially in the field of container transport. The country has developed an extensive network of ports, railways, and highways, which has enabled it to become a key player in world trade.
3	United States Americ	The United States has a well-developed multimodal transport system supported by a network of highways, railways, ports, and airports. The country has also implemented a number of initiatives to improve the efficiency of multimodal transport.
4	Japan	Japan has a highly developed multimodal transport system characterized by a high level of efficiency and reliability.
5	European Union	The European Union has developed a comprehensive multimodal transport system supported by a network of roads, railways, waterways, and airports. The EU has also implemented a number of initiatives to promote the use of multimodal transport, such as the development of intermodal terminals and the introduction of the
Note: [7] compiled by the author based on literature		

For example, China delivers cargo from Chengdu to Turkey using multimodal transport. However, several significant obstacles in this process affect the efficiency of transportation. The main causes of these problems and ways to solve them will be discussed below.

Table 4. Components and solutions

Components	Real solutions	Comment
Customs clearance	1. Introduction of an electronic predeclaration system (e-TIR)	Acceleration of customs operations with preliminary electronic registration of cargo, reduction of paper documents, improvement of control
	2. Coordination of a single customs "green corridor" regime between Kazakhstan and Azerbaijan	Speed up border crossing for transit cargo and optimize clearance
Speed of loading at the port	1. Introduction of an automated warehouse management system (WMS) at the port of Aktau	Optimization of the loading and unloading process with real-time tracking of cargo in the warehouse
	2. Purchase of additional cranes	Accelerate loading and unloading by 40% and increase port throughput
Document compatibility	1. Full implementation of international standards TIR Carnet, CMNI	Fast and reliable verification of cargo documents, simplifying customs clearance
	2. Digitization and automation of document flow with partners Kazpost or DHL	Reduction of document loss and errors, increased processing speed, and ensured transparency of information
Note: [8] compiled by the author based on literature		

Conclusion

The analysis of the concept of multimodal freight transport management has shown that the effectiveness of modern logistics systems is largely determined by the correct selection and application of key criteria for organizing the transport process. Multimodal transport, based on the use of two or more modes of transport under a single contract, ensures flexibility, reliability, and economic feasibility of cargo delivery in the context of globalization and increasingly complex supply chains.

The main criteria for multimodal freight transportation that determine the quality of management and competitiveness of logistics companies include the following:

First, the cost criterion, which includes the level of total transport and logistics costs, the structure of tariffs, and the costs of transshipment, storage, insurance, and customs clearance. Optimization of this criterion is aimed at minimizing the total cost of delivery while maintaining the required level of service.

Second, the time criterion, which characterizes the total duration of transportation, compliance with delivery times, stability of schedules, and speed of cargo handling at transport junctions. Reducing transit time is a key factor in increasing capital turnover and customer satisfaction.

Thirdly, the reliability and safety of transportation, reflecting the level of cargo safety, the frequency of damage and loss, the resilience of routes to disruptions, and the effectiveness of risk management. This criterion ensures the trust of supply chain participants and reduces the likelihood of financial losses.

Fourth, flexibility and adaptability of the system, manifested in the ability to quickly change routes, modes of transport, and logistics schemes depending on changes in demand, weather conditions, and infrastructure constraints.

Fifth, information integration, including the level of digitalization, transparency of cargo movement, the availability of a unified information platform, and the ability to monitor in real time. This criterion ensures the coordination of actions of all participants in the multimodal chain.

Sixth, environmental criteria related to emission levels, energy efficiency of the modes of transport used, and compliance with the principles of sustainable development.

Thus, the application of a system of comprehensive criteria allows for an objective assessment of the efficiency of multimodal freight transport and the formation of optimal management decisions

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Разработка ML-модели риска инфаркта миокарда без стойкого подъема сегмента ST

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Аннотация: Инфаркт миокарда без стойкого подъема сегмента ST (ИМБСПСТ) представляет собой форму ишемической болезни сердца, при которой отсутствует классический подъем ST-сегмента на ЭКГ. В связи с этим ранняя диагностика затруднена, а риск неблагоприятных исходов возрастает.

В данной работе разработана и протестирована модель машинного обучения для прогнозирования риска ИМБСПСТ на основе клинико-лабораторных показателей. Рассмотрены методы логистической регрессии, случайного леса и градиентного бустинга. Модель XGBoost показала наилучшие результаты (AUC = 0.89).

Ключевые слова: инфаркт миокарда, машинное обучение, прогнозирование риска, XGBoost, медицинская аналитика.

Development of an ML model for risk prediction of non-elevation myocardial infarction

Abstract: Non-ST-elevation myocardial infarction (NSTEMI) represents one of the most diagnostically challenging forms of ischemic heart disease, characterized by the absence of a typical ST-segment elevation on ECG. This complicates early diagnosis and increases the risk of adverse outcomes. In this study, a machine learning model was developed and tested to predict the risk of NSTEMI based on clinical and laboratory patient data. Logistic regression, random forest, and gradient boosting methods were evaluated. The XGBoost algorithm achieved the best performance with an AUC of 0.89. The findings confirm the potential of machine learning techniques in improving diagnostic accuracy and personalized cardiovascular risk assessment.

Key words: myocardial infarction, machine learning, risk prediction, XGBoost, medical analytics.

Введение

Инфаркт миокарда без стойкого подъема сегмента ST (ИМБСПСТ) является одной из наиболее распространённых форм ишемической болезни сердца и сопровождается высоким риском осложнений и смертности. В отличие от классического инфаркта с подъёмом ST, данная форма не имеет типичных электрокардиографических признаков, что затрудняет раннюю диагностику.

Современные методы машинного обучения (ML) позволяют анализировать большие массивы клинико-лабораторных данных и выявлять скрытые закономерности, способные повысить точность диагностики и прогнозирования.

Целью данного исследования является разработка и оценка модели машинного обучения для прогнозирования риска ИМБСПСТ на основании клинических и лабораторных показателей пациентов.

Материалы и методы

Данные

Для обучения модели использованы обезличенные данные 1 500 пациентов кардиологического центра.

Каждая запись содержала 25 признаков, включая:

возраст, пол, уровень тропонина Т, креатинина, холестерина, глюкозы, наличие артериальной гипертензии, сахарного диабета, курения, а также параметры ЭКГ.

Перед обработкой данные были очищены от пропусков и выбросов, а числовые признаки нормализованы с помощью стандартной шкалы Z-score:

$$z = \frac{x - \mu}{\sigma}$$

где x — исходное значение признака, μ — среднее значение, σ — стандартное отклонение. Категориальные признаки (например, пол, наличие гипертонии) были закодированы методом **One-Hot Encoding**.

Модели и методы обучения

Для решения задачи бинарной классификации (риск ИМБСПСТ: «0 — низкий», «1 — высокий») использовались три модели:

1. Логистическая регрессия (LR)
2. Случайный лес (Random Forest, RF)
3. Градиентный бустинг (XGBoost)

Обучение и оценка выполнялись в среде **Python 3.10** с использованием библиотек **pandas, scikit-learn, xgboost, matplotlib**.

Формулы

1. Логистическая регрессия

Вероятность наступления события $y = 1$ определяется как:

$$P(y = 1|x) = \frac{1}{1 + e^{-(\beta_0 + \sum_{i=1}^n \beta_i x_i)}}$$

Потери рассчитываются через логистическую функцию (Log-Loss):

$$L = -\frac{1}{N} \sum_{i=1}^N [y_i \log(p_i) + (1 - y_i) \log(1 - p_i)]$$

2. XGBoost

XGBoost минимизирует регуляризованную функцию потерь:

$$Obj = \sum_{i=1}^N l(y_i, \hat{y}_i) + \sum_{k=1}^K \Omega(f_k)$$

где $\Omega(f_k) = \gamma T + \frac{1}{2} \lambda \sum_{j=1}^T w_j^2$ — регуляризационный член,

T — число листьев дерева, w_j — веса листьев.

3. Метрики оценки

Модель оценивалась по метрикам **AUC, Accuracy, Precision, Recall** и **F1-score**.

Формула точности (accuracy):

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

Результаты и обсуждение

Модель **XGBoost** показала наилучшие результаты среди трёх протестированных алгоритмов. Итоговые метрики на тестовой выборке:

Модель	Accuracy	Recall	Precision	F1-Score	AUC
Логистическая регрессия	0.81	0.76	0.79	0.77	0.84
Случайный лес	0.85	0.80	0.84	0.82	0.87
XGBoost	0.88	0.83	0.87	0.85	0.89

Наиболее информативными признаками оказались: уровень тропонина Т, возраст, фракция выброса, креатинин и наличие диабета.

Рисунок 1 иллюстрирует важность признаков по версии XGBoost.

(Рис. 1. Значимость признаков модели XGBoost.)

Полученные результаты свидетельствуют о высокой прогностической способности разработанной модели и подтверждают потенциал применения ML-технологий в кардиологии.

Заключение

Разработанная модель машинного обучения позволяет эффективно прогнозировать риск инфаркта миокарда без стойкого подъема сегмента ST на основе стандартных клинико-лабораторных данных.

Использование алгоритма **XGBoost** продемонстрировало высокую точность (AUC = 0.89), что делает его перспективным инструментом для поддержки принятия врачебных решений в кардиологической практике.

Дальнейшие исследования планируется направить на интеграцию модели в электронную систему медицинских карт и валидацию на расширенной выборке пациентов из разных регионов.

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Разработка системы анализа данных о сетевых атаках для создания эффективных стратегий защиты от новых угроз

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Аннотация: В статье рассматривается разработка интеллектуальной системы обнаружения сетевых вторжений (NIDS) с использованием современных алгоритмов машинного обучения. В условиях стремительного роста киберугроз в Казахстане и мире, традиционные методы защиты требуют дополнения адаптивными аналитическими решениями. В качестве базы исследования использован набор данных CICIDS2017. Автором проведена комплексная предобработка данных, решена проблема дисбаланса классов с помощью методов SMOTE и Random Undersampling. Проведен сравнительный анализ моделей LightGBM, XGBoost и Random Forest. Модель LightGBM показала наилучшую точность (98%). Для интерпретации предсказаний и повышения доверия к системе применены методы SHAP и LIME.

Ключевые слова: кибербезопасность, машинное обучение, сетевые атаки, CICIDS2017, градиентный бустинг, интерпретируемость моделей, SHAP.

Development of a network attack data analysis system to create effective protection strategies against new threats

Abstract: This paper discusses the development of an intelligent network intrusion detection system (NIDS) using modern machine learning algorithms. In the context of the rapid growth of cyber threats in Kazakhstan and globally, traditional protection methods require supplementation with adaptive analytical solutions. The CICIDS2017 dataset was used as the research base. The author performed complex data preprocessing, solved the class imbalance problem using SMOTE and Random Undersampling methods. A comparative analysis of LightGBM, XGBoost, and Random Forest models was conducted. The LightGBM model showed the best accuracy (98%). SHAP and LIME methods were applied to interpret predictions and increase trust in the system.

Key words: network attacks, cybersecurity, machine learning, CICIDS2017, LightGBM, SHAP, intrusion detection.

Введение

С развитием технологий интернета вещей (IoT), облачных вычислений и сетей 5G объем передаваемых данных растет экспоненциально, что создает новые векторы для кибератак. Традиционные системы обнаружения вторжений (IDS), основанные на сигнатурах, эффективно выявляют только уже известные угрозы, но оказываются бессильны перед атаками «нулевого дня» (Zero-day attacks).

Актуальность данной работы заключается в необходимости создания адаптивных аналитических систем, способных выявлять аномалии в сетевом трафике на основе статистических закономерностей. Целью работы является разработка системы анализа данных, которая позволит автоматизировать процесс идентификации атак и сформировать базу для разработки превентивных стратегий защиты.

Обзор предметной области и данных

Для обучения и тестирования системы был выбран набор данных CICIDS2017, разработанный Канадским институтом кибербезопасности. В отличие от устаревших наборов (например, KDD99), CICIDS2017 содержит актуальные сценарии атак и реальный трафик в формате PCAP.

Таблица 1 — Распределение типов трафика в исследуемой выборке

<i>Тип трафика</i>	<i>Количество записей</i>	<i>Процентное соотношение</i>
<i>Benign (Нормальный)</i>	2,273,097	80.3%
<i>DoS/DDoS</i>	380,699	13.5%
<i>PortScan</i>	158,930	5.6%
<i>Brute Force</i>	13,835	0.5%
<i>Другие (Botnet, Web Attack)</i>	4,213	0.1%

Методология исследования

Сетевой трафик характеризуется высокой размерностью (более 80 признаков). На этапе предобработки были выполнены следующие шаги:

1. Очистка данных: Удаление бесконечных значений (Inf) и пропусков (NaN), возникающих при расчете скорости пакетов.
2. Нормализация: Приведение числовых признаков к единому масштабу с помощью z-масштабирования:

$$z = \frac{(x - \mu)}{\sigma}$$

где x — исходное значение, μ — среднее, σ — стандартное отклонение.

3. Кодирование: Преобразование целевой переменной (типа атаки) в числовой формат (Label Encoding).

Решение проблемы дисбаланса

Как видно из Таблицы 1, данные сильно несбалансированы. Для предотвращения переобучения модели на мажоритарный класс (Benign) применена комбинация методов:

SMOTE (Synthetic Minority Over-sampling Technique): Синтетическая генерация примеров редких атак.

Random Undersampling: Случайное сокращение объема избыточных данных нормального трафика.

Разработка и обучение моделей

В работе сравнивались три архитектуры: Random Forest (RF), XGBoost и LightGBM. Последняя была выбрана в качестве основной из-за использования метода GOSS (Gradient-based One-Side Sampling), который позволяет эффективно обрабатывать большие датасеты без потери точности.

Математическая модель градиентного бустинга: Целевая функция оптимизации выглядит следующим образом:

$$L^t = \sum_{i=1}^n l(y_i, \widehat{y_i^{t-1}} + f_{t(x_i)}) + \Omega(f_t)$$

Где l — функция потерь, y_i — истинное значение, y_i^{t-1} — прогноз модели на предыдущем шаге, $f_{t(x_i)}$ — новая функция (дерево решений), добавляемая в ансамбль на текущем шаге, $\Omega(f_t)$ — член регуляризации, который штрафует модель за излишнюю сложность (чтобы избежать переобучения).

Результаты

Эффективность моделей оценивалась по метрикам Accuracy, Precision, Recall и F1-score.

Таблица 2 — Сравнительные результаты работы алгоритмов

Модель	Accuracy	Recall	Precision	F1-Score	Время обучения (сек)
Logistic Regression	0.86	0.85	0.84	0.84	45
Random Forest	0.96	0.94	0.95	0.94	120
LightGBM	0.98	0.98	0.97	0.98	35

Модель LightGBM показала не только лучшую точность, но и наименьшее время обработки, что критически важно для систем, работающих в реальном времени.

Интерпретация результатов (XAI)

Для понимания того, на основе каких признаков система классифицирует трафик как атаку, использован метод SHAP (SHapley Additive exPlanations).

Основные факторы влияния:

Flow Duration: Длительность сессии (характерно для медленных DoS-атак).

Total Backward Packets: Количество обратных пакетов (индикатор сканирования портов).

Destination Port: Порт назначения (часто 80, 443 или специфические порты для брутфорса).

Заключение

В ходе исследования разработана система анализа сетевого трафика, демонстрирующая высокую точность обнаружения атак (98%). Применение методов балансировки данных позволило эффективно классифицировать даже редкие типы угроз (Botnet, Web Attacks). Разработанная модель может быть интегрирована в программные комплексы мониторинга информационной безопасности для автоматизации реагирования на инциденты.

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Сравнительный анализ эффективности алгоритмов машинного обучения и нейронных сетей в задачах обнаружения сетевых атак

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Аннотация: Статья посвящена исследованию эффективности применения различных методов искусственного интеллекта для задач кибербезопасности. Проведен сравнительный анализ классических ансамблевых алгоритмов (Random Forest), методов градиентного бустинга (XGBoost, LightGBM) и нейронных сетей (MLP) на базе набора данных CICIDS2017. Особое внимание уделено проблеме дисбаланса классов, для решения которой применена гибридная стратегия с использованием SMOTE. Результаты экспериментов показали, что, несмотря на высокую точность нейронных сетей, алгоритмы градиентного бустинга демонстрируют лучший баланс между скоростью обучения и качеством классификации, что делает их предпочтительными для систем реального времени.

Ключевые слова: обнаружение вторжений, машинное обучение, нейронные сети, дисбаланс данных, сравнительный анализ, LightGBM, XGBoost.

Comparative analysis of the effectiveness of machine learning algorithms and neural networks in network attack detection tasks

Abstract: The article focuses on researching the effectiveness of various artificial intelligence methods for cybersecurity tasks. A comparative analysis of classical ensemble algorithms (Random Forest), gradient boosting methods (XGBoost, LightGBM), and neural networks (MLP) was conducted based on the CICIDS2017 dataset. Special attention is paid to the class imbalance problem, which was addressed using a hybrid strategy involving SMOTE. Experimental results showed that despite the high accuracy of neural networks, gradient boosting algorithms demonstrate a better balance between training speed and classification quality, making them preferable for real-time systems.

Keywords: intrusion detection, machine learning, neural networks, data imbalance, comparative analysis, LightGBM, XGBoost.

Введение

В последние годы наблюдается экспоненциальный рост объема передаваемых данных, связанный с развитием технологий 5G и IoT. Параллельно с этим растет и количество киберинцидентов: во втором квартале 2024 года число атак на страны СНГ увеличилось в 2,6 раза. В таких условиях выбор оптимального алгоритма для систем обнаружения вторжений (IDS) становится критически важной задачей. Целью данной работы является проведение сравнительного анализа современных методов машинного обучения и определение

наиболее эффективного подхода для классификации вредоносного трафика в условиях сильного дисбаланса классов.

Материалы и методы

Набор данных

Экспериментальное исследование проводилось на датасете CICIDS2017, который содержит реалистичный сетевой трафик, собранный в течение 5 дней. Набор включает как нормальную активность, так и 14 типов атак, среди которых DoS, PortScan, Brute Force и Botnet. Общая доля нормального трафика составляет 80,3%, что создает проблему дисбаланса.

Подготовка данных

Для обеспечения корректности экспериментов была проведена предварительная обработка:

1. Очистка: Удаление записей с бесконечными значениями (Inf) и пропусками (NaN), возникающими при расчете статистических метрик потока.
2. Балансировка: Применена комбинированная стратегия. Для миноритарных классов (атаки Botnet, Web Attack) использован метод синтетической генерации SMOTE, а для мажоритарного класса — Random Undersampling.

Исследуемые модели

Для сравнения были выбраны три класса алгоритмов:

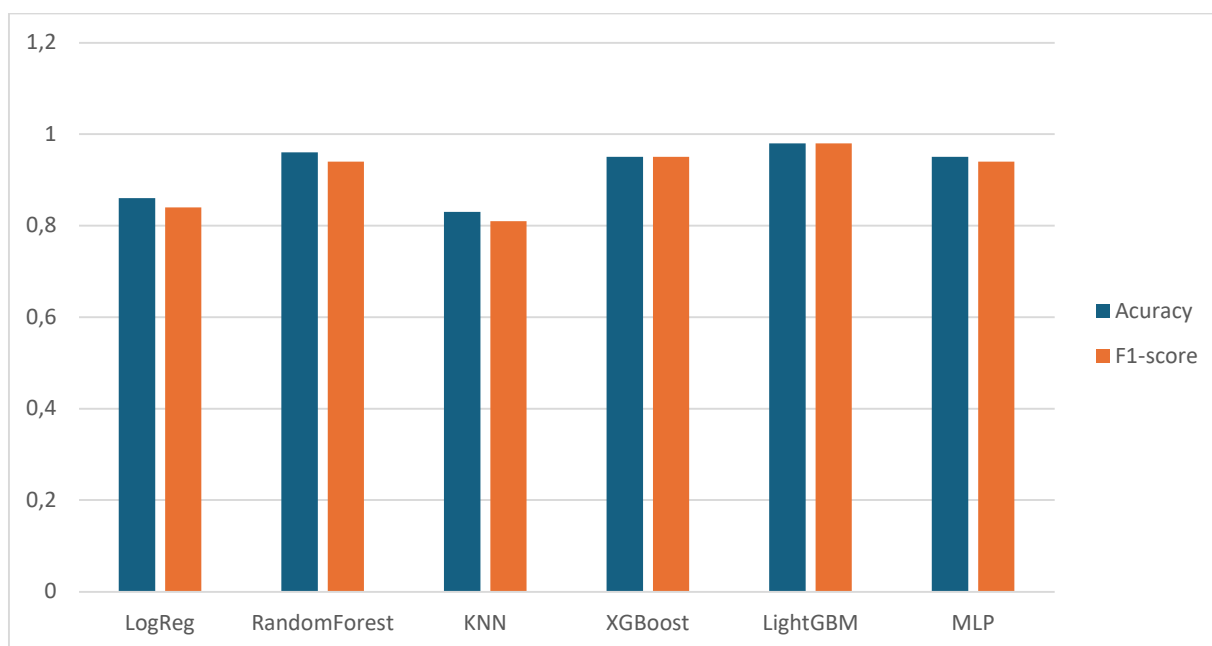
1. Классический ансамбль: Random Forest (Случайный лес).
2. Градиентный бустинг: XGBoost и LightGBM. Эти алгоритмы строят композицию решающих деревьев, минимизируя функцию потерь градиентным спуском.
3. Нейронные сети: Многослойный перцептрон (MLP), способный выявлять сложные нелинейные зависимости.

Результаты и обсуждение

Оценка качества моделей проводилась на отложенной тестовой выборке (20% от исходных данных) по метрикам Accuracy, F1-score и ROC-AUC. Также учитывалось время, затраченное на обучение, что важно для применения в реальных условиях.

Таблица 1. Сводные результаты экспериментов

<i>Модель</i>	<i>Accuracy</i>	<i>ROC-AUC</i>	<i>F1-Score</i>	<i>Скорость обучения</i>
<i>XGBoost</i>	0.96	0.97	0.95	Низкая
<i>MLP</i>	0.95	0.95	0.94	Низкая
<i>Random Forest</i>	0.96	0.97	0.94	Средняя
<i>LightGBM</i>	0.98	0.99	0.98	Высокая



Анализ результатов:

1. Random Forest показал достойный базовый результат (F1-score = 0.94), подтверждая эффективность ансамблевых методов.
2. XGBoost продемонстрировал высокую точность, сопоставимую с лучшими моделями, но потребовал значительно больше времени на обучение из-за сложности алгоритма перебора.
3. MLP (Нейросеть) показала высокую точность на уровне 0.95, однако уступила бустинговым моделям в интерпретируемости и стабильности. Кроме того, обучение нейросети требовало больших вычислительных ресурсов.
4. LightGBM оказался лидером эксперимента. Использование метода односторонней выборки на основе градиентов (GOSS) позволило достичь точности 98% при минимальных затратах времени (35 секунд).

Заключение

Проведенное исследование показало, что для задач обнаружения сетевых вторжений на табличных данных алгоритмы градиентного бустинга, в частности LightGBM, превосходят классические нейронные сети по соотношению «точность/скорость». Несмотря на потенциал глубокого обучения, сложность настройки и интерпретации («черный ящик») делает их менее предпочтительными для оперативного реагирования на инциденты по сравнению с интерпретируемыми ансамблевыми моделями.

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DATA MINING PROCESSES AND INTELLIGENT ANALYSIS METHODS

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Abstract. This article systematically explains the concept, purpose, and stages of Data Mining. The main goal of data mining is to identify hidden patterns and relationships in large datasets and enable their application to new data. The process includes problem definition, data preparation, model building, testing, and the use of results in decision support systems. The article classifies intelligent data analysis methods into basic (statistical and selection-based) and special methods. Among the special methods, fuzzy logic for handling uncertainty, neural networks for learning and prediction, and genetic algorithms for optimization are discussed in detail. The advantages of fuzzy logic in representing linguistic uncertainty and the ability of neural networks to model complex dependencies are emphasized. The role of genetic algorithms as powerful search mechanisms based on evolutionary principles is highlighted. Finally, the article concludes that hybrid neuro-fuzzy systems, which integrate these methods, are more effective in solving complex real-world problems.

Keywords. Data Mining, Data Analysis, Fuzzy Logic, Neural Networks, Genetic Algorithms, Hybrid Systems

Stages of intellectual analysis. The purpose of data mining is to identify patterns and relationships in a data set. These patterns and relationships can then be used in new data sets.

The data mining process consists of several stages: (Figure 1).

- problem definition;
- data preparation for analysis;
- application of analysis methods and model building;
- testing of built models;
- use of the results in a decision support system.

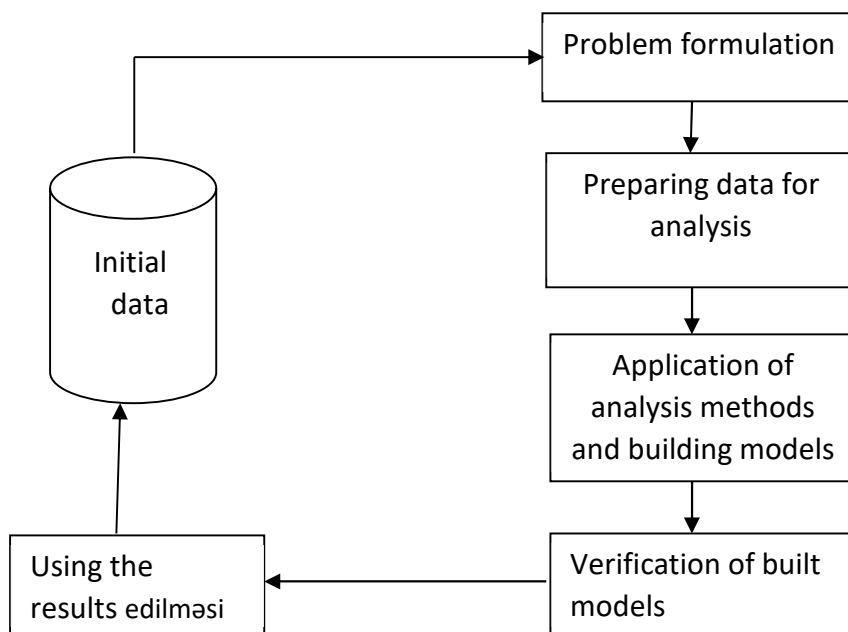


Figure 1. Stages of data mining

At stage 1, the data is studied, the purpose of the data mining is specified. Methods of mining are selected in accordance with the goals set. The correct selection of methods is considered an important condition.

At stage 2, the data is put into the form required by mining, that is, the process of extracting, transforming and loading (ETL data from the primary sources) is performed. The methods selected at stage 1 also affect the transformations performed on the data.

Stage 3 involves the direct application of analysis methods. The application scenario can be constructed in various ways (especially if the analysis is carried out from different perspectives) and can consist of a combination of several methods. The results of the analysis are often expressed in certain models.

At the next stage, these models are checked. The simplest and most commonly used method is that the analyzed data is divided into two groups: group 1 has a large size, and group 2 has a relatively small size. In the 1st group, data is analyzed and certain models are built using this or that method. In the small-sized data group, these models are checked. Based on the difference between the obtained accuracies, a conclusion is drawn about the adequacy of the built model.

At the last stage, the results of the analysis are interpreted by the user. The results can be used to make decisions and add to the knowledge base. The evaluation of the results of intellectual analysis is determined by the quality of the decisions made on their basis.

Methods of intellectual analysis

Methods of intellectual analysis can be divided into 2 groups:

- base methods;
- special methods.

Base methods. Basic methods include, first of all, algorithms based on selection. In a set of N objects, selection requires $2N$ comparison operations. In other words, as the number of data increases, the volume of calculations increases exponentially. When the number of data is large, it is practically impossible to work with such a method.

In this type of algorithm, various heuristic methods are used to reduce the number of choices to reduce the computational complexity. Optimization of such algorithms is achieved by reducing the dependence of the number of operations on the number of data to a linear

function. However, the dependence on the number of attributes remains exponential. Since the number of attributes is limited (their number is much less than the number of data), such a dependence is acceptable.

The main advantage of these algorithms is their simplicity of understanding and implementation. Their disadvantages include the lack of a formal theory in the construction of these algorithms and the difficulties in their research and development.

The basic methods of data mining also include methods that use elements of statistical theory. Considering that data mining arose as a result of the development of statistics, there are quite a few such methods. They are based on various types of statistical analysis: correlation analysis, regression analysis, factor analysis, etc. The main drawback of these methods is the commonality of values. This can lead to a loss of informativeness in the data and a decrease in the amount of knowledge obtained.

Fuzzy logic. Sometimes, when solving the problem of data analysis, uncertainty arises due to the incompleteness of the initial data. Two types of uncertainty are distinguished: physical and linguistic.

The source of physical uncertainty is the external environment. It can be of two types:

- imprecision (can arise when measuring the values of a certain quantity using measuring devices);

- randomness (the presence of several factors from the external environment that affect the object; each of them is random in nature; in this case, the law of probability distribution is assumed to be known).

To process physical uncertainties, methods of probability theory and classical set theory are used.

Linguistic uncertainty arises when a large number of situations are expressed in a limited number of words. They also distinguish two types of linguistic ambiguity:

- uncertainty of the meaning of a word (polysemy, ambiguity, vagueness); occurs when different objects are expressed by the same word;

- uncertainty of the meaning of a phrase (they also distinguish statistical and semantic types of it).

With the development of systems using the methods of artificial intelligence theory, formal methods for processing linguistic uncertainty have emerged. The basis of these methods is fuzzy logic.

The main application area of fuzzy logic is management. It is no coincidence that the famous scientist Lotfi-zadeh, who laid the foundation of fuzzy logic, is a well-known specialist in the field of management. The use of fuzzy logic at all levels of management gives good results.

For the study of systems, Lotfi-zadeh proposed a linguistic model consisting not of mathematical expressions, but of words expressing properties. The application of a linguistic model cannot ensure accuracy in mathematical modeling. However, it is possible to build a good, high-quality model. In this case, the object of discussion is the fuzziness of words in the descriptive language of the system.

In many cases, concepts and relationships with fuzzy boundaries are used when managing complex objects. The source of fuzziness is the variability of the belonging of objects to certain classes. An object may belong to that class completely, not at all, or to some extent. The usual mathematical concept of a set based on a binary characteristic function does not allow for such a description.

Two concepts proposed by Lotfi-zadeh - fuzzy set and linguistic variable - have significantly increased the formal description capabilities of such complex systems. Models of this type are called linguistic models.

A number of concepts that we use in natural language can be cited as examples of fuzzy variables: hot, very hot, cold, very cold, mild, end of the month, beginning of the month. We understand and work with these concepts and do not notice their fuzziness. From a formal point of view, a concept called “membership function (μ)” is used to evaluate a linguistic variable. The membership function, which varies in the interval (0-1), shows how much the value of a linguistic variable belongs to the set of its possible values.

Thus, the set of possible values of a linguistic variable x can be expressed as $\{x_1, x_2, \dots, x_n\}$ using the membership function.

$$\{(x_1, \mu_1), (x_2, \mu_2), \dots, (x_n, \mu_x)\} \quad (1)$$

For example, the set of values (in degrees) of the linguistic variable “very hot” in the summer season could be $\{35, 36, 37, 38, 39, 40, 41, 42\}$, and the expression of that set with a membership function could be: $\{(35, 0.5), (36, 0.6), (37, 0.7), (38, 0.75), (39, 0.8), (40, 0.9), (41, 0.95), (42, 1)\}$.

The main advantage of fuzzy logic is more pronounced in solving fuzzy management problems. Fuzzy logic allows a person to clearly express his thinking. In his daily activities, a person uses fuzzy natural language, not formal modeling based on mathematical expressions. In the decision-making process, a person understands the situation well, divides it into events and makes a decision in accordance with each event. Thus, local models are created that describe the objects or events (processes) considered in the conditions before a person and are expressed in words. These models have common foundations and are easy to understand at the qualitative level. An example of such a verbal model is the construction “if ..., then ...”.

The use of fuzzy logic in management has the following features characterized by:

- decision-making rules are expressed by conditional reasoning of the type “if..., then...” and are implemented through a logical inference mechanism;

- fuzzy logic operates with special rules; rules are given for each local area and problem, for each regulated quantity and for each management objective; this allows you to abandon the generalized objective criterion;

- the application of rules of the type “if..., then...” allows you to solve the classification problem in a dialogue mode with the operator, which increases the quality of the classifier.

Neural networks. Neural networks are a class of analytical methods based on biological analogy with the human brain. Through them, it is possible to predict the values of certain variables after the so-called “learning” stage on the available data.

When applying these methods, the first issue is the selection of a specific architecture of the network (“layers” and the number of “neurons” in each layer). In terms of formal computational complexity, the size and structure of the network depend on the object under study (event). Since the nature of the object (event) is not fully known at the initial stage of analysis, the selection of the architecture becomes complicated and is associated with a long-term “trial and error” process. However, recently, artificial intelligence methods and neural network programs have been used to select a better architecture.

The constructed network then undergoes a “learning” process. At this stage, the neural network iteratively processes the input data and makes adjustments to its “weights” in such a way that good predictions are obtained on the learned data. After the training is completed on the existing data, the network can be used for prediction.

An example of a neural network is shown in Figure 2. The network under consideration consists of 2 layers, with 4 neurons placed in the 1st layer and 5 neurons in the 2nd layer.

The network obtained as a result of learning expresses the regularities present in the data. In this approach, the neural network is a functional model reflecting the dependencies between

variables in traditional modeling. becomes equivalent. However, unlike traditional models, these dependencies are not explicitly written in neural networks.

In some cases, neural networks can provide high-quality predictions. However, in this case, there is no theoretical approach to the study.

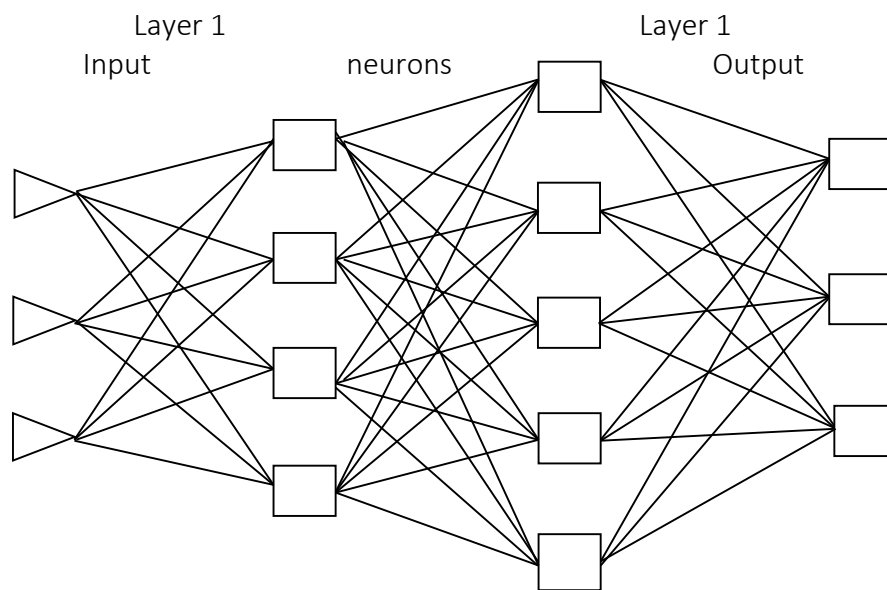


Figure 2. Example of a neural network

In this case, the main focus is on practical results - the accuracy of predictions and their practical significance.

Neural network methods can also be used in research aimed at building a model for explaining phenomena. Thus, neural networks allow analyzing data to search for valuable variables or groups of variables. Currently, there are neural network programs that detect more important input data through complex algorithms.

One of the advantages of neural networks is that they can approximate any continuous function. Therefore, the researcher does not need to make a hypothesis in advance about which variables are important.

A serious drawback of neural networks is that the final result depends on the initial setup of the network, and it is impossible to interpret this in traditional analytical terms.

Some authors liken a neural network to a processor that performs operations with high parallelism, has a natural ability to store empirical knowledge and makes it available for later use. It resembles the brain in two ways: 1) the network acquires knowledge during the learning process; 2) the intensity of connections between neurons is used to store information. This is called synoptic weight.

Most existing neural network programs run on single-processor computers. The speed of work with neural networks can be increased not only by creating software that takes advantage of multiprocessor systems, but also by building more efficient training algorithms.

Genetic algorithms. Genetic algorithms (GA) are universal optimization methods for solving various types of problems (combinatory, general problems with constraints and unconstrained ones, etc.). Genetic algorithms have single-criteria and multi-criteria search capabilities in a large space.

GA is a type of evolutionary algorithm that models natural evolutionary processes. These algorithms are based on natural evolution in nature and use its basic mechanisms. Search algorithms that model a breeding pair are called genetic algorithms. A breeding pair is

characterized by the combination of two parental lines to create offspring. Such a combination is called mating.

When working with GA, the solution to the problem should be described as a string expressed in binary, integer or real number encoding. Strings can be of fixed or variable length, and context-dependent encoding can also be used.

The main difference between a genetic algorithm and a genetic program (GP) is the use of decision trees. In this case, a genetic description of the problem is not needed in a genetic program. Such a scheme creates flexibility in describing the data structures, but the solution size can be very large. This is also true for evolutionary programs.

In the 70s of the last century, Holland proposed a basic or standard genetic algorithm. Below is a generalized version of this algorithm.

Step 1. Genetic description of the problem.

Step 2. Creation of an initial population of individuals.

Step 3. Calculation of average fitness. Calculation of a normalized value of the fitness degree for each individual.

Step 4. Determination of a probability proportional to the normalized fitness for each individual.

Step 5. Selection of N vectors from the probabilities using the obtained distributions. Thus, the set of selected parents is formed.

Step 6. From this collection, randomly select N/2 pairs.

Step 7. Apply mating, mutation, and other genetic operators to each pair to form a new population.

Step 8. Return to step 3.

The considered basic genetic algorithm was subsequently improved by sequential and parallel modification methods. Sequential modification methods are used to obtain various forms of individual selection schemes.

As can be seen, the basic algorithm is a synchronized sequential algorithm. By applying the genetic algorithm, better pairs of individuals are sequentially selected to form offspring. This significantly increases the search time in large data sets. The solution to this problem is obtained by a parallel genetic algorithm. Any sequential modification of GA can be converted into a parallel modification.

According to the degree of parallelization, the following types of genetic algorithms are distinguished: 1) population-based GA; 2) subpopulation-based GA; 3) GA based on individuals. In case 1, the standard structure of GA working with the entire population is maintained. Parallelization is implemented in the mating and mutation stages.

In case 2, subpopulations are used that compete independently with individuals through exchange at a certain frequency. In this case, each processor block performs a sequential genetic algorithm with its subpopulation. The goal here is to maximize the total values of all fitness levels. In case 3, each processor element (cell) has a constantly stored string of individuals. Individuals choose pairs and merge with other individuals in their immediate vicinity.

The efficiency of a genetic algorithm largely depends on the probability of application of genetic operators, their type, and the size of the population. In recent years, the number of works carried out in the field of development of the theory and practical application of genetic algorithms has increased significantly. The results of these studies show that genetic algorithms can be more widely applied in conditions of integration with other methods and technologies. The effectiveness of integrating genetic algorithms with fuzzy logic methods and also with neural systems has already been proven.

Integration of fuzzy neural systems. Neuro-fuzzy or hybrid systems, which combine fuzzy logic, neural networks, genetic algorithms and expert systems, are considered effective tools for solving many problems in real life.

Each method of intelligent analysis has individual characteristics that make it suitable for solving specific problems: for example, the ability to learn, the ability to explain decisions, etc. Neural networks are good tools for pattern recognition, but they are not suitable for explaining their own decisions. Fuzzy logic systems can explain their decisions well, but they cannot automatically increase the rules for making these decisions. Therefore, the creation of intelligent hybrid systems by combining two or more methods to overcome the limitations inherent in each method has emerged.

Hybrid systems play a major role in solving problems in various application areas. In many complex areas, problems are encountered with separate components that require only their own processing method. For example, suppose that in a certain application area the problem of signal processing and decision making is solved. This problem can be divided into two subproblems: signal processing and decision making. Then, subproblem 1 can be solved using a neural network, and subproblem 2 can be solved using an expert system.

Fuzzy logic provides a mechanism for logical inference from cognitive (internal thinking) uncertainty. A neural network has advantages such as learning, adaptation, stability, parallelism, and generalization. To process cognitive uncertainty, it is necessary to apply the concept of fuzzy logic to neural networks. Such hybrid networks are called fuzzy neural networks.

Neural networks are used to tune membership functions in fuzzy systems. Fuzzy logic can directly describe knowledge through linguistic variables. However, the selection and tuning of membership functions is time-consuming. Neural network training methods automate this process and significantly reduce the time required to process membership functions.

In neural networks, knowledge is automatically obtained by applying the back-and-forth extraction algorithm, but the training process is relatively slow and the analysis of the trained network is complex. It is impossible to extract structured knowledge (rules) from the trained neural network and also to collect special information to simplify the training procedure.

The behavior of fuzzy systems can be described by the rules of fuzzy logic, and these rules can be controlled and adjusted. It should be noted that obtaining knowledge is a rather complex process, in which the range of variation of each input parameter must be divided into several intervals. The application of fuzzy logic systems is limited to areas where the availability of expert knowledge and the number of input parameters are small.

To solve the problem of knowledge acquisition, the ability to automatically obtain fuzzy logic rules from numerical data is added to neural networks. The calculation process is carried out using the following fuzzy neural networks. The process begins with the creation of a “fuzzy neuron” based on the recognition of the morphology of a biological neuron in accordance with the training mechanism. In this case, the following stages of the calculation process of a fuzzy neural network can be distinguished:

- construction of fuzzy neural models based on biological neurons;
- construction of a synoptic connection model that introduces uncertainty into neural networks;
- construction of training algorithms (methods for adjusting synoptic weight coefficients).

Figure 3 depicts a possible model of a fuzzy neural system. The interface block converts the received linguistic arguments into the input vector of a multi-level neural network. The neural network can be trained to produce the necessary output commands or decisions.

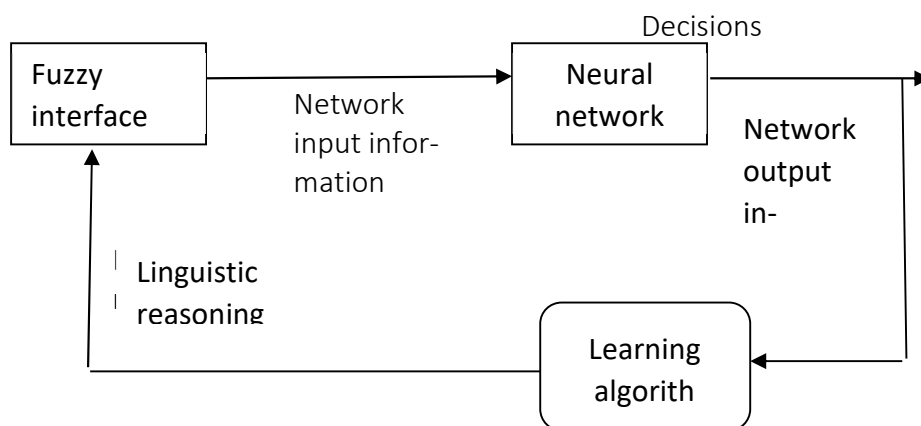


Figure 3. Fuzzy system model

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УДК: 004.852:616-001.17

Разработка модели машинного обучения для автоматизированного распознавания степени тяжести ожоговых поражений

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Аннотация: Ожоговая болезнь является системной реакцией организма на термическое повреждение, где критически важна ранняя и точная диагностика глубины поражения. В данной работе разработана модель машинного обучения для классификации степеней ожога и прогнозирования риска осложнений на основе комбинированных данных: визуальных характеристик раны и биохимических показателей крови. Сравнительный анализ алгоритмов показал, что ансамблевый метод CatBoost обеспечивает наивысшую точность (AUC = 0.92) в условиях малых медицинских выборок.

Ключевые слова: *ожоговая болезнь, машинное обучение, комбустология, классификация, CatBoost, медицинская диагностика.*

Development of an ML Model for Burn Severity Recognition and Outcome Prediction

Abstract: Burn disease is a systemic response to thermal injury, where early and accurate assessment of lesion depth is critical. In this study, a machine learning model was developed to classify burn degrees and predict the risk of complications based on combined data: visual wound characteristics and biochemical blood parameters. A comparative analysis of algorithms demonstrated that the CatBoost ensemble method provides the highest accuracy (AUC = 0.92) in the context of small medical datasets. The findings suggest that integrating ML-based decision support systems can significantly reduce diagnostic errors in emergency burn care.

Keywords: *burn disease, machine learning, combustiology, classification, CatBoost, medical diagnostics.*

Введение

Ожоговая болезнь остается одной из самых сложных областей экстренной медицины из-за высокого риска развития шока, сепсиса и полиорганной недостаточности. Ключевой проблемой является субъективность визуальной оценки глубины ожога, точность которой у врачей общего профиля не превышает 60–70%.

Современные методы машинного обучения (ML) позволяют интегрировать визуальные признаки раны с биохимическими маркерами крови для создания объективных систем поддержки принятия врачебных решений. Целью данного исследования является разработка модели, способной с высокой точностью дифференцировать степени ожога и прогнозировать риск развития ожогового шока.

Материалы и методы

Данные

Для обучения модели использованы ретроспективные данные 1 200 пациентов ожогового центра. Каждая запись включала 22 признака, разделенных на три группы:

1. **Анамнестические:** возраст, пол, этиология (пламя, пар, химический агент).
2. **Клинические:** общая площадь поражения (S_p), индекс Франка, локализация.
3. **Лабораторные:** уровень лактата, гемоглобина, креатинина, общего белка и лейкоцитарный индекс интоксикации.

Перед обучением данные прошли этап нормализации (Z-score) и кодирования категориальных признаков (One-Hot Encoding).

Математический аппарат

Для оценки тяжести состояния использовался индекс Франка (IF), рассчитываемый по формуле:

$$IF = S_p + 3 \times S_g$$

где S_p — площадь поверхностных ожогов (I-II ст.), S_g — площадь глубоких ожогов (III-IV ст.).

Модели и методы обучения

Для классификации риска неблагоприятного исхода (0 — стабильное состояние, 1 — высокий риск шока) использовались:

1. **Случайный лес (Random Forest)**
2. **XGBoost**
3. **CatBoost** (выбран из-за эффективной обработки категориальных данных о локализации ожогов).

Оценка качества проводилась с помощью кросс-валидации по 5 блокам. Основная метрика — **Log-Loss**, которую алгоритм стремится минимизировать:

$$LogLoss = -\frac{1}{N} \sum_{i=1}^N [y_i \log(p_i) + (1 - y_i) \log(1 - p_i)]$$

Результаты и обсуждение

Алгоритм **CatBoost** показал наиболее высокую точность и устойчивость к пропускам в данных.

Итоговые метрики на тестовой выборке:

Модель	Accuracy	Recall	Precision	F1-Score	AUC
Random Forest	0.84	0.80	0.83	0.81	0.88
XGBoost	0.87	0.84	0.86	0.85	0.90
CatBoost	0.90	0.87	0.89	0.88	0.92

Анализ важности признаков (Feature Importance) показал, что наибольший вклад в прогноз вносят:

- Уровень лактата крови (маркер гипоксии тканей).
- Возраст пациента.
- Индекс Франка.

Полученные результаты подтверждают, что модель способна распознавать критические состояния при ожоговой болезни точнее, чем традиционные статистические шкалы.

Закключение

Разработанная модель на базе алгоритма CatBoost позволяет с точностью 90% прогнозировать риски при ожоговой болезни. Интеграция данной модели в клиническую практику позволит врачам быстрее принимать решение о необходимости ранней некрэктомии (операции) или интенсивной инфузионной терапии, что потенциально снизит летальность в группе тяжелых пациентов.

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МРНТИ: 28.23.15; 76.29.39

УДК: 004.932:616-001.17

Разработка нейросетевого алгоритма сегментации ожоговых поверхностей на основе архитектуры U-Net

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Аннотация: Точное определение площади ожога () является критическим фактором для расчета объема инфузионной терапии. В данной работе предложена модель глубокого обучения на базе архитектуры U-Net с энкодером EfficientNet-B0 для автоматической сегментации зон термического поражения на цифровых изображениях. Использование разработанного алгоритма позволяет снизить ошибку в расчете площади поражения на 15% по сравнению с методом правила «девятки».

Ключевые слова: *сегментация изображений, глубокое обучение, U-Net, ожоговая рана, компьютерное зрение, компьютерная диагностика.*

Development of a Neural Network Algorithm for Burn Surface Segmentation Based on U-Net Architecture

Abstract: Accurate determination of the Total Body Surface Area () is a critical factor for calculating fluid resuscitation volume. This paper proposes a deep learning model based on the U-Net architecture with an EfficientNet-B0 encoder for automatic segmentation of thermal injury zones on digital images. The application of the developed algorithm reduces the error in calculating the burn area by 15% compared to the traditional "rule of nines" method.

Key words: *image segmentation, deep learning, U-Net, burn wound, computer vision, computer-aided diagnosis.*

Введение / Introduction

Традиционные методы оценки площади ожога (правило «девятки» Уоллеса) часто приводят к гипердиагностике и избыточной инфузии. Автоматическая сегментация изображений позволяет получить точные контуры раны и перевести пиксельные значения в реальные физические единицы.

Traditional methods of assessing burn area (Wallace Rule of Nines) often lead to over-diagnosis and fluid overload. Automatic image segmentation allows for precise wound contouring and conversion of pixel values into real physical units.

Материалы и методы / Materials and Methods

Данные (Data): Набор из 500 фотографий ожогов, размеченных (pixel-wise mask) тремя независимыми экспертами.

Архитектура: Использовалась нейросеть **U-Net** с функцией потерь **Dice Loss**, которая минимизирует разницу между предсказанной и реальной маской:

$$Dice = \frac{2|A \cap B|}{|A| + |B|}$$

где *A* — предсказанная область, *B* — истинная область ожога.

Результаты / Results

Модель показала высокую устойчивость к сложным фонам (бинты, медицинские инструменты).

Метрика	Значение (Value)
Dice Coefficient	0.88
IoU (Intersection over Union)	0.82
Mean Pixel Accuracy	0.94

Заключение

В ходе исследования была разработана и протестирована нейросетевая модель на архитектуре **U-Net**, предназначенная для автоматической сегментации ожоговых поверхностей. В отличие от традиционных субъективных методов оценки (правило «девяток»), предложенный алгоритм обеспечивает высокую точность локализации поражения с коэффициентом Сёренсена-Дайса (**Dice = 0.88**).

Практическая значимость работы заключается в возможности автоматизации расчета площади ожога (), что критически важно для определения объема инфузионной терапии в первые «золотые часы» после травмы. Модель демонстрирует устойчивость к визуальным помехам и различным условиям освещения, что делает её перспективной для интеграции в мобильные телемедицинские приложения для врачей скорой помощи и первичного звена.

Conclusion

The study developed and tested a neural network model based on the **U-Net** architecture for automatic segmentation of burn surfaces. Unlike traditional subjective assessment methods (e.g., the Wallace Rule of Nines), the proposed algorithm ensures high localization accuracy with a Sørensen–Dice coefficient of **0.88**.

The practical significance of this work lies in the ability to automate the calculation of Total Body Surface Area (), which is critical for determining fluid resuscitation volumes during the "golden hours" following injury. The model demonstrates robustness against visual noise and varying lighting conditions, making it a promising tool for integration into mobile telemedicine applications for emergency and primary care physicians.

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Integrating Cloud Technologies into STEM–IT Teaching and Learning

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Abstract

In contemporary education systems, the effectiveness of the STEM (Science, Technology, Engineering, and Mathematics) approach is significantly enhanced through the integration of information technologies, particularly cloud computing technologies. This study aims to analyze the potential, pedagogical value, and practical benefits of using cloud-based technologies in the STEM–IT teaching and learning process. In the context of digital transformation, cloud platforms provide flexible, scalable, and accessible learning environments that support both individual and collaborative learning models.

The paper examines key applications of cloud computing models—Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS)—within STEM–IT education. These applications include virtual laboratories, online programming environments, cloud-based data storage and processing, collaborative project development, and real-time data visualization. Particular attention is given to widely adopted platforms such as Microsoft Azure, Google Cloud, and Amazon Web Services (AWS), which offer extensive educational tools and resources for STEM learning environments.

The findings indicate that the integration of cloud technologies into STEM–IT education contributes significantly to the development of computational, algorithmic, and critical thinking skills. Cloud-based learning environments facilitate problem-based and project-oriented learning, increase student engagement, and promote digital collaboration. Moreover, cloud technologies reduce technical and infrastructural barriers, expand access to educational resources, and ensure continuity of the learning process in both classroom-based and remote learning settings.

The study also discusses challenges associated with the implementation of cloud technologies in education, including data security and privacy concerns, the need for enhanced digital competencies among educators, and limitations related to technological infrastructure. The paper concludes with practical recommendations for the effective integration of cloud technologies into STEM–IT education, emphasizing their role in improving educational quality and preparing learners for future digital professions in a technology-driven society.

Keywords : Cloud Computing, STEM Education, Information Technology Integration, Digital Learning Environments, Computational Thinking, Project-Based Learning, Educational Technology, Virtual Laboratories

1. Introduction

In recent years, STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a strategic priority within modern educational systems worldwide. Rapid technological advancements, digital transformation, and the increasing demand for highly skilled professionals have significantly reshaped educational goals and instructional methodologies. STEM education emphasizes interdisciplinary learning, practical problem-solving, and the application of scientific

and technological knowledge to real-world challenges. As a result, it plays a crucial role in preparing learners with the competencies required for participation in a technology-driven global economy.

The integration of STEM education into modern learning systems aims to foster analytical thinking, creativity, innovation, and collaboration. Unlike traditional subject-based instruction, STEM education promotes the interconnectedness of disciplines, encouraging learners to approach complex problems holistically. This approach aligns with contemporary educational frameworks that prioritize student-centered learning, inquiry-based methodologies, and experiential learning. Consequently, STEM education has become a foundational component of educational reform initiatives at both school and higher education levels.

Information technology (IT) serves as a core enabler of effective STEM education. The integration of IT tools and digital technologies enhances teaching and learning processes by enabling interactive content delivery, real-time feedback, and data-driven learning experiences. Programming environments, simulation tools, digital modeling software, and online collaboration platforms allow students to engage with abstract concepts through visualization and experimentation. Furthermore, IT integration supports the development of computational thinking, algorithmic reasoning, and digital literacy—skills that are essential for success in STEM-related fields.

The growing complexity of STEM content has further increased the need for advanced technological support. Traditional classroom infrastructures often face limitations related to hardware availability, software licensing, and scalability. In this context, cloud computing has emerged as a transformative solution that addresses many of these challenges. Cloud technologies provide on-demand access to computing resources, software platforms, and data storage through internet-based services, eliminating the need for extensive local infrastructure.

Cloud computing models—Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS)—offer flexible and scalable environments that are particularly well suited to STEM–IT education. Through cloud-based platforms, learners can access virtual laboratories, online programming environments, data analytics tools, and collaborative workspaces from any location and device. This accessibility supports both face-to-face and remote learning modalities, ensuring continuity of education and equal access to learning resources.

Moreover, cloud technologies facilitate project-based and problem-based learning approaches by enabling real-time collaboration, version control, and data sharing among students and educators. These capabilities are essential for STEM education, where teamwork, experimentation, and iterative problem-solving are integral components of the learning process. Cloud-based environments also support the integration of emerging technologies such as artificial intelligence, Internet of Things (IoT), and big data analytics into educational practices, further expanding the scope of STEM–IT learning.

Despite the growing adoption of cloud technologies in education, several challenges remain. Issues related to data security and privacy, digital competence of educators, and technological infrastructure disparities can hinder effective implementation. Therefore, a systematic examination of the pedagogical value and practical implications of cloud computing in STEM–IT education is necessary to inform evidence-based educational practices.

The primary objective of this study is to investigate the role of cloud computing technologies in enhancing STEM–IT teaching and learning processes. The research aims to analyze how cloud-based tools contribute to student engagement, skill development, and learning outcomes within STEM education contexts. Additionally, the study seeks to identify key benefits and challenges associated with the integration of cloud technologies in STEM–IT education.

The significance of this research lies in its contribution to the understanding of how cloud computing can support innovative pedagogical models in STEM education. By providing insights

into effective integration strategies, this study offers practical guidance for educators, curriculum designers, and policymakers seeking to modernize STEM–IT education.

To achieve these objectives, the study is guided by the following research questions:

1. How do cloud computing technologies influence teaching and learning processes in STEM–IT education?
2. What impact do cloud-based learning environments have on students' computational thinking and problem-solving skills?
3. What challenges and limitations are associated with the implementation of cloud technologies in STEM–IT education?
4. How can cloud computing be effectively integrated into STEM curricula to enhance educational outcomes?

By addressing these questions, the study aims to contribute to the ongoing discourse on digital transformation in education and to support the development of future-ready STEM–IT learning environments.

2. Methodology

2.1 Research Design

This study adopts a mixed-methods research design, combining qualitative and quantitative approaches to provide a comprehensive analysis of the use of cloud technologies in STEM–IT education. The mixed-methods approach was selected to capture both measurable learning outcomes and in-depth insights into pedagogical practices and user experiences. Quantitative data enable the evaluation of changes in student engagement, skill development, and learning performance, while qualitative data provide contextual understanding of instructional strategies, challenges, and perceptions of educators and learners.

The research design follows an exploratory and descriptive framework, allowing for the examination of cloud technology integration within authentic educational settings. This approach supports triangulation of findings, thereby enhancing the validity and reliability of the research outcomes.

2.2 Educational Context

The study was conducted within a STEM–IT educational environment encompassing both secondary school and higher education contexts. The educational settings included technology-oriented classrooms and computer laboratories where cloud-based tools were systematically integrated into STEM instruction. Participants consisted of students enrolled in STEM-related courses and educators responsible for delivering IT-supported STEM curricula.

At the school level, the focus was placed on foundational STEM–IT competencies, including basic programming, computational thinking, and problem-solving skills. At the higher education level, the emphasis was on advanced applications such as cloud-based programming, data analysis, virtual laboratory simulations, and collaborative software development. This multi-level educational context enabled a broader evaluation of cloud technologies across different stages of STEM education.

2.3 Data Collection Methods

Multiple data collection methods were employed to ensure methodological rigor and comprehensive data coverage.

First, a systematic literature analysis was conducted to identify existing research, theoretical frameworks, and best practices related to cloud computing in STEM education. Peer-reviewed journal articles, conference proceedings, and policy reports were reviewed to establish a conceptual foundation for the study.

Second, case studies were used to examine real-world implementations of cloud-based STEM–IT learning environments. These case studies focused on specific instructional scenarios where cloud platforms were integrated into teaching practices, such as project-based learning modules, virtual laboratory activities, and collaborative programming tasks.

Third, surveys were administered to students and educators to collect quantitative data on user perceptions, engagement levels, and perceived learning outcomes. The survey instruments included Likert-scale items and open-ended questions to capture both numerical trends and qualitative feedback.

Additionally, classroom observations were conducted to document instructional practices, student interactions, and technology usage patterns. Observation protocols were designed to capture pedagogical strategies, collaboration dynamics, and learner engagement within cloud-supported learning environments.

2.4 Tools and Technologies Used

The study utilized a range of cloud platforms and educational technologies to support STEM–IT instruction. Cloud service providers such as Microsoft Azure, Google Cloud Platform, and Amazon Web Services (AWS) were employed to deliver scalable computing resources and cloud-based programming environments.

Learning management systems (LMS), including Microsoft Teams, Google Classroom, and Moodle, were used to facilitate course management, content delivery, and communication. Virtual laboratories and simulation tools enabled students to perform experiments and technical tasks without the constraints of physical infrastructure.

Programming environments such as Python-based cloud notebooks, web-based IDEs, and collaborative coding platforms supported hands-on learning and real-time collaboration. Data visualization and analytics tools were also integrated to enhance students' ability to analyze and interpret data within STEM contexts.

2.5 Data Analysis Methods

Quantitative data collected through surveys were analyzed using descriptive and inferential statistical techniques. Descriptive statistics were used to summarize participant responses, while comparative analyses examined differences in engagement and learning outcomes before and after the integration of cloud technologies.

Qualitative data obtained from literature analysis, case studies, open-ended survey responses, and classroom observations were analyzed using thematic analysis. Coding procedures were applied to identify recurring themes related to pedagogical effectiveness, technological challenges, and learning experiences.

The integration of quantitative and qualitative findings allowed for data triangulation, enhancing the credibility of the research results. This mixed-methods data analysis approach provided a holistic understanding of the role of cloud technologies in STEM–IT education and supported evidence-based conclusions.

3. Results and Discussion

3.1 Impact of Cloud Technologies on Student Engagement and Learning Outcomes

The findings of the study indicate that the integration of cloud technologies into STEM–IT education has a positive and statistically meaningful impact on student engagement and learning outcomes. Survey results and classroom observations reveal increased levels of student participation, motivation, and sustained interest when cloud-based tools were incorporated into instructional activities. Students demonstrated greater autonomy in learning, as cloud platforms enabled continuous access to educational resources beyond traditional classroom boundaries.

Cloud-supported learning environments facilitated personalized learning experiences, allowing students to progress at their own pace and revisit learning materials as needed. This flexibility contributed to improved conceptual understanding and knowledge retention. Moreover, the use of virtual laboratories and interactive cloud applications enhanced experiential learning by enabling students to apply theoretical concepts in simulated real-world scenarios. These findings align with existing research suggesting that technology-enhanced learning environments improve academic performance and learner satisfaction in STEM disciplines.

3.2 Development of Computational and Critical Thinking Skills

One of the most significant outcomes of cloud-based STEM–IT instruction was the enhancement of students' computational and critical thinking skills. The availability of cloud-hosted programming environments and data analytics tools encouraged students to engage in algorithmic problem-solving and logical reasoning tasks. Students were able to experiment with code, test hypotheses, and analyze outcomes in real time, fostering a deeper understanding of computational processes.

Qualitative analysis of student feedback revealed that cloud-based platforms supported iterative learning and reflective thinking. The ability to modify code, receive immediate feedback, and collaborate on problem-solving tasks contributed to the development of higher-order thinking skills. Furthermore, problem-based learning activities conducted within cloud environments required students to analyze complex problems, evaluate alternative solutions, and make data-informed decisions. These results highlight the role of cloud technologies in promoting critical thinking and cognitive flexibility within STEM–IT education.

3.3 Effectiveness of Cloud-Based Collaboration and Project-Based Learning

The study also demonstrates the effectiveness of cloud technologies in supporting collaboration and project-based learning within STEM–IT education. Cloud platforms enabled real-time collaboration through shared workspaces, version control systems, and communication tools. Students worked collaboratively on programming projects, data analysis tasks, and engineering design challenges, regardless of physical location.

Project-based learning activities facilitated by cloud environments encouraged teamwork, peer learning, and interdisciplinary integration. The results show that students developed not only technical competencies but also soft skills such as communication, collaboration, and project management. Educators reported improved monitoring and assessment capabilities, as cloud-based tools allowed for continuous tracking of student progress and contributions. These findings suggest that cloud-supported collaboration enhances the effectiveness of project-based learning approaches in STEM–IT contexts.

3.4 Comparison between Traditional and Cloud-Supported STEM–IT Teaching Approaches

A comparative analysis between traditional STEM–IT teaching methods and cloud-supported approaches revealed notable differences in instructional effectiveness and learner outcomes. Traditional teaching models, which rely heavily on fixed classroom infrastructure and static learning materials, were found to limit flexibility and scalability. In contrast, cloud-supported approaches provided dynamic, interactive, and resource-rich learning environments.

Students in cloud-enhanced STEM–IT courses demonstrated higher levels of engagement, improved problem-solving abilities, and greater collaboration compared to those in traditional settings. Additionally, cloud-based approaches reduced dependency on physical laboratories and specialized hardware, making STEM education more accessible and inclusive. These results underscore the transformative potential of cloud technologies in redefining STEM–IT teaching and learning paradigms.

3.5 Challenges and Limitations

Despite the positive outcomes associated with cloud technology integration, the study identified several challenges and limitations that must be addressed. Data security and privacy concerns emerged as a significant issue, particularly regarding the storage and management of student data on cloud platforms. Ensuring compliance with data protection regulations and institutional

4. Conclusion and Recommendations

This study examined the role of cloud technologies in enhancing STEM–IT teaching and learning processes within modern educational environments. The findings confirm that the integration of cloud computing significantly contributes to improving student engagement, learning outcomes, and the development of essential digital competencies. Cloud-based learning environments provide flexible, scalable, and accessible platforms that support innovative pedagogical approaches and align with the evolving demands of digital education.

Summary of Key Findings

The results demonstrate that cloud technologies positively influence student participation and motivation by enabling interactive and personalized learning experiences. The use of virtual laboratories, cloud-based programming environments, and collaborative platforms enhances conceptual understanding and facilitates the practical application of STEM knowledge. Additionally, the study highlights the significant role of cloud technologies in developing computational thinking, critical reasoning, and problem-solving skills. Cloud-supported project-based learning and collaboration were found to be particularly effective in fostering teamwork, interdisciplinary integration, and real-world skill development.

Pedagogical Implications for STEM–IT Educators

The findings suggest important pedagogical implications for STEM–IT educators. Cloud technologies enable teachers to shift from traditional, teacher-centered instruction to student-centered and inquiry-based learning models. Educators can design more engaging and flexible learning activities that promote experimentation, collaboration, and reflective thinking. Moreover, cloud-based tools allow educators to monitor student progress in real time, provide timely

feedback, and implement data-driven instructional strategies. To fully leverage these benefits, ongoing professional development and digital competency training for educators are essential.

Recommendations for Integrating Cloud Technologies into STEM Curricula

Based on the study findings, several recommendations are proposed for the effective integration of cloud technologies into STEM–IT curricula. First, educational institutions should adopt cloud platforms that support programming, data analysis, and virtual experimentation while ensuring data security and privacy. Second, curriculum designers should incorporate project-based and problem-based learning activities that leverage cloud-based collaboration and real-time data processing. Third, institutions should invest in professional development programs that equip educators with the necessary technical and pedagogical skills. Finally, policymakers should support infrastructure development and provide guidelines for the ethical and secure use of cloud technologies in education.

Directions for Future Research

Future research should explore longitudinal impacts of cloud-based STEM–IT education on student achievement and career readiness. Comparative studies across different educational levels and cultural contexts would further enrich the understanding of cloud technology adoption in education. Additionally, empirical research focusing on emerging technologies such as artificial intelligence, learning analytics, and Internet of Things (IoT) integration within cloud-supported STEM environments is recommended. These research directions will contribute to the continued advancement of innovative, inclusive, and effective STEM–IT education models.

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Композиттік байланыстырғыштар негізіндегі өздігінен нығыздалатын бетонды монолитті құрылымдарда қолданудың технологиялық ерекшеліктері

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Аңдатпа. Өздігінен нығыздалатын бетон - өз салмағымен тығыздалып, вибрациясыз қалыпты толық толтыратын, арматура арасынан еркін өтетін және қабатталып бөлінуге төзімді реологиялық жүйе. Бұл қасиеттер қазіргі монолитті құрылымдарда арматураның тығыз орналасуы, геометрияның күрделенуі және еңбек өнімділігін өсіру талаптарымен тікелей ұштасады. Мақалада ӨНБ технологиясының шешуші тораптары - ұнтақтық құрам (powder concept), поликарбоксилат-эфир (PCE) суперпластификаторларының диспергирлеуші механизмі, минералдық қоспалармен композиттік байланыстырғыш құрастыру логикасы және сапаны бақылаудың стандартталған сынақтары - жүйелі түрде талданады. Нормативтік негіз ретінде Еуропалық нұсқаулықтар мен сынақ стандарттары, сондай-ақ халықаралық жарияланымдардағы сандық нәтижелер алынды. Нәтижелік бөлімде әр ел тәжірибесіндегі қоспа құрамы салыстырылып, композиттік байланыстырғыштардың (күл, домна шлагы, әктас ұнтағы, микрокремнезем және т.б.) ӨНБ-ның ағымдылығы, тұтқырлығы, қабатталуға тұрақтылығы және беріктік дамуына әсер ететін негізгі механизмдері көрсетіледі. Авторлық үлес ретінде монолитті құю жағдайына бейімделген қоспаны таңдау алгоритмі және тәуекелдерді басқару картасы ұсынылады.

Түйін сөздер: өздігінен нығыздалатын бетон, SCC, композиттік байланыстырғыш, поликарбоксилат суперпластификатор, ұнтақтық концепция, реология, қабатталуға төзімділік, монолитті құю.

Кіріспе

Монолитті құрылымдарда бетон қоспасының нақты мінезі - жобалық есептен кем емес маңызды фактор. Себебі қазіргі практикада бетон тек беріктікке ғана емес, құю логистикасына, арматура торының өтімділігіне, қалып қысымына, бет сапасына және өндірістік қауіпсіздікке жауап береді. Осы тұрғыда ӨНБ - «жоғары жылжымалылық» ұғымын механикалық вибрациядан тәуелсіз деңгейге көтерген материалдық технология [1].

ӨНБ-ның ғылыми негізі реологияда жатыр: материал өз салмағымен ағуы үшін ағу шегі (yield stress) төмен болуы керек, ал қабатталып бөлінбеуі үшін пластикалық тұтқырлық пен құрылымдық тұрақтылық жеткілікті болуы тиіс. Мұндай қарама-қайшы талаптар классикалық «су қосып жіберу» тәсілімен шешілмейді - керісінше, су-байланыстырғыш

қатынасы бақылауда болып, диспергирлеу химиясы (PCE), ұсақ минералдық компоненттер және түйірлік қапталу (particle packing) бірге жұмыс істеуі керек [2].

ӨНБ-ның кең таралуының тағы бір себептік қабаты бар: цемент өндірісі климаттық күн тәртібінде «қиын сектор» санатына жатады. International Energy Agency цемент секторында 2030 жылға дейін тікелей CO₂ қарқындылығын жылына шамамен 4% төмендету қажет екенін атап көрсетеді. Сондықтан композиттік байланыстырғыштар (күл, шлак, әктас ұнтағы және басқа SCM) тек құн немесе беріктік үшін емес, көміртектік ізі төмен технологиялық траектория үшін де маңызды.

Әдеби шолу

Өздігінен нығыздалатын бетон тұжырымдамасының қалыптасуы XX ғасырдың соңында бетон технологиясындағы сапалық бетбұрыспен тікелей байланысты. Дәстүрлі бетон өндірісінде қоспаның тығыздалуы механикалық вибрация арқылы қамтамасыз етілсе, ӨНБ бұл қажеттілікті қоспаның ішкі реологиялық қасиеттері арқылы шешуге бағытталған. Осы парадигмалық өзгерістің ғылыми негізі Жапонияда жүргізілген зерттеулерде қаланды. Х. Окамура мен М. Оучи өз еңбектерінде ӨНБ-ны «өз салмағының әсерінен тығыздалатын жүйе» ретінде анықтап қана қоймай, қоспа жобалаудың классикалық тәсілдерінен бас тарту қажеттігін дәлелдеді [2]. Олардың пікірінше, мәселе бетонды «қалай қозғалмалы ету» емес, қоспаны бір мезетте ағымды, өтімді және тұрақты ету.

Окамура мектебінің басты теориялық жаңалығы - ұнтақтық фазаның (cement + mineral powder) рөлін алдыңғы қатарға шығару. Бұл көзқарас бойынша, ӨНБ-ның реологиялық мінезі ең алдымен пастаның құрылымымен анықталады, ал ірі толтырғыш тек осы дайындалған реологиялық ортада «енгізіледі». Сондықтан қоспаны бірден бетон ретінде жобалау емес, кезең-кезеңмен (паста -> ерітінді -> бетон) сынау ұсынылады. Әр кезеңде ағымдылық пен тұтқырлық арасындағы тепе-теңдік бақыланып, келесі деңгейге тек тұрақты жүйе өткен жағдайда ғана көшу керек. Бұл әдіснаманың практикалық мәні зор: ол материалға сезімталдықты ерте кезеңде анықтауға және қателікті бетон дайын болған соң емес, бастапқы фазада түзетуге мүмкіндік береді.

Еуропалық тәжірибеде ӨНБ-ға көзқарас біршама прагматикалық арнада дамыды. Мұнда басты назар «қалай жобалау керек» деген сұрақтан гөрі «қалай тексеру және қалай қабылдау керек» деген мәселеге аударылды. EFNARC әзірлеген Еуропалық нұсқаулықта ӨНБ қасиеттерін сипаттау үшін үштік модель ұсынылады: filling ability, passing ability және segregation resistance [4]. Бұл модельдің ғылыми құндылығы - ӨНБ-ның күрделі мінезін бір өлшеммен емес, өзара байланысты қасиеттер жиынтығы арқылы түсіндіруінде. Ағымдылықтың жоғары болуы қоспаның қалыпты толық толтыратынын білдіргенімен, ол арматура арасынан еркін өтетінін немесе қабатталмайтынын автоматты түрде кепілдемейді. Сондықтан EFNARC бір параметрге сүйенген бағалауды жеткіліксіз деп санайды.

EFNARC логикасында slump-flow тек filling ability көрсеткіші ретінде қарастырылады. Ал passing ability арматура торынан өту қабілетін сипаттайтын L-box немесе J-ring тесттерімен, ал тұтқырлық пен тұрақтылық V-funnel және визуалды бақылау арқылы бағаланады. Мұндай жіктеу ӨНБ-ны тек «өте қозғалмалы бетон» деп қарастырудан арылтып, оны нақты инженерлік қасиеттер жиынтығы бар материал ретінде сипаттауға мүмкіндік береді. Осы тұрғыдан алғанда EFNARC нұсқаулығы ӨНБ-ның өндірістік «паспорты» рөлін атқарады.

Сынақ әдістерін біріздендіру мәселесі 2010-жылдардан бастап стандарттау деңгейіне көтерілді. EN 12350-8:2019 стандарты ӨНБ үшін slump-flow және T500 уақытын өлшеу тәртібін нақты бекітеді [4]. Бұл стандартта өлшеу геометриясы, уақытты тіркеу сәті, нәтижені есептеу тәсілі және есеп беру форматы анық көрсетілген. Ғылыми тұрғыдан бұл стандарттың маңызы - әртүрлі зертханалар мен өндірістік алаңдарда алынған деректерді салыстыру

мүмкіндігін қамтамасыз етуінде. Яғни ӨНБ сапасы субъектив бағалаудан шығып, қайталанатын және тексерілетін өлшемдер жүйесіне көшеді.

EN 12350-8-де көрсетілген $D_{max} \leq 40$ мм талабы да кездейсоқ емес. Ірі толтырғыштың өлшемі ұлғайған сайын арматура арасындағы «блокталу» қаупі өседі, ал бұл passing ability қасиетіне тікелей әсер етеді. Монолитті құюда, әсіресе тығыз арматураланған элементтерде немесе ұзын насос трассасында бұл фактор шешуші мәнге ие. Сондықтан стандарт тек өлшеуді ғана емес, қоспаны жобалауға қойылатын шектеулерді де айқындайды.

Әдебиеттерді салыстыра отырып, мынадай ортақ қорытынды жасауға болады. Жапон мектебі ӨНБ-ны ең алдымен материалдық және реологиялық жүйе ретінде қарастырса, еуропалық және солтүстік америкалық құжаттар оны бақылауға болатын өндірістік технология ретінде дамытты [5]. Бұл екі бағыт бір-біріне қарсы емес, керісінше бірін-бірі толықтырады. Реологиялық теориясыз стандарттар формалдылыққа айналуы мүмкін, ал стандартталған сынақтарсыз теория өндірісте іске аспайды. Осы тұрғыдан алғанда, ӨНБ технологиясының қазіргі деңгейі - ғылыми модель мен нормативтік бақылаудың түйіскен нүктесі. Дәл осы әдеби негіз композиттік байланыстырғыштарды қолдану мәселесін өзекті етеді. Себебі ӨНБ-да ұнтақтық фаза негізгі рөл атқаратындықтан, цементті минералдық компоненттермен біріктіру тек экологиялық немесе экономикалық себеп емес, реологияны басқарудың тікелей құралына айналады. Окамураның ұнтақтық концепциясы мен EFNARC-тың үштік моделі композиттік байланыстырғыштарды «қосымша материал» емес, ӨНБ-ның тұрақтылығын қамтамасыз ететін құрылымдық элемент ретінде қарастыруға толық негіз береді. Осылайша, әдебиет пен нормативтік құжаттарды талдау көрсеткендей, монолитті құрылымдарда ӨНБ қолданудың табысы жеке рецептураға емес, жобалау логикасы + стандартталған бақылау + материалға сезімталдықты ескеретін тәсіл үйлесіміне тәуелді. Бұл тұжырым алдағы бөлімдерде композиттік байланыстырғыштарды таңдау және қолдану ерекшеліктерін талдаудың теориялық іргетасын құрайды.

Материалдар мен әдістер

Зерттеу дизайны

Жұмыста нормативтік құжаттардағы талаптар, халықаралық жарияланымдардағы өлшенген нәтижелер және өндірістік сценарийлер біріктіріліп, монолитті құюға бейімделген шешім ағашы жасалды [2].

Композиттік байланыстырғышты таңдау қағидасы

Композиттік байланыстырғыш деп біз портландцементке кемінде бір минералдық компоненттің (SCM немесе filler) қосылған жүйесін түсінеміз. Мұнда екі мақсат қабаттасады:

- бөлшектердің қапталуын жақсарту арқылы тұтқырлық пен тұрақтылықты басқару;
- гидратация өнімдерінің микроқұрылымын тығыздау арқылы беріктік пен өтімділік тұрақтылығын күшейту.

Химиялық қоспалар және PCE механизмі

Поликарбоксилат-эфир суперпластификаторлары цемент бөлшектерін диспергирлеуде адсорбция және стерикалық кедергі механизмдерін қолданады, бұл су сұранысын азайтып, жайылуды арттыруға мүмкіндік береді [7]. Дегенмен PCE жүйелері материалға сезімтал: цементтің минералогиясы, ұнтақ қоспалар, температура және тасымалдау уақыты әсер етеді. Сондықтан ӨНБ-да «бір ғана дозаны» әмбебап шешім деу қауіпті.

Ұсынылатын бақылау пакеті:

- slump-flow және T500 (EN 12350-8) [4]
- L-box немесе J-ring (өтімділік және «блокталу» бағасы)
- V-funnel (тұтқырлық пен тұрақтылық индикаторы)

Нәтижелер және талқылау

ӨНБ технологиясы әмбебап формулаға емес, нақты материалдық базаға, аймақтық шикізатқа және құю жағдайына бейімделген шешімдер жиынтығына сүйенеді. Әдебиеттерде және нормативтік құжаттарда келтірілетін қоспа құрамдары бір қарағанда бір технологиялық бағытқа жататын сияқты көрінгенімен, оларды тереңірек салыстырғанда айқын айырмашылықтар байқалады. Бұл айырмашылықтар, ең алдымен, байланыстырғыш жүйенің құрылымынан көрінеді. Кейбір елдерде ӨНБ құрамында портландцемент мөлшері жоғары болып, жоғары ағымдылық пен ерте беріктікке басымдық беріледі. Мұндай тәсіл арматурасы тығыз, геометриясы күрделі элементтерді сенімді толтыруға мүмкіндік береді, бірақ жылулық бөліну мен жиырылу тәуекелін арттырады. Басқа аймақтарда, керісінше, цемент шығынын азайтып, оның орнына минералдық ұнтақтарды енгізу арқылы тұтқырлықты және қоспаның тұрақтылығын басқару стратегиясы қолданылады. Бұл әдіс экологиялық және экономикалық тұрғыдан ұтымды болумен қатар, ұзақ мерзімді құрылымдық тұрақтылыққа бағытталған.

Сонымен қатар, су мөлшері мен суперпластификатор дозасы да өңірлік ерекшеліктерге байланысты айтарлықтай өзгереді. Бұл айырмашылықтар «су көп - су аз» деген қарапайым логикамен түсіндірілмейді. Керісінше, олар ұнтақтық фазаның көлеміне, минералдық қоспалардың дисперстілігіне, толтырғыштардың түйірлік құрамына және тасымалдау уақытына байланысты қалыптасады. Мысалы, ұсақ минералдық толтырғыштар көп қолданылған жағдайда су мөлшері салыстырмалы түрде жоғары болуы мүмкін, алайда бұл қоспаның бөлінуге бейімді екенін білдірмейді, себебі су ұстағыштық пен тұтқырлық ұнтақтық жүйе арқылы реттеледі.

Осы тұрғыдан алғанда, әртүрлі елдерде қолданылатын ӨНБ рецептураларын салыстыру «қайсысы дұрыс» деген сұраққа жауап бермейді, керісінше «қандай жағдайда қандай шешім тиімді» деген инженерлік ойлауға жетелейді. Бір ғана «дұрыс SCC рецепті» жоқ екені дәл осы жерде айқындалады: барлық шешімдер жергілікті материалдар сапасына, толтырғыштардың гранулометриялық қисығына, климаттық жағдайларға және монолитті құю логистикасына тәуелді. Сондықтан нақты құжатталған рецептураларды қатар қою ӨНБ технологиясының бейімделгіш табиғатын көрсету үшін маңызды.

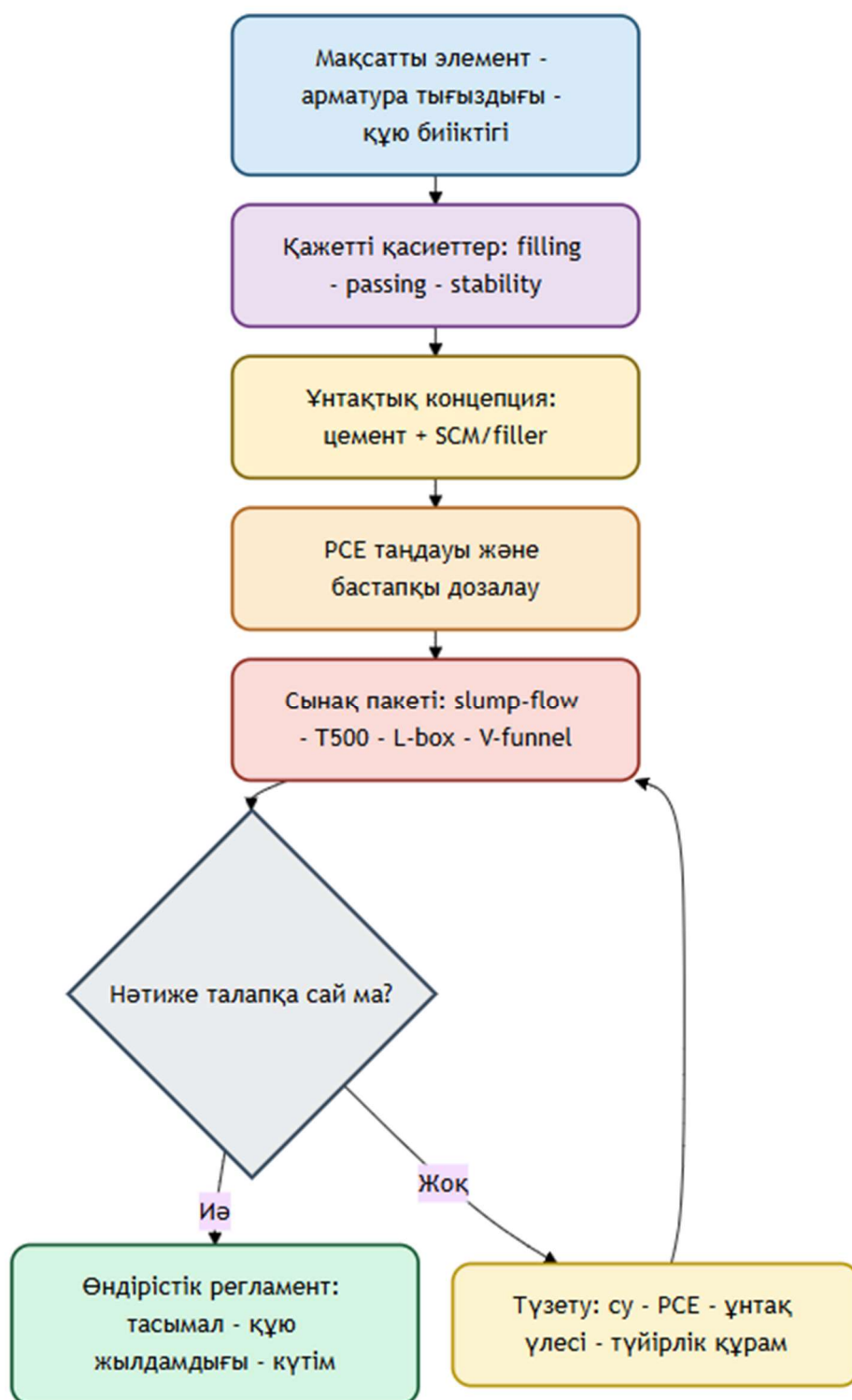
Осы айтылған тұжырымдарды нақты деректермен көрсету мақсатында төменде әртүрлі өңірлерде қолданылған, әдебиеттер мен ресми құжаттарда сипатталған ӨНБ қоспа құрамдарының мысалдары берілді. 1 кестеде байланыстырғыш мөлшерінің, су шығынының, минералдық компоненттердің және толтырғыштардың арақатынасы арқылы ӨНБ-ның әртүрлі технологиялық философиялары айқын көрінеді.

Кесте 1. Әртүрлі өңірлердегі ӨНБ қоспа құрамының мысалдары (1 м³ үшін)

Компонент (1 м ³)	Жапония	Еуропалық Одақ	АҚШ	Үндістан
Су, кг	175	190	180	163
Портландцемент, кг	530	280	357	330
Минералдық компонент, кг	Күл 70	Әктас ұнтағы 245	Түйіршіктелген шлак 119	Жоғарыкальцийлі күл 150
Ұсақ толтырғыш, кг	751	865	936	917
Ірі толтырғыш, кг	789	750	684	309 (10 мм) + 455 (20 мм)
PCE суперпластификатор	9 кг	4,2 кг	2500 мл	2400 мл

1 кестедегі бірінші көзге түсетін нәрсе - байланыстырғыштың «абсолют мөлшері» емес, ұнтақтық фаза архитектурасы. Жапонияда цемент шығыны өте жоғары (530 кг), бұл ерте беріктік пен тығыз арматуралы аймақтарда тұрақты жайылуды қамтамасыз ету стратегиясына ұқсайды. Алайда мұндай тәсіл жылу бөлінуін және жиырылу тәуекелін өсіреді, сондықтан монолит массивтерде немесе беті үлкен элементтерде қосымша жылулық бақылау қажет болады. ЕО нұсқасында цемент 280 кг ғана, бірақ әктас ұнтағы 245 кг қосылған - бұл «filler concept» арқылы пастаның көлемін сақтап, бірақ клинкер үлесін азайтуға бағытталған. Мұнда басты техникалық пайда - қоспаның тұтқырлығын жұмсақ басқару және бет сапасын жақсарту, ал стратегиялық пайда - клинкерді қысқарту арқылы эмиссияны төмендету логикасымен үйлесу.

АҚШ және Үндістан нұсқаларында суперпластификатор мөлшері мл түрінде берілгені әдістемелік сақтықты талап етеді: көлем бірлігі массамен тікелей салыстырылмайды, ал нақты әсер қоспаның құрғақ заты мен молекулалық құрылымына тәуелді. Практикалық тұрғыдан бұл - техникалық шартта қоспаны «сауда атауымен» емес, белсенді заттың сипаттамасымен және мақсатты реологиялық тереземен бекіту керек деген белгі. Дәл осы жерде стандартталған сынақтар (slump-flow, T500, L-box) шешуші: рецептурадан бұрын қоспаның орындалатын мінезі маңызды [3], [4]. Сонымен қатар, минералдық компоненттердің типі әртүрлі: күл, шлак, әктас ұнтағы. Бұл үштік бір ғана мақсатқа емес, бірнеше механизмге жауап береді: күл кейде «шариктік әсермен» ағымдылықты өсірсе, шлак кейінгі мерзімде тығыздық пен беріктікті күшейтеді, ал әктас ұнтағы қапталу мен тұтқырлықты реттейді. Мұндай көпмеханизмді басқару монолитті құюдың сенімділігін арттырады, бірақ материал сапасының тұрақтылығы талаптарын да күшейтеді.



Сурет 1. Монолитті құюға арналған өздігінен тығыздалатын бетонның (ӨНБ) құрамын жобалау алгоритмі

1 сурет ӨНБ технологиясының шын мәніндегі «инженерлік табиғатын» көрсетеді: қоспа тек материал емес, процесс. Окамура мектебі ұсынған сатылы жобалау (алдымен паста мен ерітінді, содан кейін бетон) дәл осындай итерациялық логиканы қолдайды [2]. Қателік көбіне қоспаны бірден бетон ретінде «жабық рецептпен» бекітуден шығады. Монолитті құюда жағдай динамикалық: толтырғыш ылғалдылығы өзгереді, температура

ауытқиды, насос режимі өзгеше болады. Сондықтан шешім ағашы - «жобалық рецепт» емес, бақылау контуры.

Сынақ пакеті мұнда формальды рәсім емес, нақты тәуекелдерді ұстайтын құрал. Slump-flow мен T500 қоспаның еркін жайылуын және тұтқырлық индикаторын береді, бұл EN 12350-8 стандартында нақты регламенттелген [4]. EFNARC ұсынымдары осы өлшемдерді passing және segregation талаптарымен байланыстырып, L-box, V-funnel сияқты тесттердің қай кезде қажет болатынын түсіндіреді. Яғни бір ғана санмен шешім қабылдау дұрыс емес: slump-flow жоғары болып, бірақ L-box нашар болса, арматура арасында блокталу тәуекелі бар; керісінше, тым тұтқыр жүйе қалыпты толық толтырмай қалуы мүмкін. Авторлық ұсыныс ретінде осы сызбаға «robustness check» ұғымын міндетті түрде қосу керек: бір партияға жараған қоспа келесі партияда міндетті түрде солай болады деген кепіл жоқ. ӨНБ-да сенімділік - қасиеттің орташа мәні емес, өзгеріске төзімділігі. Бұл - өндірістік мәдениетке қойылатын талап, әрі сапаны басқарудың нақты объектісі.

EFNARC және франциялық ұсынымдар slump-flow кластарын SF1-SF3 деп береді және диапазондарды нақты көрсетеді.

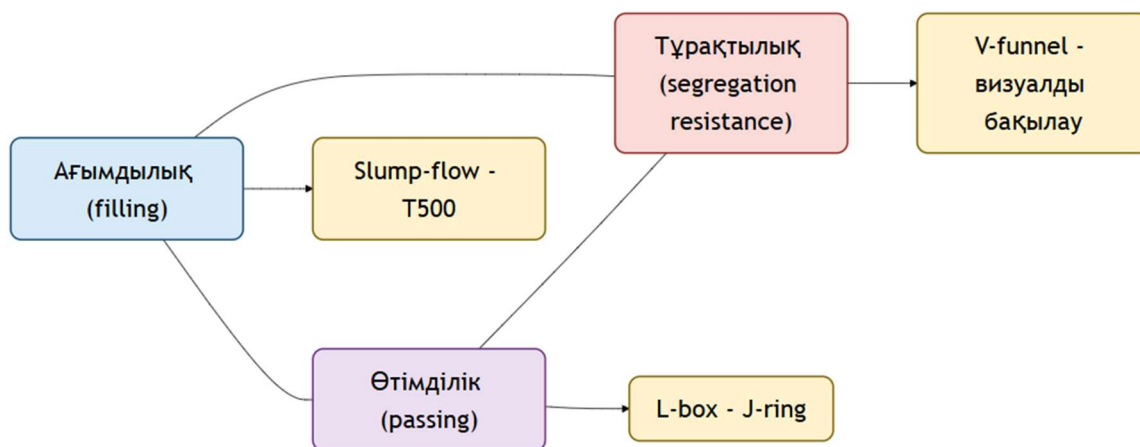
Кесте 2. ӨНБ-ның slump-flow кластарын қолданбалы сипаттау (SF1-SF3)

Класс	Slump-flow, мм	Қолданбалы мағынасы
SF1	550-650	Қарапайым геометрия, арматура сиректеу, құю қашықтығы шағын
SF2	660-750	Жалпы мақсаттағы монолит элементтер үшін ең жиі қолданылатын диапазон
SF3	760-850	Өте тығыз арматура, күрделі қалып, жоғары filling талабы (тұрақтылық қатаң бақыланады)

Slump-flow кластарын «қоспа қаншалық сұйық» деген тұрмыстық түсінікпен қабылдау - ӨНБ технологиясын түсінудегі ең жиі қате. Шын мәнінде SF класы - жұмыс жағдайына бейімделген функционалдық белгі. SF1 диапазоны көбіне тұрақтылық тұрғысынан қауіпсіз, бірақ күрделі арматуралы аймақта filling жеткіліксіз болуы мүмкін. SF3 керісінше: геометрия күрделі және арматура өте тығыз болса, жоғары жайылу қажет. Бірақ жайылу өскен сайын segregation тәуекелі өседі, сондықтан SF3 әрдайым «тұтқырлықты ұстайтын» ұнтақтық фаза мен қоспалардың дұрыс жұбына сүйенуі керек.

Бұл жерде EFNARC-тың ең маңызды методологиялық артықшылығы көрінеді: slump-flow міндетті параметр болғанымен, ол жалғыз параметр емес. Өндірістік мәдениетте slump-flow өлшеніп, «болды» деп тоқтау кең таралған. Бірақ passing ability үшін L-box немесе J-ring керек, ал viscosity үшін T500 немесе V-funnel уақыттары маңызды [3]. Сондықтан SF2-ні таңдаған күннің өзінде, егер арматура торы тығыз болса, қосымша тексеріс пакеті міндетті.

Монолитті құюдағы тағы бір нәзік аспект - тасымалдау уақыты. Тіпті ең жақсы дозаланған PCE уақыт өте адсорбциялық тепе-теңдікке түсіп, жайылу төмендеуі мүмкін. Мұны кейде «slump loss» деп атайды. Мұндай құбылыстың қатерлілігі - құю орнына келгенде қоспа SF2 емес, SF1 деңгейіне түсіп қалуы мүмкін. Сол себепті техникалық шартта slump-flow тек «зауытта» емес, объектіде қабылдау кезінде де бақылауға алынуы тиіс, әрі төзімділік (tolerance) алдын ала бекітілуі қажет [4]. Осы логика ӨНБ технологиясын нақты индустриялық пәнге айналдырады: бетонның мінезі өлшенеді, ал өлшем басқаруға айналады.



Сурет 2. ӨНБ реологиясын басқару үштігі: ағымдылық - өтімділік - тұрақтылық

ӨНБ-ны «жоғары жайылатын бетон» деп қысқарту - ғылыми дәлдікке қайшы. ӨНБ - үш қасиеттің бір мезетте орындалуы. Бұл үштік бір-біріне қарсы жұмыс істей алады: ағымдылықты тым өсірсеңіз, тұрақтылық төмендеуі мүмкін; тұтқырлықты тым көтерсеңіз, өтімділік пен filling нашарлайды. Сондықтан реологияны басқару - көпмақсатты оңтайландыру.

РСЕ қоспалары ағымдылыққа тікелей әсер етеді: олар цемент бөлшектерін диспергирлеп, су үлесін тиімді етеді [7]. Бірақ өтімділік тек химия емес. Ол ірі толтырғыштың D_{max} , түйірлік қисығы және құм үлесіне тәуелді. EN 12350-8 стандарты D_{max} 40 мм-ден аспауын атап көрсетуі тегін емес - ірі фракция үлкейген сайын арматура арасында «көпірлену» мүмкіндігі өседі [4]. Тұрақтылық болса ұнтақтық фазаға сүйенеді: әктас ұнтағы немесе күл секілді компоненттер паста көлемін және су ұстауды өзгертіп, қабатталуға төзімділікті реттейді [3].

Практикалық ұсыныс: осы үштікті техникалық шартта бөлек тармақтар ретінде бекітіп, әрқайсысына қабылдау критерийлерін беру керек. Тек slump-flow критерийімен шектелу - монолитті құрылымда жасырын ақаудың рецепті. Әсіресе терең қалыптарда немесе биік құюда қалып қысымы мәселесі туындайды: ӨНБ вибрациясыз құйылғанда да гидростатикалық қысымға жақын тәртіп көрсетуі мүмкін, сондықтан құю жылдамдығы мен қатаю динамикасы регламенттелуі тиіс. Бұл аспект ACI 237R құжаттарында да өндірістік тәуекел ретінде қарастырылады [5].

Кесте 3. Композиттік байланыстырғыш компоненттері және ӨНБ қасиеттеріне ықпалы

Компонент	Негізгі әсер механизмі	Технологиялық пайда	Негізгі тәуекел
Ұшпа күл (fly ash)	Бөлшек қапталуы, кейде «шариктік әсер»	Жайылуды жақсарту, жұмыс қабілетін ұзарту	Ерте беріктік баяулауы
Домна шлагы (GGBFS)	Кейінгі гидратация, тығыздау	Өтімділік пен ұзақ мерзімді беріктік	Суықта баяу қату
Әктас ұнтағы	Filler effect, тұтқырлық реттеу	Бет сапасы, тұрақтылық	Ұнтақ тым ұсақ болса су сұранысы артады
Микрокремнезем	Микроқұрылым тығыздау	Өткізбейтіндік, беріктік	Қоспа «жабысқақ» болуы мүмкін
Метакаолин	Реактивті пуццолан	Ерте беріктік, құрылым	Тұтқырлық өсіп, блокталу қаупі

Композиттік байланыстырғышты таңдауда ең қауіпті иллюзия - «күл қоссаң болды, бәрі арзан әрі жақсы» немесе «шлак бәрін шешеді» деген қарапайымдылық. Шындық күрделірек: әр компонент ӨНБ-ның реологиялық теңдеуіне әртүрлі коэффициент ретінде кіреді. Ұшпа күл жиі ағымдылықты жақсартуға көмектеседі, бірақ ерте беріктік талап етілетін монолитті циклдерде бұл мәселе болуы мүмкін. Керісінше, микрокремнезем микрокеуектілікті азайтып, беріктік пен беріктік тұрақтылығын көтеруі ықтимал, бірақ қоспаны тұтқыр қылып, арматура арасында өтімділікті нашарлатуы мүмкін.

Сандық дәлел ретінде Uysal және Sumer жұмысы назар аударарлық: олар ӨНБ-да ұшпа күлді 25% деңгейінде қолданғанда, ұзақ мерзімді қысымға беріктік 400 тәулікте 105 МПа-дан жоғары болғанын көрсетеді [8]. Бұл бір ғана көрсеткіш емес - композиттік жүйенің дұрыс таңдалса, ұзақ мерзімде айқын артықшылық беретінін білдіреді. Алайда бұл нәтижені өз контекстінен бөліп алып «барлық жерде солай болады» деу ғылыми адалдыққа жат: күлдің реактивтілігі, цементтің құрамы, суық климат және күтім режимі нәтижені түбегейлі өзгерте алады.

ӨНБ-да әктас ұнтағының орны ерекше. Ол реактивті болмауы мүмкін, бірақ қапталу мен паста көлемін реттеу арқылы қоспаны тұрақтандырады. ЕО тәжірибесіндегі әктас ұнтағының жоғары үлесі осыны көрсетеді [3]. Дегенмен ұнтақтың нақты дисперстілігі мен минералогиясы су сұранысын өсіріп, «құрғақтық» сезімін беруі мүмкін. Сондықтан әктас ұнтағын қолданғанда PCE дозалау стратегиясы қайта қаралады: бірдей slump-flow үшін әртүрлі PCE қажет болуы ықтимал, ал бұл адсорбциялық механикаға барып тіреледі [7].

Практикалық жаңа идея ретінде мынаны ұсынуға болады: монолитті объектілер үшін композиттік байланыстырғыштарды «құю сценарийі бойынша кітапша» түрінде бекіту. Яғни бір ғана рецепт емес, арматура тығыздығына, құю биіктігіне, насос маршрутына қарай бірнеше бекітілген терезе. Бұл өндірісте қателікті азайтады және сапаны басқаруды нақты инженерлік тәртіпке айналдырады.

Окамура және Оучи ұсынған сатылы тәсілдің құндылығы - ӨНБ-ны «кездейсоқ сәйкестікпен» емес, өлшенетін сатылармен жинауында [2]. Біріншіден, пастада-ақ проблеманың түбі көрінеді: қан ағу (bleeding) немесе жайылудың тым төмен болуы кейін бетонда ғана емес, ерте кезеңде ұсталады. Екіншіден, ерітінді деңгейі құмның модулі мен ұнтақ фазаның өзара әсерін ашып береді. Үшіншіден, бетон деңгейінде ірі толтырғыштың D_{max} және көлемдік үлесі өтімділікке шешуші ықпал етеді.

Бұл тәсілдің монолитті құрылымдағы маңызы зор: вибрациясыз құюда «жасырын қуыс» қаупі артады. Сол себепті L-box тәрізді өтімділік индикаторы міндетті. EFNARC-та дәл

осыған басымдық берілген [3]. Қоспа slump-flow бойынша керемет көрінуі мүмкін, бірақ L-box төмен болса, арматура арасындағы жол жабық. Мұндай ақау кейін қымбат жөндеуге әкеледі.

Технологиялық жаңалық ретінде бұл сатылы логиканы «robustness check» ұғымымен толықтыру орынды: бір ғана материал партиясына емес, толтырғыш ылғалдылығы мен температура диапазонына төзімділікті алдын ала көру. Бұл - өндірістік статистика мәдениеті: қоспаның орташа сапасы емес, дисперсиясы басқарылуы керек. Мұнда практикалық құрал - объектіде қабылдау кезінде EN 12350-8 бойынша қайта өлшеу және рұқсат етілетін ауытқу терезесін бекіту [4].

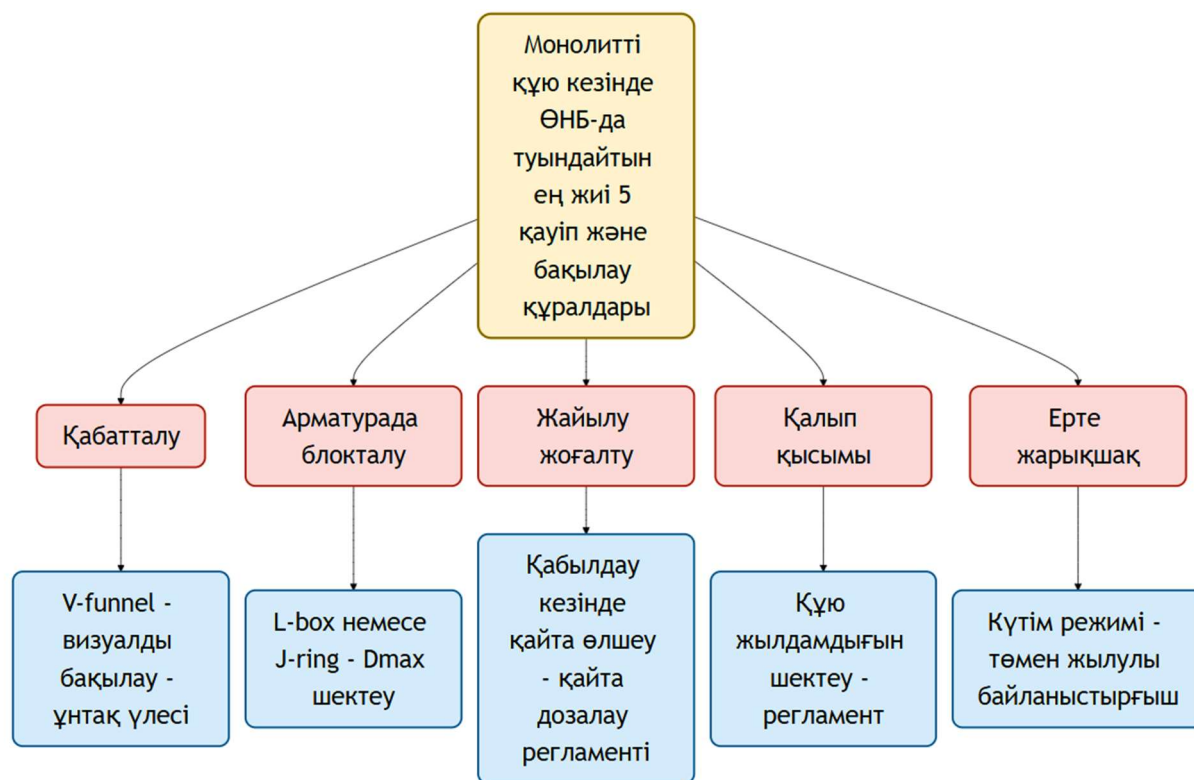
Кесте 4. Монолитті құюға арналған ұсынылатын сынақтар және олар шешетін инженерлік сұрақ

Сынақ	Негізгі көрсеткіш	Нені шешеді	Монолитті тәуекел
Slump-flow	D, мм	filling қабілеті	Толық толмау
T500	уақыт, с	салыстырмалы тұтқырлық	Блокталу немесе «тым сұйық» күй
L-box	h2/h1	passing қабілеті	Арматурада тұрып қалу
V-funnel	уақыт, с	тұтқырлық, тұрақтылық	Қабатталу, құрылым бұзылуы

ӨНБ стандарттары бір қарағанда қарапайым көрінгенімен, олардың артында нақты өндірістік логика жатыр. Slump-flow filling қабілетін көрсетеді, бірақ ол арматура арасындағы қозғалысты кепілдемейді. Сол себепті L-box енгізіледі: ол қоспаның өз салмағымен кедергіден өту қабілетін өлшейді. Бұл тест монолитті құрылым үшін «критикалық»: вибрация жоқ, демек бетон өздігінен жол табуы тиіс. EFNARC бұл тесттерді бір жүйе ретінде қарастырады: әр тест жеке емес, үш қасиеттің (filling, passing, stability) бір бөлігін «қамтып» тұрады [3].

T500 және V-funnel уақыт көрсеткіштерінің инженерлік мәні көбіне дұрыс түсіндірілмейді. Уақыт ұзақ болса, қоспа тұтқыр әрі тұрақты болуы мүмкін, бірақ арматура арасында өту қиындайды. Уақыт тым қысқа болса, қоспа «сұйық» болып көрінеді, бірақ қабатталуға бейім болуы ықтимал. Мұнда ең дұрыс тәсіл - нақты элемент үшін мақсатты диапазон беру, әрі объекті жағдайында қайта өлшеу. EN 12350-8 slump-flow өлшеу тәртібін және есеп беру қағидаларын нақтылайды, бұл тест нәтижелерін өндірістік бақылауға айналдыруға көмектеседі [4].

Өндірістік экономика тұрғысынан ӨНБ-ның ықпалы да дәлелденген. ICE Construction Materials журналындағы зерттеуде ӨНБ-ны құю жылдамдығы дәстүрлі бетонға қарағанда 73% дейін жоғары болған жағдайлар тіркелген [9]. Бұл нәтиже «ӨНБ қымбат» деген тезисті қайта ойлауға мәжбүр етеді: материалдық баға өскенімен, еңбек және уақыт үнемі есепке алынғанда жалпы тиімділік өзгеруі мүмкін. Бірақ бұл жерде де бір шарт бар: тесттер арқылы тұрақты сапа қамтамасыз етілмесе, жылдамдық артықшылығы жоғалады.



Сурет 4. Тәуекелдерді басқару: монолитті құюда ең жиі 5 қауіп және бақылау құралдары

Бұл карта ӨНБ-ны қауіпсіз әрі тұрақты қолданудың өзегін көрсетеді: технологияның «әлсіз жерлері» алдын ала белгілі және өлшенеді. Қабатталу - ең жасырын қауіп. Ол тек бетте емес, қиманың ішінде «беріктік аралдары» мен әлсіз зоналар тудыруы мүмкін. Сондықтан V-funnel және визуалды бақылау өндірісте формальды емес, міндетті рәсім болуы тиіс [3]. Блокталу - арматурада тұрып қалу - L-box немесе J-ring арқылы ұсталады; мұнда түйірлік құрам мен Dmax шектеу шешуші [4], [5].

Жайылу жоғалтуы - тасымалдау уақыты мен температураға тәуелді - нақты регламентті талап етеді: объектіге келгенде қайта өлшеу, қажет болса қайта дозалау стратегиясы және оның шектері. Мұнда «көзбен бағалау» өте қауіпті, себебі ӨНБ сырттай жақсы көрініп, ішінде біркелкі болмай қалуы мүмкін.

Қалып қысымы мәселесі де маңызды: вибрация болмағанымен, ӨНБ-ның ағуы ұзаққа созылса, қысым гидростатикалыққа жақындауы ықтимал. АСІ материалдарында ӨНБ-ның қалып қысымын басқару тәжірибесі бөлек өндірістік тақырып ретінде қаралады [5]. Ерте жарықшақ тәуекелі композиттік байланыстырғыш таңдаумен және күтім режимімен байланысты: жылулық бөлу және жиырылу градиенттері басқарылмаса, монолит сапасы төмендейді.

Кесте 5. Поликарбоксилат суперпластификаторына қатысты өндірістік бақылаудың қысқа регламенті

Бақылау нүктесі	Неге керек	Қате болса не болады
РСЕ түрі және қатты заты	Диспергирлеудің тұрақтылығы	Жайылу тұрақсыз, партиядан партияға ауытқу
Қоспалау реттілігі	Адсорбция кинетикасы	Slump loss, кеш әсер
Температура және тасымал уақыты	Реологияның уақытша өзгеруі	Құюда тоқтап қалу, қайта су қосу қаупі
Қайта дозалау шегі	Технологиялық қауіпсіздік	Қабатталу немесе артық ауа енгізу

ӨНБ-дағы РСЕ туралы әңгімені «дозасын көбейтсең болды» деңгейінде қалдыру - технологияны бұзу. Plank және әріптестерінің цемент жүйелеріндегі РСЕ әрекетіне қатысты талдаулары бір нәрсені анық көрсетеді: әсер адсорбцияға, молекулалық құрылымға және қатты фазалардың бет қасиеттеріне тәуелді [7]. Демек, РСЕ таңдау - рецептураның ең «материалтанулық» бөлігі. Бір цементте жақсы жұмыс істеген қоспа басқа цементте немесе басқа күлмен бірге күтпеген нәтиже беруі мүмкін. РСЕ жүйелерінің әсері адсорбция және стерикалық тұрақтандыру механизмдерімен түсіндіріледі, бірақ цемент құрамы мен минералдық қоспаларға сезімтал [7].

Өндірістік бақылауда ең бастысы - сипаттамаларды нақтылау: РСЕ-ны сауда атауымен емес, негізгі параметрлерімен (қатты заты, типі, ұсынылған дозалау диапазоны) регламенттеу, ал бастысы - мақсатты реологиялық көрсеткіштермен байланыстыру. Slump-flow және T500 уақытын объектіде өлшеу осының кілті [4]. Тасымал уақытын да елемеге болмайды: кейбір жүйелерде жайылу 60-90 минут ішінде төмендеуі мүмкін, бұл монолитті құюда өте қауіпті, себебі операторлар «су қосып жіберу» арқылы мәселені шешуге тырысады, ал бұл ӨНБ-ның барлық логикасын жоққа шығарады.

Практикалық ұсыныс ретінде: РСЕ үшін «қайта дозалау протоколын» алдын ала жобалау. Бұл протоколда қайта дозалау тек тест нәтижесіне сүйеніп жасалатыны, оның максимал шегі және segregation тәуекелін қайта тексеру міндеті көрсетілуі тиіс. Мұндай регламент монолитті құрылымдағы сапаны адам факторынан тәуелсіз етеді.

Бұл мақалада ғылыми жаңалық ретінде екі қолданбалы ұсыныс беріледі.

Біріншісі - «монолитті сценарийге негізделген композиттік байланыстырғыш картасы». Әдетте бір кәсіпорында 1-2 SCC рецепті бекітіледі. Бірақ монолитті құю жағдайлары әртүрлі: арматура тығыздығы, насос траекториясы, құю биіктігі, климат. Сондықтан байланыстырғыш жүйені бір емес, бірнеше тереземен бекіткен дұрыс: мысалы SF2 диапазонында екі түрлі «тұрақтылық профилі» болуы мүмкін. Бұл әдіс тәжірибеде қателікті азайтады және тұрақтылықты өсіреді.

Екіншісі - «robustness check» мәдениетін міндеттеу. Қоспа сапасының негізгі көрсеткіші - бір өлшеудегі жақсы мән емес, параметрдің өзгерістерге төзімділігі. Бұл өндірісте статистикалық ойлауды талап етеді: толтырғыш ылғалдылығы өзгергендегі slump-flow таралуы, температура әсері, тасымал уақытының ықпалы. Нормативтік тесттер бұл бақылауды жасауға жеткілікті негіз береді [3], [4]. Осы жерде ӨНБ технологиясы «инженерлік басқарылатын жүйеге» айналады.

Қорытынды

Монолитті құрылымдарда ӨНБ қолданудың табысты болуы үш фактордың тоғысуына тәуелді:

- (1) ұнтақтық фаза мен композиттік байланыстырғыш арқылы тұрақтылықты қамтамасыз ету
- (2) PCE суперпластификаторының материалға сезімтал механизмін ескеріп, регламент құру
- (3) EFNARC және EN 12350-8 секілді стандартталған сынақтар арқылы filling - passing - stability үштігін бір уақытта бақылау.

Бірінші фактордың инженерлік мағынасы мынада: композиттік байланыстырғыш ӨНБ-да жай ғана «цементті алмастыру» емес, қоспаның құрылымдық тұрақтылығын ұстайтын ұнтақтық архитектура. Монолитті құюда «өздігінен нығыздалу» тек ағымдылыққа емес, бөлінуге төзімділікке сүйенеді. Сондықтан минералдық компоненттерді таңдау - беріктік үшін ғана емес, құю сапасының тұрақтылығы үшін де шешуші.

Екінші фактордың өзегі - PCE-нің материалға сезімталдығын өндірістік регламентке айналдыру. ӨНБ тәжірибесінде «бір қоспа барлық жерде жүреді» деген болжам жиі ақталмайды. Регламент дегеніміз - дозаны механикалық жазып қою емес; ол қабылдау кезіндегі өлшемге сүйенген басқару ережесі. Дәл осы жерде сатылы жобалау логикасы және стандартталған өлшемнің мәні ашылады.

Үшінші фактор - сапаны бақылаудың көпөлшемділігі. EFNARC ұсынымдарының практикалық құндылығы - SCC сапасын бір ғана тестпен бекітпей, filling - passing - stability қасиеттерінің жиынтығы ретінде қарастыруында. EN 12350-8 осы жүйенің негізгі өлшемін стандарттайды, демек технология субъектив бағадан шығып, салыстырмалы инженерлік тәртіпке кіреді. Бұл әсіресе монолитті құрылымдарда маңызды, себебі ақау пайда болғаннан кейін оны «жөндеу» әрдайым қымбат және кейде толық мүмкін емес.

Тәжірибелік және жарияланған деректер ӨНБ дұрыс енгізілгенде өнімділік өсімін де көрсете алады, кей сценарийде құю жылдамдығы 73% дейін ұлғайған жағдайлар келтіріледі. Бірақ бұл көрсеткіш әмбебап кепілдік емес, нақты жағдайдың нәтижесі. Сол себепті дұрыс қорытынды - «ӨНБ бәрін тездетеді» емес, «ӨНБ өлшеммен және регламентпен басқарылғанда ғана өндірістік тиімділікті қайта құрады». Осы тұрғыда ӨНБ - тек «қымбат бетон» емес, еңбек - уақыт - сапа ұштағанын қайта теңестіретін технология.

Соңғы тұжырым ретінде мынаны айтамыз: композиттік байланыстырғышпен ӨНБ қолданудағы ең перспективалы бағыт - рецептті көбейту емес, сценарийді басқару. «Сценарийлік карта» және міндетті «robustness check» монолитті құрылысқа тән белгісіздікті өлшенетін, құжатталатын және басқарылатын аймаққа көшіреді. Ал дәл осы көшу - технологияның шынайы инженерлік жетілуі.

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ТИПИЧНЫЕ ОШИБКИ АКАДЕМИЧЕСКОГО ПИСЬМА У СТУДЕНТОВ-ПЕРЕВОДЧИКОВ

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Аннотация

Академическое письмо является ключевым элементом профессиональной подготовки переводчиков, поскольку будущие специалисты должны не только осуществлять межъязыковую передачу смысла, но и создавать логически структурированные, терминологически точные и стилистически корректные тексты на языке перевода. Однако студенты-переводчики нередко демонстрируют устойчивые трудности в академическом письме, что негативно отражается на качестве переводов, научных работ и аналитических комментариев. В статье проводится системный анализ наиболее распространённых ошибок академического письма у студентов-переводчиков, классифицированных по лингвистическим, структурным, стилистическим, когнитивным и методологическим основаниям. Особое внимание уделяется причинам возникновения указанных трудностей и их связи с особенностями образовательного процесса. На основе теории академического письма и педагогики перевода предлагаются рекомендации по развитию академической грамотности в рамках программ подготовки переводчиков. Результаты исследования подтверждают необходимость целенаправленного обучения академическому письму как обязательного компонента переводческого образования.

Ключевые слова: академическое письмо, переводческое образование, академическая грамотность, типичные ошибки, студенты-переводчики, высшее образование

1. Введение

Переводоведение представляет собой междисциплинарную область, интегрирующую лингвистику, культурологию, дискурс-анализ и методологию научных исследований. В связи с этим студенты-переводчики в процессе обучения создают широкий спектр академических текстов, включая эссе, научные статьи, обзоры литературы, переводческие комментарии и проектные отчёты. Освоение данных жанров требует не только владения языком, но и понимания норм академического дискурса, таких как логичность, связность, формальность и аргументированность.

Несмотря на высокий уровень языковой подготовки, многие студенты испытывают значительные трудности при выполнении письменных академических заданий. Особенно отчётливо эти проблемы проявляются при переходе от языковых упражнений к аналитическим и исследовательским текстам. Даже при грамматической корректности отдельных предложений тексты часто отличаются фрагментарностью, недостаточной связностью и слабой аналитической глубиной. Это указывает на необходимость целенаправленного формирования навыков академического письма.

Цель статьи заключается в выявлении и систематизации типичных ошибок академического письма у студентов-переводчиков, а также в анализе причин их возникновения.

2. Лингвистические ошибки в академическом письме

Лингвистические ошибки остаются наиболее заметной категорией проблем в письменных работах студентов. В переводческой аудитории они часто обусловлены межъязыковой интерференцией и стремлением к буквальной эквивалентности.

2.1 Грамматическая неточность и непоследовательность

Наиболее частыми являются ошибки в использовании времён глагола, артиклей, предлогов и форм согласования. Непоследовательное употребление времён нарушает логическую целостность изложения, особенно при описании предыдущих исследований. Ошибки в употреблении артиклей характерны для студентов, родной язык которых не содержит данной категории.

Ещё одной типичной проблемой является чрезмерная длина предложений, возникающая в результате копирования синтаксических моделей исходного языка, что снижает читаемость текста.

Примеры:

Subject–verb agreement

- ✗ The number of students have increased in recent years.
- ✓ The number of students has increased in recent years.
- ✗ One of the main problems are lack of academic vocabulary.
- ✓ One of the main problems is the lack of academic vocabulary.

Incorrect use of verb tenses

- ✗ Researchers have studied this problem in 2015.
- ✓ Researchers studied this problem in 2015.
- ✗ In this article, the author discusses studies that were conducted recently.
- ✓ In this article, the author discusses studies that have been conducted recently.

2.2 Лексические ошибки и «ложные друзья переводчика»

Серьёзные трудности вызывает выбор лексики, особенно в контексте академического дискурса. Студенты нередко используют слова, формально совпадающие с единицами родного языка, но не соответствующие нормам академического английского.

Примеры:

Incorrect word choice (false friends)

- ✗ The results of the research are actual and important.
- ✓ The results of the research are relevant and important.
- ✗ The author gives actual examples to explain the concept.
- ✓ The author gives relevant examples to explain the concept.

Inappropriate use of synonyms (wrong register)

- ✗ The problem is very big in the academic field.
- ✓ The problem is significant in the academic field.
- ✗ Students face a lot of difficulties while writing.
- ✓ Students encounter numerous difficulties while writing.

Incorrect collocations

- ✗ Students make a research on academic writing.
- ✓ Students conduct research on academic writing.
- ✗ The study takes a place in the university.
- ✓ The study takes place at the university.

Wrong use of academic vocabulary (overgeneralization)

- ✗ The author uses many information in the article.
- ✓ The author provides much information in the article.

✗ Students do a lot of analysis.

✓ Students conduct a lot of analysis.

3. Структурные ошибки и организация текста

3.1 Слабое развитие абзацев

В академическом тексте каждый абзац должен быть логически завершён и ориентирован на раскрытие одной идеи. Однако в работах студентов часто отсутствует тематическое предложение или в одном абзаце объединяются несколько несвязанных идей, что нарушает внутреннюю структуру текста. В результате читателю сложно определить основную мысль абзаца и проследить развитие аргументации.

Дополнительной проблемой является несбалансированность объёма абзацев: одни из них ограничиваются одним-двумя предложениями и напоминают заметки, тогда как другие чрезмерно перегружены информацией и охватывают несколько смысловых блоков. Такая организация текста отрицательно влияет на связность изложения и снижает академическую чёткость работы.

Примеры:

Lack of clear paragraph structure (topic sentence)

✗ Students make grammar mistakes. Vocabulary is also difficult. Academic writing is important.

✓ One of the major difficulties in academic writing is students' limited control of grammar and vocabulary.

✗ Academic texts are complex. Students face many problems. Writing is difficult.

✓ Academic writing poses significant challenges for students due to the complexity of academic texts.

3.2 Нарушение связности и когнитивности

Связность текста часто нарушается из-за недостаточного использования логических связей, местоимений и средств референции, в результате чего текст теряет логическую цельность.

Примеры:

Lack of logical connection between sentences

✗ Students need to improve their academic writing. Many students find grammar difficult.

✓ Students need to improve their academic writing because many of them find grammar difficult.

Abrupt topic shifts (no transition)

✗ Academic writing is important for students. The internet provides many resources. Teachers should give more assignments.

✓ Academic writing is important for students. Therefore, the internet provides many resources that can support their learning. Consequently, teachers should assign more writing tasks to develop students' skills.

Incorrect use of cohesive devices (overuse or misuse)

✗ Firstly, students make grammar mistakes. Secondly, they also make vocabulary mistakes. Finally, they make mistakes in punctuation. In addition, grammar mistakes are common.

✓ Firstly, students make grammar mistakes. Secondly, they have difficulties with academic vocabulary. Finally, they encounter problems with punctuation.

Lack of reference words

✗ Students read academic texts. Academic texts are complex. Academic texts require special skills.

✓ Students read academic texts, which are complex and require special skills.

Poor paragraph unity

✗ Academic writing is difficult. Students also have problems with listening. Reading is important. Teachers should help students.

✓ Academic writing is difficult for many students due to limited exposure to academic vocabulary and insufficient practice. Therefore, teachers should provide more structured writing tasks and feedback.

4. Стилистические и регистровые ошибки

Одной из наиболее распространённых стилистических проблем в работах студентов-переводчиков является нарушение академического регистра, проявляющееся в использовании разговорных элементов, сокращённых форм, неформальных дискурсивных маркеров и субъективных оценок. Подобные языковые средства характерны для устной коммуникации и неакадемических жанров, однако в научном тексте они снижают уровень формальности и подрывают объективность изложения.

Часто в академических работах встречаются разговорные квантификаторы (*a lot of, kind of*), сокращения (*don't, isn't*), а также дискурсивные маркеры, типичные для устной речи (*so, well, you know*). Их использование создаёт эффект неформального повествования и противоречит требованиям академического стиля, предполагающего нейтральность, точность и дистанцированность автора от текста.

Дополнительным источником данной проблемы является активное взаимодействие студентов с неакадемическими англоязычными ресурсами — блогами, социальными сетями и популярными онлайн-платформами, где доминируют разговорные и гибридные формы письменной речи. В результате элементы этих регистров переносятся в академические тексты без осознания их стилистической неуместности.

Нарушение академического регистра особенно негативно сказывается на восприятии аргументации: даже при наличии корректного содержания использование неформальной лексики и разговорных конструкций снижает научную убедительность текста и может быть интерпретировано как недостаточная академическая компетентность автора.

Примеры:

Use of informal expressions

✗ Nowadays, a lot of students don't really understand how academic writing works.

✓ Nowadays, many students do not fully understand the conventions of academic writing.

Colloquial verbs and phrases

✗ Students often mess up the structure of their academic papers.

✓ Students often fail to organize the structure of their academic papers effectively.

Use of contractions

✗ Academic writing doesn't allow students to express their ideas freely.

✓ Academic writing does not allow students to express their ideas freely.

Overly conversational tone

✗ So, when students write essays, they usually don't pay much attention to structure.

✓ Therefore, when students write essays, they often pay insufficient attention to textual structure.

Vague and imprecise language

✗ Academic texts are kind of difficult for students.

✓ Academic texts are often challenging for students.

5. Когнитивные и методологические ошибки

5.1 Описательное вместо аналитического письма

Одной из наиболее серьёзных проблем академического письма у студентов-переводчиков является преобладание описания над анализом. В своих работах студенты часто пересказывают содержание источников, не сопоставляя различные точки зрения и не осуществляя их критическую интерпретацию. В результате текст приобретает

информативный, но не исследовательский характер и не демонстрирует сформированность аналитического мышления.

Подобная тенденция особенно ярко проявляется в обзорах литературы и аналитических комментариях, где вместо синтеза идей и выявления исследовательских закономерностей наблюдается последовательное перечисление источников. Отсутствие анализа снижает научную ценность работы и препятствует формированию у студентов навыков аргументированного академического письма.

Примеры:

✗ The article discusses academic writing. It explains what academic writing is and gives examples. The author also mentions that students have difficulties.

✓ The article examines the concept of academic writing and analyzes the specific difficulties students face, highlighting the factors that contribute to these challenges.

✗ Many researchers have studied academic writing. They say that it is important for students. Different problems are described in their studies.

✓ Although numerous researchers emphasize the importance of academic writing, their findings reveal recurring problems related to students' limited genre awareness and insufficient practice.

6. Причины трудностей академического письма

Рассмотрев вышеуказанные ошибки можно сделать вывод что трудности академического письма обусловлены совокупностью факторов: межъязыковой интерференцией, недостаточным вниманием к академическому письму в образовательных программах, ограниченным чтением научных текстов и практикой обратной связи, ориентированной преимущественно на исправление грамматических ошибок. В результате у студентов формируется фрагментарное представление об академическом тексте, при котором внимание сосредотачивается на языковой форме, а не на логике аргументации и структуре изложения.

Кроме того, отсутствие систематической работы с академическими жанрами препятствует развитию навыков критического мышления и осознанного использования источников, что приводит к воспроизводству одних и тех же типичных ошибок на разных этапах обучения.

7. Педагогические рекомендации

Для эффективного преодоления выявленных трудностей академическое письмо должно быть интегрировано в программы подготовки переводчиков как самостоятельная и системно выстроенная дисциплина, а не как вспомогательный элемент языковой подготовки. Обучение академическому письму целесообразно начинать на ранних этапах обучения и последовательно развивать на протяжении всего учебного курса.

Особое внимание следует уделять формированию жанровой компетенции, умению выстраивать аргументацию, обеспечивать логическую связность текста и корректно работать с научными источниками. Важно обучать студентов не только языковым средствам, но и принципам академического мышления, включая анализ, синтез, сопоставление и критическую оценку информации.

Эффективной педагогической практикой является поэтапное обучение, при котором студенты сначала анализируют образцы академических текстов в области перевода и смежных дисциплин, затем выполняют контролируемые задания (написание абзацев, аннотаций, обзоров), и лишь после этого переходят к созданию самостоятельных исследовательских работ. Такая последовательность позволяет снизить когнитивную нагрузку и обеспечить постепенное формирование академической компетенции.

Кроме того, важную роль играет обратная связь, направленная не только на исправление языковых ошибок, но и на развитие структуры текста, логики аргументации и качества анализа. Использование взаимного рецензирования и редактирования также способствует

развитию у студентов осознанного отношения к академическому письму и повышает их способность критически оценивать, как собственные, так и чужие тексты.

Заключение

Анализ показывает, что ошибки академического письма у студентов-переводчиков носят системный характер и выходят за рамки лингвистических трудностей. Структурные, стилистические и методологические ошибки существенно снижают качество письменных работ и требуют целенаправленной педагогической коррекции.

Формирование устойчивых навыков академического письма является необходимым условием подготовки компетентных переводчиков, способных эффективно функционировать в академическом и профессиональном пространстве.

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ISSUES OF STRENGTHENING THE STATUS OF THE KAZAKH LANGUAGE WITHIN CLIL AND BILINGUAL EDUCATION

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Abstract. This article examines the issue of strengthening the status of the Kazakh language within CLIL (Content and Language Integrated Learning) and bilingual education contexts. The study aims to analyze the functional integration of Kazakh as a subject-academic language and to identify the conditions under which it can operate as a full-fledged medium of disciplinary knowledge construction. A qualitative research design was employed, with content analysis applied to instructional and methodological materials used in CLIL and bilingual teaching practices. The analysis focused on the functional roles of Kazakh and the presence of academic discourse elements across different types of educational resources. The results indicate that while the Kazakh language demonstrates substantial potential for subject-academic use, its integration into higher-order discursive functions remains inconsistent. The study argues that the academic status of the Kazakh language within integrated learning environments depends on systematic methodological support and purposeful instructional design. The findings contribute to the theoretical and practical understanding of how CLIL models can be aligned with national language priorities in multilingual education systems.

Keywords: CLIL; bilingual education; Kazakh language status; academic discourse; subject-based language; multilingual education; language policy in education

In the context of contemporary globalization, multilingual education policy has become a strategic direction of educational systems, necessitating the development of new models for the formation of linguistic competence. In this regard, CLIL (Content and Language Integrated Learning) and bilingual education approaches, which are based on the integration of subject content and language, are widely implemented in the international educational space as effective pedagogical technologies. However, when introducing these models into the national education system, the issue of preserving and strengthening the status of the state language particularly the Kazakh language acquires special significance.

The language policy of the Republic of Kazakhstan aims to ensure the full functioning of the state language in all spheres of public life. Nevertheless, under conditions of multilingual and bilingual education, there is a risk of limiting the functional potential of the Kazakh language, with emerging tendencies to use it not as a primary medium of instruction but rather as an auxiliary or translation language. Such practices may negatively affect the status of the Kazakh language as a language of academic, scientific, and subject-based communication. Therefore, strengthening the role of the Kazakh language within CLIL and bilingual education frameworks and establishing it as a substantive medium of instruction constitutes one of the pressing issues of modern pedagogy.

The relevance of the research problem is determined by the fact that CLIL technology is predominantly oriented toward the dominant use of foreign languages (English or Russian), while the potential of the Kazakh language as a carrier of subject content remains insufficiently realized. This, in turn, hinders the development of learners' abilities to engage in academic thinking, scientific reasoning, and professional communication in Kazakh. Moreover, in bilingual education

practice, the lack of methodological coherence and an imbalance between language and subject content may further weaken the position of the Kazakh language in the educational space.

The main objective of this study is to conduct a scientific and methodological analysis of the issues related to strengthening the status of the Kazakh language within CLIL and bilingual education contexts, and to identify the pedagogical foundations for using Kazakh as a full-fledged medium for mastering subject content. To achieve this objective, the study comprehensively examines theories of multilingual education, the integration of language and content, as well as approaches to developing the functional and academic potential of the Kazakh language.

The research findings are expected to clarify the scientific foundations for aligning CLIL and bilingual education models with national linguistic interests, enhance the status of the Kazakh language in the educational process, and contribute to its establishment as a competitive subject-based and communicative language within the contemporary multilingual educational environment.

The CLIL (Content and Language Integrated Learning) approach has been extensively examined in international scholarly literature as an effective model for the integrated teaching of content and language. In their seminal works, Coyle, Hood, and Marsh conceptualize CLIL as a dual-focused pedagogical approach, substantiating the role of language both as a medium and as an object of subject-content learning [1]. This position highlights the need to address language status not merely at the linguistic level, but also at the methodological and institutional levels. During the adaptation of the CLIL model to a national education system, the choice of which language functions as the primary language of subject discourse becomes a matter of strategic importance.

The specific features of language–content interaction in CLIL classrooms have been demonstrated by Dalton-Puffer through discourse analysis, showing that the acquisition of subject content largely depends on the organization of academic language [2]. According to her interpretation, language is not only a means of communication but also a structuring factor of disciplinary thinking. From this perspective, the use of the Kazakh language as the principal medium for delivering subject content constitutes a key condition for enhancing its academic status.

Nikula analyzes the interrelationship between subject literacy and language through CLIL-based tasks, emphasizing that subject knowledge is constructed through linguistic genres and terminological systems [3]. These findings substantiate the necessity of employing the Kazakh language not merely as an explanatory or auxiliary language, but as a full-fledged instrument of scientific and disciplinary thinking.

The theoretical foundations of bilingual education are comprehensively articulated in the works of Cummins. According to his Linguistic Interdependence Hypothesis, academic skills developed in the first language positively influence learning in the second language [4]. This assertion indicates that the development of subject-specific academic competence in Kazakh can serve as a foundation for academic achievement in other languages as well.

The social dimensions of language and education policy are addressed in García's theory of bilingual education, which emphasizes the unequal status of languages within educational spaces [5]. The author demonstrates that bilingual education is not merely a methodological solution, but also a mechanism for reproducing the social and symbolic capital of languages. This perspective enables the issue of strengthening the status of the Kazakh language to be substantiated from a sociolinguistic standpoint.

The management of linguistic repertoires in multilingual classrooms is examined by Creese and Blackledge within the framework of translanguaging pedagogy, highlighting the importance of purposeful use of learners' entire linguistic resources [6]. Similarly, Cenoz and Gorter describe pedagogical translanguaging as an effective strategy in multilingual education [7]. However, this

approach requires clear regulation and methodological balance in order to avoid diminishing the status of the state language.

The effectiveness of CLIL in terms of language outcomes has been assessed in studies by Lasagabaster, which reveal a positive relationship between subject-content learning and language development [8]. Ruiz de Zarobe, drawing on empirical data, demonstrates the impact of CLIL on linguistic competence, emphasizing the decisive role of systematic support for disciplinary language [9].

In the Kazakhstani context, studies by Mehisto, Kambatyrova, and Kurakbayev analyzing CLIL and trilingual education policy reveal a noticeable gap between policy and practice [10]. The authors note that although CLIL principles are reflected at the documentary level, there is a risk of their mechanical implementation in the teaching process.

Quantitative investigations of CLIL effects in higher education in Kazakhstan conducted by Satybaldina and colleagues demonstrate that language achievement depends on the learning environment, subject specificity, and the level of teacher preparedness [11]. This finding underscores the importance of teachers' competence in working with academic language when introducing CLIL elements in Kazakh.

An analysis of CLIL practices in school settings by Karabassova, based on the example of Nazarbayev Intellectual Schools, shows that the quality of language support and lesson design constitutes a key factor in CLIL effectiveness [12]. This result confirms the decisive role of methodological design in establishing Kazakh as a language of subject-based communication.

A systematic literature review of trilingual education policy in Kazakhstan conducted by Sarmurzina and colleagues indicates that insufficient teacher training, limited instructional resources, and weak institutional support reduce the effectiveness of the policy [13]. The authors emphasize that strengthening the status of the state language should not remain at a declarative level, but must be implemented through the educational ecosystem as a whole.

In addition, studies by Kazakhstani researchers Abdykarimova [14], Zhunusova [15], and Tolegenova [16] address the enhancement of the subject-related potential of the Kazakh language under conditions of bilingual education, highlighting the importance of linguistic balance and methodological coherence. Kirkpatrick, in turn, analyzes the preservation of national languages in multilingual education from the perspective of regional language policy, substantiating the central role of the national language within the education system [17].

Overall, international theories of CLIL and bilingual education, together with empirical research conducted in Kazakhstan, indicate that the CLIL model has substantial potential for strengthening the status of the Kazakh language. However, this potential can be realized only when Kazakh is systematically employed as the primary language of subject-academic communication.

The study was grounded in a qualitative pedagogical research design and aimed to analyze the formation of the subject-academic status of the Kazakh language under conditions of CLIL and bilingual education. The research sought to identify the functional role of language in the instructional process through a systematic analysis of specific educational materials.

Content Analysis was employed as the principal research method. This method enables the systematic identification of linguistic patterns, semantic units, and functional uses within textual and instructional materials and is widely applied in educational research.

The theoretical and methodological foundations of content analysis are comprehensively articulated in the works of K. Krippendorff. According to his definition, content analysis is an empirical method aimed at producing reliable and replicable inferences from communicative data while taking into account the context in which these data are used (Krippendorff, 2018).

The research materials comprised a total of 36 instructional and methodological resources derived from educational practices incorporating elements of CLIL and bilingual education, including:

- 12 subject lesson plans (in natural sciences and social sciences/humanities);
- 8 instructional texts (subject-specific texts presented in the Kazakh language);
- 10 task samples (terminological, explanatory, and argumentative in nature);
- 6 fragments of methodological guidelines for teachers related to content and language integrated instruction.

These materials made it possible to determine the role of the Kazakh language in conveying subject content, the frequency of academic terminology use, and the level of subject discourse formation.

Content analysis was conducted in accordance with the stages proposed by Krippendorff and included the following procedures:

- identification of units of analysis (subject concepts, academic terminology, argumentative and explanatory structures);
- development of coding categories (use of Kazakh as the primary language of subject instruction, an auxiliary language, or an explanatory language);
- systematic coding of all 36 materials;
- interpretation and generalization of the obtained data.

During the coding process, it was acknowledged that a single material could be assigned to multiple categories, which allowed for a more nuanced representation of the multifunctional role of language in the educational process.

The conducted content analysis made it possible to determine the functional roles performed by the Kazakh language in instructional materials under CLIL and bilingual education conditions, as well as to assess the extent to which it is integrated into subject-academic discourse. The findings indicate that the use of the Kazakh language is not uniform; rather, its role varies depending on the type of material, the purpose of the task, and the level of complexity of the subject content. Particular attention was paid to the distribution of the Kazakh language as the primary language of subject instruction, an auxiliary explanatory language, and an episodic support language (Figure 1).

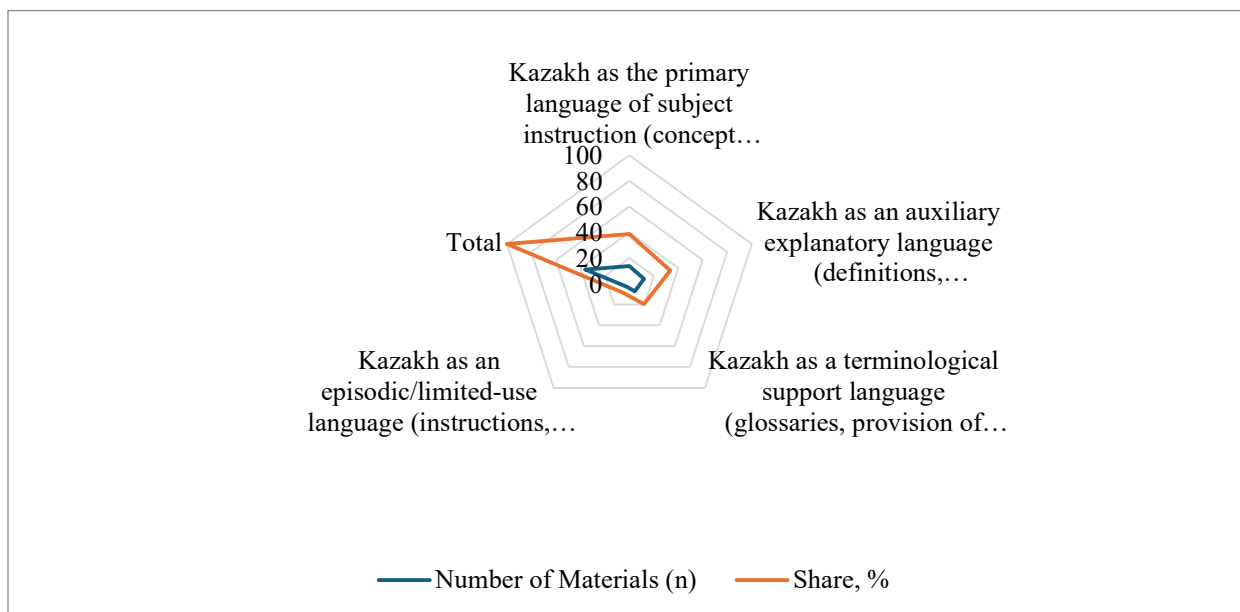


Fig. 1. Distribution of Functional Uses of the Kazakh Language in CLIL and Bilingual Education Materials (n = 36)

The content analysis results presented in Figure 1 clearly demonstrate that, under CLIL and bilingual education conditions, the Kazakh language is employed in instructional materials at different functional levels. In 38.9% of the analyzed materials, Kazakh functions as the primary language of subject instruction, indicating its capacity to fully perform the functions of concept formation, explanation, and summarization. This proportion provides empirical evidence that Kazakh can be used not merely as a language of everyday or auxiliary communication, but as a language that organizes academic and cognitive activity. This finding is consistent with CLIL theory, which emphasizes the structuring role of language in subject-content learning, and confirms that the academic status of a language is consolidated through actual instructional practice.

At the same time, the use of Kazakh as an auxiliary explanatory language in 33.3% of the materials indicates the persistence of a linguistic hierarchy. In such cases, Kazakh is mainly employed for defining terms, providing explanations, or clarifying complex content, while the primary subject discourse is conducted in another language. This pattern suggests that the cognitive load carried by Kazakh is limited and that its role in developing subject-based thinking is only partially realized. From a scientific perspective, this phenomenon corresponds to the “auxiliary language” pattern commonly observed in bilingual education and represents a methodological risk zone in terms of strengthening the status of the state language.

The finding that Kazakh is used exclusively as a terminological support language in 19.4% of the materials is also of considerable scholarly significance. This result indicates that the use of Kazakh is often confined to the lexical level and does not become the main channel for deep engagement with subject content. It is well established that limiting a language to terminological support privileges its nominative function over its communicative and cognitive functions, which is insufficient for the full development of academic discourse. From this standpoint, enhancing the subject-related potential of the Kazakh language requires its systematic use not only for providing equivalents, but also as a tool for conceptual analysis, argumentation, and synthesis.

The episodic or limited use of Kazakh in 8.4% of the materials suggests that, in some instructional resources, linguistic balance is not maintained at all under CLIL and bilingual education conditions. The use of Kazakh solely at the level of instructions or isolated fragments significantly weakens its subject-communicative function and may reduce its role to a symbolic or merely formal status. From a scholarly perspective, this outcome highlights the risk that, in the course of mechanical implementation of CLIL, language-related objectives may be relegated to a secondary position.

Overall, the obtained data demonstrate that the Kazakh language has substantial potential to function as a subject-academic language within CLIL and bilingual education contexts; however, the full realization of this potential depends on systematic methodological support. As the use of Kazakh as the primary language of subject instruction increases, its academic status is strengthened, and learners’ subject-based thinking and linguistic competence develop simultaneously. Consequently, the analyzed results underscore the scientific and pedagogical significance of establishing Kazakh as a central language of subject discourse within the CLIL model.

During the content analysis, the structural elements of academic language were also recorded quantitatively (multiple elements could co-occur within a single material) (Figure 2).

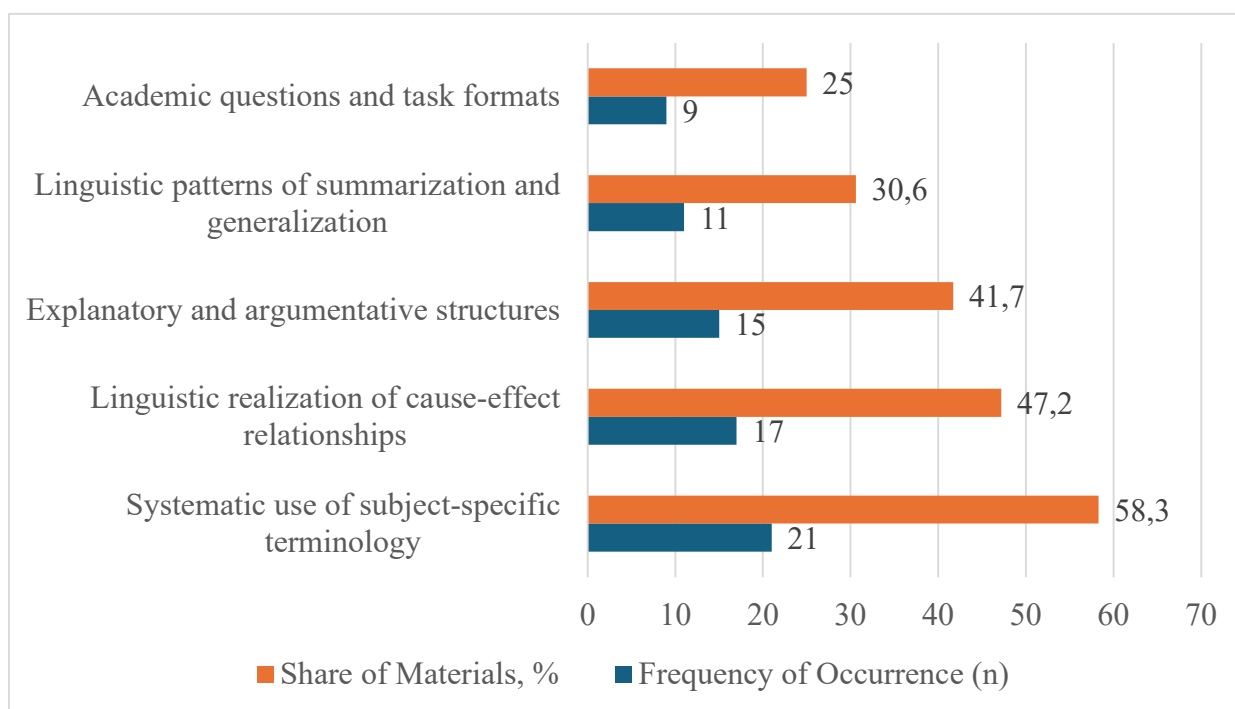


Fig. 2. Frequency of Academic Discourse Elements in the Kazakh Language

The data presented in Figure 2 provide a deeper characterization of the extent to which the Kazakh language is used as a language of academic discourse under CLIL and bilingual education conditions. The varying frequencies of academic discourse elements across the materials indicate that the cognitive load carried by Kazakh in subject-content learning is unevenly distributed. This finding demonstrates that the integration of language and subject knowledge is determined not merely by the presence of a language in instruction, but by the specific discursive functions it performs.

The systematic use of subject-specific terminology observed in 58.3% of the materials indicates that Kazakh substantially fulfills its function of naming and nominating disciplinary concepts. This result confirms the capacity of the Kazakh language to accommodate scientific vocabulary and integrate it into instructional content. However, from a scholarly perspective, the presence of terminology alone does not ensure the full formation of academic discourse, as terminological units contribute to the development of subject-based thinking only when combined with cognitive operations such as analysis, comparison, argumentation, and synthesis.

The fact that linguistic realization of cause–effect relationships accounts for 47.2% suggests that Kazakh partially supports logical thinking structures in subject learning. Since cause–effect relations constitute the core of academic discourse, their presence in fewer than half of the materials indicates that the explanatory potential of Kazakh as a language of subject reasoning is not yet fully exploited. This pattern is characteristic of bilingual models in which the main logical structure of subject content is constructed in another language, while Kazakh is used primarily for supplementary explanation.

The registration of explanatory and argumentative structures at a level of 41.7% demonstrates that the argumentative function of Kazakh is realized only to a limited extent. Given that academic argumentation represents a high level of cognitive activity, its insufficient use in Kazakh weakens the language’s role in fostering subject-based thinking. From a scientific standpoint, this result suggests that instructional materials tend to assign Kazakh a predominantly

reproductive function, while productive functions such as reasoning and justification are more often delegated to other languages.

The relatively low occurrence of summarization and generalization patterns (30.6%) indicates that Kazakh is rarely employed as a means of completing higher-order academic activities in instructional materials. Since summarization constitutes a key stage in structuring and systematizing subject knowledge, its limited realization in Kazakh may lead to insufficient development of learners' ability to conceptualize and synthesize subject knowledge in this language. This issue represents a significant methodological concern in the context of strengthening the academic status of Kazakh.

The lowest proportion observed for academic questions and task formats (25.0%) points to the underuse of Kazakh in its interactive and guiding functions within the instructional process. As academic questions are among the primary tools for activating learners' cognitive engagement and initiating subject-based thinking, their infrequent use in Kazakh weakens the language's role as a means of managing and directing learning activities.

Overall, the results presented in Figure 2 indicate that the Kazakh language possesses the potential to incorporate elements of academic discourse; however, this potential remains largely confined to lower- and mid-level discursive functions. To establish Kazakh as a fully-fledged subject-academic language within CLIL and bilingual education contexts, it is essential to systematically elevate its use from the terminological level to logical, argumentative, and synthesizing levels of academic discourse.

This study demonstrates that the effectiveness of CLIL and bilingual education in a national context is not determined solely by the formal inclusion of multiple languages in instruction, but by the functional positioning of those languages within subject-academic discourse. The analysis confirms that the status of the Kazakh language within integrated learning environments is shaped by how consistently it is embedded into the cognitive architecture of teaching and learning, rather than by its nominal presence in instructional materials.

The findings highlight that the academic consolidation of a state language requires deliberate pedagogical design, where linguistic choices are aligned with disciplinary reasoning, knowledge construction, and higher-order cognitive processes. When Kazakh is systematically integrated into explanatory, argumentative, and synthesizing practices, it acquires not only communicative value but also epistemic legitimacy as a language of knowledge production.

From a broader perspective, the study underscores that CLIL models must be adapted to national linguistic priorities through context-sensitive methodological frameworks. Without such adaptation, integrated learning risks reinforcing existing language hierarchies rather than contributing to balanced multilingual development. Strengthening the status of Kazakh within CLIL and bilingual education therefore depends on institutional support, teacher preparedness, and instructional models that explicitly recognize the state language as a central medium of academic meaning-making.

The conclusions of this research contribute to ongoing discussions on multilingual education by offering empirically grounded insights into how state languages can be positioned as academically robust within globally oriented pedagogical models. The results may inform curriculum development, teacher training, and language policy decisions aimed at ensuring the sustainable academic functioning of the Kazakh language in multilingual educational settings.

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Восприятие языка через изображение мира

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Мировоззрение и сознание любого народа обновляются в зависимости от быта, обычаев, культуры и истории этноса, то есть восприятие языка через изображение мира подтверждает высокую степень специфики мышления нации.

Языковая картина мира каждого этноса формируется на основе исторического опыта, духовных ценностей и культурных традиции, что находит отражение в структуре и семантике языковых единиц.

Одним из свидетельств такого наблюдения являются фразеологизмы, которые с точки зрения внутреннего смысла связываются друг с другом и становятся устойчивыми фразеологическими единицами. Особое место среди них занимают словосочетания с числовыми компонентами, поскольку числительные выступают на протяжении многих веков элементами концептуальной системы, участвуют во всех сферах жизни как: экономика, медицина, техника, архитектура, машиностроение, биология, география, нанотехнология, образование и лингвистика, обеспечивая точность в планировании и измерении. В.М. Ярцева считает, что в философии измерение – это познавательный процесс, который определяет количественное отношение измеряемой величины к другой, служащей стандартом, эталоном. Согласно ЛЭС «измерение – это совокупность действий, выполняемых при помощи средств измерений с целью нахождения числового значения измеряемой величины чего-либо». Когда мы что-то измеряем, то мы сравниваем эту величину, с какой-либо постоянной величиной и эта постоянная величина называется единицей измерения.

Фразеологизмы с числительными представляют собой значимый материал для исследования взаимодействия пространства, количества и национально обусловленной картины мира. «Смысловым результатом регулярных выражений является фразеологическое значение. Получается, что при компенсации потребности в речи люди выбирают фразеологизмы в первую очередь исходя из значения понятия» [1, 4]. Следует отметить, что из фразеологизмов казахского языка часто встречаются поговорки, слова заповеди и мудрые слова, пословицы. Термин «фразеология» в языкознании имеет широкое значение, т. е. отражает понятие совокупности устойчивых оборотов речи и выражений, свойственных в определенном языке» [2, с. 34].

Казахский язык, входящий в семью тюркских языков, отличается богатством образных выражений, среди которых особое место занимают лексико-фразеологические единицы, связанные с числительными. В составе фразеологизмов числительные приобретают новые, нетипичные семантические характеристики и подвергаются качественным преобразованиям, формируя особое смысловое своеобразие.

Числительные в некоторых языках используются в качестве основных компонентов устойчивых словосочетаний, передавая информацию об общественном устройстве, происхождении, а также о материальной и духовной культуре народов – носителей этих языков.

Например, в отношении казахского языка отмечается, что наиболее часто встречающиеся числительные в устойчивых словосочетаниях единицы «бір», «екі», «үш»,

«жеті», «тоғыз», «қырық», «жүз», «мың», и эти числовые единицы входят в состав фразеологизмов, отражающих обычаи, традиции и религиозные представления народа.

Что касается английского языка, то числовые единицы активно участвуют в формировании фразеологических фраз, нарративов и пословиц, что способствует развитию и наполнению большого фразеологического словарного запаса. На английском языке часто встречаются фразеологические единицы, встречающиеся с 1-10 единицами первого ряда чисел (A.P. Cowie, C.D. Fillmore, O. Pyskach, V.V. Шевченко, J.R. Taylor, V.N. Toporov, S. Sadovigova).

В немецком языке числовые компоненты образуют устойчивый пласт фразеологии, в котором числа функционируют как семантические усилители, культурные символы или элементы образной характеристики ситуации. Наиболее продуктивными являются единицы *eins, zwei, drei, hundert, tausend*, что отражает как универсальные когнитивные модели, так и национально-специфические представления (Пивоварова Е.В., Суге-Баадырович Н.Ц.)

Древние верования и обычаи, составляющие основу английской, немецкой и казахской этнической культуры, а также кодирование накопленного опыта в системе общественно-социальных отношений числами «*kueli – holy – heilig*» и «*dəstүрлі – traditional – traditionell*», имеющими отношение к системе счисления, тесно связаны с кумулятивной деятельностью языка. В целом, в настоящее время человечество вряд ли выживет без цифр, потому что передвижение людей, еда, которую мы едим, одежда, которую мы носим, зарплата, которую мы получаем, лечение, отпуск зависят от цифр. В эпоху цифровизации любая информация, текст, передается через код, состоящий из известных чисел, поэтому числа сами по себе являются священными и традиционными, потому что мы зависим от чисел, и каждый момент нашей жизни исчисляется числами.

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THE IMPACT OF TASK-BASED ASSIGNMENTS ON STUDENTS' LANGUAGE SKILLS IN ENGLISH LANGUAGE LEARNING

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This study examines the impact of using task-based assignments on the language skills of university students learning English. Data were collected from 120 students at a university through a descriptive survey and experimental research methods. The results indicate that the implementation of task-based assignments significantly improved students' speaking, listening, writing, and reading comprehension skills. Students' motivation for autonomous learning increased, while linguistic errors and grammatical difficulties decreased. However, some students reported challenges in managing their time effectively when completing tasks. This study demonstrates the effectiveness of task-based assignments in higher education and highlights their potential to enhance interaction between instructors and students during the learning process.

Keywords: task-based assignments, English language, language skills, higher education, students, learning motivation

Introduction

In contemporary higher education, the effective development of students' language skills in English has become a critical concern. Mastery of language skills directly influences students' academic, professional, and social success. Task-Based Learning (TBL) is a pedagogical approach aimed at enhancing students' language competencies through the completion of specific, goal-oriented tasks. This approach integrates communicative, cognitive, and motivational aspects, making the learning process both effective and engaging for students.

A review of the literature indicates that TBL not only facilitates the development of language skills but also promotes students' motivation for autonomous learning. However, research examining the effectiveness and practical impact of this approach among university students in Kazakhstan remains limited. Therefore, this study aims to empirically investigate the effects of task-based assignments on students' language skills.

The development of language skills in universities is not limited to grammatical and lexical knowledge. It is equally important to cultivate students' communicative competence, critical thinking, and problem-solving abilities. Task-based assignments provide an opportunity to develop these skills in an integrated manner, as students learn to organize their thoughts systematically, analyze information, and collaborate effectively in group work while completing specific language tasks. Compared to traditional instructional methods, this approach increases student engagement, responsibility, and participation in the learning process.

Furthermore, TBL plays a significant role in enhancing students' motivation. Tasks often simulate real-life and professional contexts, allowing students to observe the outcomes of their

learning activities and heightening their interest in mastering language skills. The application of such methods within the higher education system of Kazakhstan contributes not only to improving students' foreign language proficiency but also to strengthening their self-assessment and learning motivation. This study seeks to provide concrete evidence of the effectiveness of the TBL approach in promoting students' language development.

Research Methods

The study was conducted using a combination of descriptive survey and experimental methods. The implementation of task-based assignments involved collecting data from 120 students enrolled in a university-level English course. To assess students' speaking, writing, listening, and reading skills, both pre-tests and post-tests were administered. Additionally, a survey was conducted to gather information on students' attitudes toward the tasks, their motivation, and their time-management experiences.

The survey consisted of four sections:

Demographic information: age, year of study, and language proficiency level.

Assessment of language skills: speaking, writing, listening, and reading.

Experience with task participation: task complexity, clarity, and time management.

Motivation and self-directed learning: students' engagement and willingness to learn independently.

Data analysis involved the use of percentage indicators, graphical representations, and statistical correlation analyses.

During the experimental phase, students were assigned specific task-based activities in each lesson. The tasks were designed to develop communicative skills, enhance text comprehension, and perform written assignments logically and coherently. Students' performance on each task was monitored by instructors, and feedback sessions were conducted to discuss errors and achievements. This approach ensured active student participation in the learning process and allowed them to apply language skills in practical contexts.

Moreover, students' motivation and time-management abilities were evaluated by comparatively analyzing survey results and observational data. Statistical analysis enabled the identification of correlations between students' task engagement levels and the improvement of their language skills. This methodological approach enhanced the reliability of the study and provided empirical evidence of the effectiveness of the TBL approach in developing students' language competencies.

Results and Discussion

The results of the study indicated that students significantly improved their language skills through the completion of task-based assignments.

Speaking skills: 68% of students reported improvement in their speaking abilities. During conversations, students' vocabulary expanded, and the number of grammatical errors decreased.

Listening skills: 62% of students noted an increased level of text comprehension while performing listening tasks.

Writing skills: 70% of students indicated enhancements in logical organization and linguistic accuracy when completing written assignments.

Reading comprehension skills: 65% of students demonstrated an increased ability to understand texts quickly and comprehensively.

Additionally, 74% of students reported higher motivation for self-directed learning, while 28% experienced difficulties in managing their time effectively. These findings confirm that the TBL approach not only enhances students' language skills but also promotes their learning motivation comprehensively.

The study also revealed that the implementation of task-based assignments positively affected students' communicative skills. During group activities, students learned to express their

opinions systematically, ask questions, and engage in active listening. This was particularly evident during free discussions and debates, as students were required to interact with one another to achieve specific linguistic objectives. Moreover, collaborative tasks increased students' confidence: anxiety about speaking in public decreased, and they became more adaptable in correcting language errors.

Furthermore, the data demonstrated the development of students' cognitive skills. Analytical abilities, such as text analysis, information organization, and logical reasoning during written tasks, were enhanced. Improvements in reading comprehension and effective completion of written assignments illustrated that the TBL method facilitates deeper mastery of learning materials. These findings indicate that the approach contributes not only to language development but also to fostering critical thinking, creativity, and self-assessment skills within the learning process.

Conclusion

The study demonstrated that the implementation of task-based assignments significantly enhances university students' English language proficiency. This approach contributes to the development of speaking, listening, writing, and reading comprehension skills, as well as increases students' interest in and motivation for self-directed learning. However, time management during the learning process posed challenges for some students. Therefore, it is recommended that university instructors provide guidance and support to help students plan and manage their time effectively when applying the TBL method.

The findings also indicated that the TBL approach fosters the development of students' critical thinking and problem-solving skills. While completing specific tasks, students learned to analyze texts, organize information, and express their ideas logically. These skills are not only beneficial for mastering English but also for academic research, written assignments, and professional communication.

Furthermore, the method was found to enhance students' participation in group work and support the development of social skills. During collaborative tasks, students actively interacted with one another, learning cooperation and mutual support. This, in turn, makes the learning process more engaging and effective while consistently maintaining students' learning motivation. The results of the study provide a basis for considering the TBL approach as a core strategy in university-level English language instruction.

Overall, this research provides both practical and theoretical evidence for the effective application of task-based assignments in the context of higher education in Kazakhstan and highlights the potential for increasing interaction and engagement between instructors and students.

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ARTIFICIAL INTELLIGENCE AND THE COMMUNICATIVE APPROACH: AN INTEGRATIVE METHOD IN ENGLISH LANGUAGE TEACHING

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Abstract

This article examines the theoretical and practical aspects of integrating artificial intelligence (AI) with the communicative approach in English language teaching. The findings indicate that AI enables the personalization of the learning process, assessment of students' language skills, and automatic error analysis. The communicative approach focuses on developing students' speaking, listening, writing, and reading skills, while AI tools facilitate the efficient and individualized enhancement of these competencies. The article analyzes the synergistic effect of combining both methods and addresses the roles of the instructor and institutional support in implementing this integrative approach.

Keywords: artificial intelligence, communicative approach, English language, integrative method, foreign language teaching, higher education, pedagogy

ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ И КОММУНИКАТИВНЫЙ МЕТОД: ИНТЕГРАТИВНЫЙ ПОДХОД В ПРЕПОДАВАНИИ АНГЛИЙСКОГО ЯЗЫКА

Аннотация

В статье рассматриваются теоретические и практические аспекты интеграции искусственного интеллекта (ИИ) с коммуникативным методом в преподавании английского языка. Результаты исследования показывают, что ИИ обеспечивает персонализацию учебного процесса, оценку языковых навыков студентов и автоматический анализ ошибок. Коммуникативный метод направлен на развитие у студентов навыков устной и письменной речи, аудирования и чтения, в то время как инструменты ИИ способствуют эффективному и индивидуализированному совершенствованию этих компетенций. В статье анализируется синергетический эффект сочетания обеих методик, а также рассматриваются роль преподавателя и институциональная поддержка при реализации интегративного подхода.

Ключевые слова: искусственный интеллект, коммуникативный метод, английский язык, интегративный подход, обучение иностранным языкам, высшее образование, педагогика

Introduction

The education system of the twenty-first century has undergone profound transformations due to globalization, digitalization, and the rapid development of information technologies. These

changes have also influenced foreign language teaching methodologies, creating a need for new pedagogical approaches. Since English serves as a primary tool for international communication, academic research, and professional interaction, its effective instruction constitutes a crucial element of higher education quality.

Artificial intelligence introduces new opportunities in education for personalizing the learning process, providing feedback, and assessing language skills. While the communicative approach focuses on developing students' speaking and listening abilities, AI tools automate these processes and allow for the adaptation of individualized learning trajectories. This study examines the pedagogical effectiveness of integrating AI with the communicative approach and explores its potential in the training of foreign language teachers.

The application of AI enables real-time correction of students' language errors, enrichment of vocabulary, and the organization of interactive exercises aimed at the proper use of grammatical structures. Such technologies not only reduce the instructor's workload but also support students' autonomous learning and self-monitoring of their learning progress. From this perspective, AI emerges as an effective tool that transforms foreign language instruction from mere information delivery into the development of practical language skills.

Moreover, combining the communicative approach with AI tools enhances student motivation. Through interactive tasks and simulation-based speaking exercises, learners immerse themselves in authentic language environments and develop their communicative competence in real-life contexts. This integrative approach extends the educational process beyond theoretical knowledge, fostering practical skills, critical thinking, and the development of creative abilities.

Theoretical Foundations

Artificial intelligence (AI) refers to a set of technologies designed to model human cognitive abilities, including thinking, learning, and decision-making, within computer systems. In the educational context, AI performs functions such as adapting learning materials, optimizing the learning process based on individual student abilities, and automatically analyzing errors.

The communicative approach (Communicative Language Teaching, CLT) positions the student as an active participant in the learning process. Language acquisition occurs through authentic communicative situations and task-based interactions. AI tools complement the CLT methodology by automating the assessment and enhancement of students' speaking, listening, writing, and reading skills. For example, language models identify grammatical and lexical errors and provide students with targeted recommendations, while conversational simulators allow learners to engage in communication within realistic linguistic contexts.

Research indicates that AI-based instruction facilitates the rapid and effective development of students' language competence. Additionally, personalized feedback and interactive tasks enhance the effectiveness of the communicative approach. Whereas the teacher's role in traditional instruction is primarily that of a knowledge provider, in an AI-integrated model the instructor assumes the roles of facilitator and evaluator, guiding and monitoring the student's learning process.

The integration of AI with the communicative approach allows students to establish individualized learning trajectories. Learning materials and tasks are adapted according to each student's language proficiency, learning style, and personal interests. This approach increases student motivation and encourages the application of language skills not only through practice exercises but also within real-life and professional contexts. As a result, the synergy between AI tools and the communicative approach makes the learning process efficient, interactive, and outcome-oriented, providing an opportunity to establish new pedagogical standards in the training of future foreign language teachers.

Practical Aspects of Integrating AI with the Communicative Approach

Integrating artificial intelligence (AI) with the communicative approach offers several advantages for developing students' language skills:

Personalized Learning: AI analyzes each student's individual level, errors, and achievements, providing tailored recommendations.

Feedback: AI evaluates students' written and oral work and offers precise corrections.

Interactivity: Simulators and chatbots provide opportunities to practice within authentic communicative scenarios.

Assessment and Monitoring: AI continuously tracks students' progress and evaluates their achievements using quantitative metrics.

Research indicates that an AI-integrated model can enhance students' speaking skills 20–30% faster (Smith, 2022). Moreover, it is essential for instructors to pedagogically interpret AI tools and adhere to ethical standards.

From a practical perspective, integrating AI with the communicative approach enables teachers to plan lessons more effectively, adapt learning materials to individual student needs, and monitor each student's progress accurately. Simultaneously, students can expand their vocabulary and increase speaking confidence through virtual conversational practice and interactive exercises. Such an integrated model not only improves language skills but also fosters critical thinking, decision-making, and communicative flexibility, establishing a new level of practical effectiveness in the training of future foreign language teachers.

The Role of the Teacher

Artificial intelligence (AI) does not replace the teacher; rather, it transforms the teacher's role. The instructor is no longer merely a knowledge provider but acts as a designer, facilitator, and evaluator within the learning process.

Key Responsibilities of the Teacher:

- Pedagogically utilizing AI tools;
- Supporting students' critical thinking and independent learning skills;
- Ensuring academic integrity;
- Enhancing digital competence.

AI transforms the interaction between teacher and student: the instructor analyzes data and provides guidance, while the student becomes an active participant. In this model, the teacher's role as a monitor and evaluator is strengthened.

Furthermore, the teacher must apply AI tools not only at a technical level but also with pedagogical intent. By considering students' individual characteristics, learning styles, and motivation, the teacher adapts tasks and directs learning trajectories. This approach encourages autonomous learning and fosters the development of critical thinking, communication, and problem-solving skills. As a result, the integration of AI and the communicative approach elevates the teacher from a mere transmitter of information to a strategic coordinator of the learning process.

Discussion

The findings of the study indicate that integrating artificial intelligence (AI) with the communicative approach possesses significant pedagogical potential in foreign language teaching. However, this potential is realized only when didactic principles are properly maintained. Mechanical or uncritical use of AI may not fully impact students' cognitive and linguistic development.

Institutional support, instructors' digital competence, and methodological preparedness are critical factors for successful implementation. Effective use of AI requires specialized methodological models, training of instructors in digital competencies, monitoring of learning

outcomes, and the incorporation of personalized learning. Additionally, it is essential to preserve the authentic nature of linguistic interaction and to consider cultural and social contexts.

The research demonstrates that integrating AI with the communicative approach enhances student motivation, promotes autonomous learning, and accelerates the correction of language errors. Through interactive tasks and simulation exercises, students practice applying language skills in real-life and professional contexts. This approach fosters active, collaborative interaction between instructors and students, transforming the learning process from mere information delivery into an effective system oriented toward practical and communicative outcomes.

Conclusion

The integration of artificial intelligence (AI) with the communicative approach proves effective in training future foreign language teachers across the following dimensions:

- Personalized instruction;
- Rapid and continuous feedback;
- Enhancement of students' linguistic and cognitive engagement;
- Development of academic and professional competencies.

The study demonstrates that teachers' professional competence and institutional support are key factors in ensuring the effectiveness of AI. Pilot projects and practical trials provide opportunities to refine AI-based instructional models. Additionally, training instructors in digital competence and implementing ethical and methodological guidelines can serve as a foundation for sustainably improving higher education quality and fostering students' academic and cognitive potential.

The integration of AI and the communicative approach facilitates the development of students' autonomous learning abilities, critical thinking skills, and linguistic creativity. Interactive exercises and virtual simulations enable students to apply language skills in real-life and professional contexts, thereby enhancing their communicative confidence. Consequently, the learning process extends beyond theoretical knowledge, transforming into a practical, holistic, and development-oriented educational experience.

To fully realize the potential of AI in foreign language instruction, educational institutions must enhance strategies for integrating innovative technologies. Increasing the digital literacy of both instructors and students, providing methodological support, and adhering to ethical standards are essential conditions for the successful implementation of the integrated model. Such an approach not only improves the quality of higher education but also ensures the preparation of foreign language teachers in accordance with contemporary pedagogical requirements.

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DIDACTIC PRINCIPLES OF USING ARTIFICIAL INTELLIGENCE IN TEACHING GENERAL LINGUISTICS

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Abstract

This article examines the didactic principles underlying the use of artificial intelligence (AI) technologies in teaching the course *General Linguistics* in higher education institutions. The study is conducted within a descriptive-analytical framework and analyzes the pedagogical potential of AI tools in facilitating the acquisition of the theoretical content of general linguistics. Based on key didactic principles—scientific rigor, systematicity and consistency, consciousness and learner activity, individualization, the unity of theory and practice, and academic integrity—the article identifies both the possibilities and limitations of AI application in the educational process. The research findings demonstrate that artificial intelligence, when employed as a supplementary didactic tool in teaching general linguistics, contributes to the development of students' conceptual thinking, research skills, and cognitive engagement. At the same time, it is substantiated that the unsystematic or methodologically ungrounded use of AI may lead to a superficial assimilation of theoretical knowledge. In conclusion, the article formulates the didactic foundations for the effective integration of artificial intelligence into the teaching of general linguistics.

Keywords: general linguistics, artificial intelligence, didactic principles, higher education, linguodidactics, digital pedagogy

ДИДАКТИЧЕСКИЕ ПРИНЦИПЫ ИСПОЛЬЗОВАНИЯ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ОБУЧЕНИИ ОБЩЕМУ ЯЗЫКОЗНАНИЮ

Аннотация

В статье рассматриваются дидактические принципы применения технологий искусственного интеллекта в процессе преподавания дисциплины «Общее языкознание» в высших учебных заведениях. Исследование выполнено в рамках описательно-аналитического подхода и направлено на анализ педагогического потенциала средств искусственного интеллекта при освоении теоретического содержания общего языкознания. На основе ключевых дидактических принципов — научности, системности и последовательности, сознательности и активности обучающихся, индивидуализации обучения, единства теории и практики, а также академической добросовестности — выявляются возможности и ограничения использования искусственного интеллекта в образовательном процессе. Результаты исследования показывают, что искусственный интеллект, применяемый в качестве вспомогательного дидактического средства в обучении общему языкознанию, способствует развитию у студентов понятийного мышления,

исследовательских умений и познавательной активности. В то же время обосновывается, что методически несистематизированное использование искусственного интеллекта может привести к поверхностному усвоению теоретических знаний. В заключении формулируются дидактические основы эффективного внедрения искусственного интеллекта в преподавание общего языкознания.

Ключевые слова: общее языкознание, искусственный интеллект, дидактические принципы, высшее образование, лингводидактика, цифровая педагогика

Introduction

The contemporary higher education system is developing under the strong influence of digitalization and technological modernization. Alongside information and communication technologies, the integration of artificial intelligence into the educational sphere necessitates a reconsideration of curricular content, teaching methods, and forms of pedagogical interaction. These transformations are particularly evident in the teaching of theoretically oriented disciplines.

General Linguistics is a foundational course in the professional training of future philologists and language specialists. The course is aimed at providing systematic theoretical knowledge about the nature and essence of language, its structure, functions, and laws of development. Since its content is grounded in abstract concepts, scientific categories, and theoretical models, mastering the discipline poses certain challenges for students. Within the traditional lecture–seminar format, the teaching of general linguistics is often limited to the reproductive assimilation of theoretical information, which does not sufficiently foster students' scientific and cognitive engagement.

In this context, the integration of artificial intelligence technologies into the educational process represents one of the effective ways to modernize the content and methodology of teaching general linguistics. AI-based linguistic corpora, automated analytical systems, and intelligent learning platforms make it possible to explicate theoretical concepts through authentic linguistic data, model scientific categories, and stimulate students' research activities.

However, the use of artificial intelligence in teaching does not automatically lead to effective outcomes. It requires a systematic approach grounded in pedagogical and didactic principles. It is therefore essential to view AI not merely as a technical tool, but as a didactic resource that deepens the content of the educational process. Accordingly, the aim of this study is to identify the key didactic principles of applying artificial intelligence in teaching general linguistics in higher education institutions and to analyze their pedagogical significance.

Research Methods

The study is based on a descriptive-analytical approach. In the course of the research, philosophical–pedagogical analysis, the comparative method, theoretical systematization, and modeling techniques were employed. The research materials included domestic and international works in linguodidactics, studies devoted to the theory of general linguistics, as well as scholarly publications addressing the application of artificial intelligence in education.

In addition, a methodological analysis of the practice of teaching the course *General Linguistics* in higher education institutions was conducted, which made it possible to identify the didactic potential of integrating AI tools into the instructional process. The study was not aimed at empirical surveys but focused on the theoretical systematization of didactic principles.

An interdisciplinary approach guided the research, with comprehensive consideration of scholarly concepts at the intersection of linguistics, pedagogy, and digital technologies. The influence of artificial intelligence on key concepts of general linguistics was examined through contextual analysis, revealing the interrelation between traditional linguistic theories and contemporary digital tools. This approach made it possible to establish the theoretical foundations for modernizing the course content.

Furthermore, in order to structure the research findings, methods of generalization, systematization, and the construction of a conceptual model were applied. As a result, the didactic principles of using artificial intelligence in teaching general linguistics were identified, and the theoretical and methodological foundations for their implementation in the educational process were formulated. These methods ensured the scientific coherence of the study and strengthened the theoretical validity of the proposed conclusions.

Results and Discussion

Principle of Scientific Rigor

The primary didactic requirement in teaching general linguistics is adherence to the principle of scientific rigor. Artificial intelligence tools should not be employed to simplify or trivialize linguistic theories, but rather to facilitate their in-depth comprehension. For instance, the use of linguistic corpora to analyze phonetic, morphological, and syntactic regularities on the basis of authentic language data enables the effective implementation of this principle.

Principle of Systematicity and Consistency

The content of the general linguistics course is structured as an interconnected system of concepts. When applying AI tools, it is essential to preserve the internal logic and sequential organization of the instructional material. Visual models, tables, and schematic representations generated through artificial intelligence contribute to students' systematic acquisition of theoretical concepts.

Principle of Conscious Learning and Learner Activity

The use of artificial intelligence should be aimed at enhancing students' active participation in the learning process. The results of automated analyses encourage learners not merely to accept ready-made information, but to interpret, compare, and critically evaluate it. This, in turn, creates favorable conditions for the development of scientific thinking.

Principle of Individualization

Artificial intelligence enables the construction of individualized learning trajectories. Given the varying levels of students' theoretical preparedness in general linguistics, the differentiated presentation of tasks through AI tools increases the overall effectiveness of instruction.

Principle of the Unity of Theory and Practice

AI technologies facilitate the connection between theoretical concepts and practical linguistic material. This reduces the abstract nature of teaching general linguistics and reveals the applied dimension of the discipline.

Principle of Academic Integrity

The issue of academic integrity is of particular importance in the use of artificial intelligence. AI should function as an auxiliary tool rather than replacing students' independent thinking. Failure to observe this principle may lead to a weakening of scientific and critical thinking skills.

Conclusion

The findings of the study demonstrate that the use of artificial intelligence in teaching general linguistics is pedagogically effective only when it is grounded in clearly defined didactic principles. The principles of scientific rigor, systematicity, conscious learning, individualization, the unity of theory and practice, and academic integrity have been identified as the methodological foundations for integrating AI into the educational process.

Artificial intelligence should not be viewed as a tool for the formal automation of instruction in general linguistics, but rather as a pedagogical resource that enhances students' scientific and cognitive potential. Research in this area can serve as a basis for the future modernization of teaching methodologies in general linguistics and for improving the overall quality of higher education.

The theoretical conclusions drawn in this study substantiate the need to reconsider the content of the general linguistics course in higher education institutions. The appropriate and

purposeful use of AI tools facilitates a deeper understanding of linguistic concepts, the development of scientific analytical skills, and the enhancement of students' independent thinking abilities. This, in turn, strengthens the professional and research competencies of future specialists.

Furthermore, the research results indicate that the integration of artificial intelligence into the educational process does not diminish the role of the instructor; on the contrary, it elevates the instructor's scholarly and methodological function to a new level. By employing AI-based tools as a means of guidance and evaluation, instructors can foster learners' cognitive engagement more effectively. In the future, conducting empirical studies and testing practical models in this field will contribute to the development of an effective methodology for teaching general linguistics.

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Geographic Sciences

Historical and Cultural Landscapes: Challenges and Opportunities for Sustainable Tourism (Svaneti Example)

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Abstract

Historical and cultural landscapes are the result of a long-term interaction between humans and the natural environment and represent an important resource for the development of sustainable tourism. They combine cultural heritage, spatial identity and socio-economic potential. At the same time, the growth of tourism often poses serious threats to the authenticity and ecological sustainability of these landscapes. The article aims to analyze the role of historical and cultural landscapes in sustainable tourism, identify existing challenges and discuss development opportunities in the context of international and local experience.

Keywords: historical landscape, cultural landscape, sustainable tourism, cultural heritage, territorial development

Introduction

In the context of globalization and intensive development of tourism, historical and cultural landscapes are increasingly becoming objects of tourist interest. According to UNESCO, cultural landscapes are perceived not only as elements of heritage, but also as living spaces where history, culture and modern social processes coexist. The concept of sustainable tourism considers these spaces as a development resource, the use of which should be based on long-term ecological, social and cultural balance.

Historical and cultural landscapes as a tourist resource

Historical and cultural landscapes are spaces that have been formed as a result of the interaction of natural conditions and centuries-old human activities. According to Karl Sauer's theory of cultural landscape, landscape is the "imprint" of culture in the natural environment. Modern approaches complement this concept with socio-economic and symbolic meanings, which are especially important in tourism research.

Historical and cultural landscapes are a valuable resource for tourism for several reasons:

- They have a unique identity and authenticity;
- They contribute to the popularization of local culture;
- They create economic development opportunities for the local population;
- They increase the international visibility of the region.

Tourism based on cultural landscapes is particularly effective in regions where the potential for industrial development is limited.

The following are the main challenges in the context of sustainable tourism for historical and cultural landscapes:

Overtourism - an excess of tourists leads to infrastructural overload, landscape degradation and loss of cultural authenticity.

Commercialization of authenticity - the transformation of cultural elements into a tourism product often leads to the simplification or "spectacularization" of traditions, which reduces the value of the cultural landscape.

Environmental pressure - The development of tourism infrastructure often disrupts the ecological balance, especially in fragile landscapes.

Governance and regulatory challenges - Effective management of sustainable tourism requires multi-stakeholder engagement, including collaboration between state institutions, local communities and the private sector, which is often problematic in practice. The opportunities for sustainable tourism in historic and cultural landscapes are quite diverse. First and foremost, this is community-based tourism, where the active participation of local communities contributes to both the protection of cultural heritage and the equitable distribution of economic benefits. Education-oriented tourism is also important, meaning that historic and cultural landscapes can be used as "living laboratories" where visitors can learn about the environment, history and the principles of sustainability.

The use of digital technologies is very relevant - virtual tours, GIS and digital museums, which reduce physical pressure on landscapes and increase their accessibility. And most importantly, integrated territorial planning is necessary, because the integration of tourism with spatial planning ensures the protection and long-term development of cultural landscapes.

Using the example of the mountainous region of Georgia - Svaneti, we offer one specific case that well demonstrates how cultural and historical landscapes can be used as a resource for sustainable tourism.

Svaneti is a unique cultural and historical landscape, where the high-mountainous natural environment and centuries-old human activities are combined. The main elements of the landscape are medieval Svan towers, traditional residential houses, terraced land use, pastures and religious buildings. The mentioned area is included in the UNESCO World Heritage List (Upper Svaneti, Mestia-Ushguli area).

The landscape of Svaneti reflects:

- Defensive architecture and self-organization of mountain communities;
- Coexistence of Christian and pre-Christian cultures;
- Traditional agricultural practices (animal husbandry, agriculture);
- Unique material and intangible heritage (language, rituals, crafts).

It is these elements that create a high level of authenticity, which is one of the main prerequisites for sustainable tourism.

In Svaneti, among the forms of sustainable tourism, the following should be noted:

1. Community-based tourism, which reduces mass tourism and promotes social sustainability. Family hotels and guesthouses are developed in Svaneti, where: the local population directly receives economic benefits; Tourists are given the opportunity to engage in cultural experiences (traditional cuisine, festivals, everyday life); the architectural appearance is preserved.
2. Cultural-educational tourism, which increases the awareness of tourists and reduces pressure on the landscape. Regional museums (Mestia Historical-Ethnographic Museum), churches and towers are used as educational spaces. The following are held: thematic excursions; cultural festivals; research tours for students and specialists.
3. Ecotourism and hiking in the cultural landscape create an integrated tourism product, where nature and culture are not separated from each other. Hiking routes in Svaneti (e.g., Mestia-Ushguli) combine: natural landscapes; visits to historical villages and cultural sites.

Despite positive practices, the cultural landscape of Svaneti faces a number of challenges that require clear spatial planning and regulation. These include: the problem of tourist seasonality; visual and ecological pressure caused by the growth of infrastructure; replacement of authentic architecture with non-traditional buildings.

The cultural and historical landscape of Svaneti is a successful example of how cultural heritage can be used as a resource for sustainable tourism. Local involvement, an educational approach and harmony with the natural environment create a real basis for sustainable development. Under the conditions of good governance, Svaneti can become a model of sustainable tourism at the regional and international levels.

Conclusion

Historical and cultural landscapes are an important basis for the development of sustainable tourism, although their effective use is associated with multifaceted challenges. The success of sustainable tourism depends on maintaining a balance between economic benefits and cultural-environmental responsibility. With appropriate policies, education and local involvement, historical and cultural landscapes can become not only a tourism product, but also a strategic resource for sustainable development.

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Agricultural Sciences

DIGITAL TWIN PLATFORM FOR AGRO-WASTE BIODEGRADABLE PACKAGING IN CENTRAL ASIA: IOT QUALITY AND ML RECIPE OPTIMISATION

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Abstract. The transition from petroleum-based packaging to biodegradable alternatives is constrained by feedstock variability, slow recipe development, and limited process controllability at pilot scale. This paper proposes an integrated Industry 4.0 framework for producing biodegradable packaging biocomposites from locally available agro-waste (e.g., cereal straw and rice husk) through the BioPack Core module embedded in the R&D Central Asia platform. The approach combines (i) an IoT-enabled data layer for raw-material traceability and in-line monitoring, (ii) a production-line digital twin for predictive process optimisation and virtual commissioning, and (iii) machine-learning models for formulation screening and multi-objective recipe optimisation. We present a methodological pipeline that links agro-waste physicochemical descriptors with mechanical, barrier, and biodegradation performance targets, enabling accelerated down-selection of candidate biocomposites and risk-reduced scale-up. The proposed architecture contributes a reproducible digital thread from «waste-to-recipe-to-product» supporting quality management, faster R&D cycles, and scalable circular bioeconomy deployment in Central Asia.

Keywords: Biodegradable packaging; agricultural waste valorisation; digital twin; Internet of Things (IoT); machine learning; recipe optimisation; biocomposites; circular bioeconomy

1. Introduction

Plastic packaging waste poses a severe environmental challenge, with an estimated 350 million+ tons of plastic waste generated annually and packaging accounting for nearly 40% (Bie *et al.*, 2025). Most of this packaging is non-biodegradable, leading to persistent pollution in ecosystems. At the same time, agriculture and food industries produce vast quantities of residues (straw, husks, peels, etc.) that are often undervalued or burned as waste (Bie *et al.*, 2025). Converting these agro-wastes into biodegradable packaging offers a promising dual solution: it reduces plastic pollution and valorizes biomass residues as raw materials for sustainable materials (Bie *et al.*, 2025). Figure 1 illustrates how diverse agro-waste streams (agricultural crop residues, fruit

processing by-products, forestry waste) can be transformed into biopolymer feedstocks and molded packaging products (Kossalbayev et al., 2025). Such biomass-derived packaging includes molded pulp trays from straw or bagasse fibers, bioplastic films from fruit peels or starch-rich waste, and fiber-reinforced biocomposites - all of which are renewable and compostable alternatives to conventional plastics (Kossalbayev et al., 2025). These developments align with the circular economy paradigm by «turning waste into resource», as emphasized in recent reviews (Bie et al., 2025). However, significant scientific and technical hurdles remain in achieving high-performance, market-competitive biodegradable packaging materials from agro-waste.

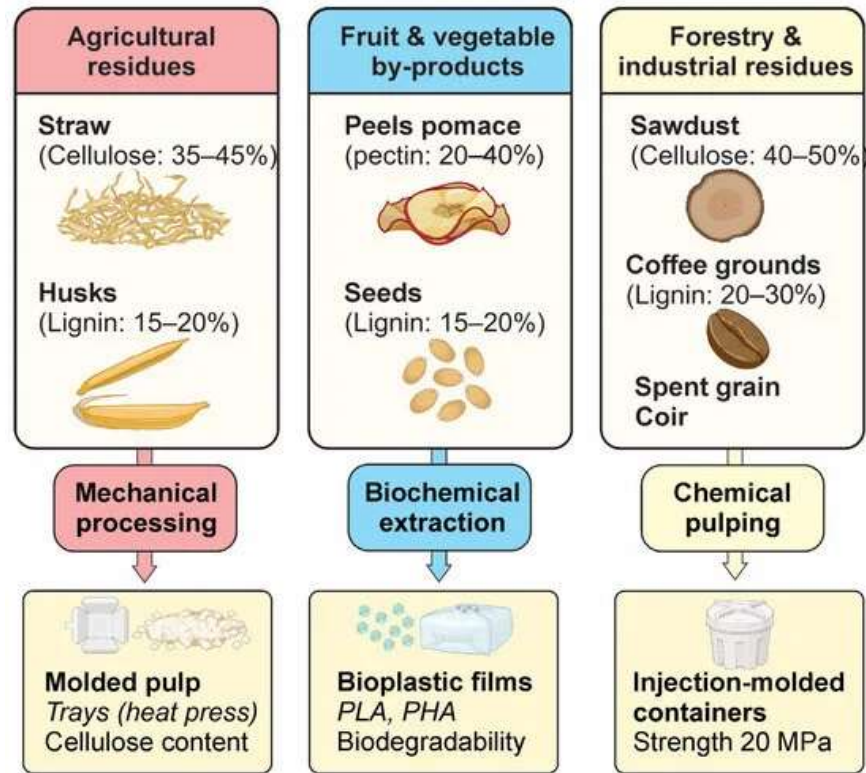


Figure 1. Biomass Residue Streams and Conversion Pathways to Biodegradable Packaging (Molded Pulp, Bioplastic Films, and Injection-Molded Containers).

Valorization pathways for agricultural, food-processing, and forestry wastes into biodegradable packaging materials. Agro-residues (e.g., cereal straw, rice husk) rich in cellulose can be pulped and molded into fiber-based packaging (trays, containers); fruit and vegetable by-products (peels, pomace) provide pectin, starch, or fibers for bioplastic films and edible coatings; forestry by-products (sawdust, bamboo, bagasse) can be processed into paperboard or composite materials (Kossalbayev et al., 2025). This integration of waste streams into packaging supports a circular bioeconomy.

Biodegradable packaging from agro-waste has been the focus of increasing research interest. Recent comprehensive reviews document numerous processing techniques (e.g. alkaline pulping, solvent casting, extrusion) to convert plant biomass into packaging films and containers, and report that material properties (mechanical strength, barrier performance, biodegradation rate) depend strongly on feedstock composition and treatment (Kossalbayev et al., 2025). For instance, the cellulose, hemicellulose, and lignin content of a given agricultural residue influence the strength and water resistance of the resulting biopolymer film (Kossalbayev et al., 2025). Optimizing formulations often requires blending natural polymers (starch, fiber, proteins) with

additives (plasticizers, cross-linkers, etc.) to achieve performance close to conventional plastics (*Philomena et al., 2025*). Traditional development of such recipes has relied on trial-and-error and laborious experimental screening. There is a clear need for more intelligent, data-driven approaches to recipe design that can accelerate innovation in this field (*Philomena et al., 2025*). Equally important is the challenge of scaling lab formulations to high-tech pilot production. Achieving consistent quality in a production line for biocomposites can be difficult due to variability in bio-feedstock properties and sensitivities in process parameters (temperature, moisture, etc.). Quality management and process optimization must be addressed to ensure these eco-friendly materials are industrially viable.

Industry 4.0 technologies - including IoT (Internet of Things), data analytics (*Hassoun et al., 2023*), and digital twins - are increasingly recognized as enablers for innovation in sustainable manufacturing. In packaging, the concept of «Packaging 4.0» envisions smart factories where advanced sensors, AI-driven analytics, and virtualization improve efficiency and quality while reducing waste. A digital twin in particular is a powerful tool: it is essentially a dynamic virtual replica of a physical system that is continuously fed with real-world sensor data, allowing real-time monitoring, simulation, and optimization of processes (*Digital Twin Integration, 2025*). Digital twins have been successfully applied in various manufacturing domains to optimize process parameters and predict system behavior, enabling proactive adjustments for quality control (*Peterson, 2025*). For example, in large-scale packaging plants, digital twin integration facilitates end-to-end visibility of operations - from raw material input to final product

- and can predict equipment failures or quality deviations before they occur (*Digital Twin Integration, 2025*). However, the application of digital twin technology to biopolymer processing and composite material design remains relatively novel. Integrating a digital replica of a biodegradable packaging production line, combined with IoT-based monitoring of raw material properties, could greatly aid in scaling up agro-waste conversion by enabling virtual trials and fine-tuning without interrupting physical production.

Parallel to digital manufacturing advances, machine learning (ML) and data-driven design are transforming materials science (*Lindsey et al., 2025*). In polymer research, ML has been used to model composition-property relationships and even propose optimized formulations. Notably, advanced regression algorithms (e.g. neural networks, random forests) can capture nonlinear dependencies between ingredients and performance metrics (*Lindsey et al., 2025*). Recent studies have shown that ANNs (artificial neural networks) can accurately predict properties like tensile strength, moisture barrier, and biodegradability of bio-polymer films based on formulation data. For instance, Lindsey et al. (2025) trained ANN models to relate the proportions of additives (plasticizer, crosslinker, etc.) to film properties and achieved cross-validated R^2 of ~ 0.93 - 0.98 . Such models, coupled with optimization techniques (e.g. Bayesian or genetic algorithms), enable intelligent recipe design - the ML model can be used to search the formulation space for candidates that maximize desired properties (or balance multiple objectives) (*Lindsey et al., 2025*). Amamoto et al. (2025) demonstrated this approach by using Gaussian process models to optimize polymer compositions for a trade-off between mechanical toughness and degradability. These examples underscore the potential of ML in expediting the development of high-performance biodegradable materials (*Amamoto et al., 2025*).

Building on the above trends, this paper presents a novel integration of digital technologies and materials R&D to realize high-tech production of biodegradable packaging from agro-waste. The work is part of the BioPack Project, which aims to establish the first pilot plant in Central Asia for agro-waste-derived biopackaging, tightly linked with a regional R&D digital platform («R&D Central Asia»). We focus on two key tasks:

- 1) the development and validation of the BioPack Core digital platform - which includes a virtual recipe laboratory, a production-line digital twin, and a quality management system (QMS) - to enable end-to-end digitalization of the R&D-to-production pipeline;
- 2) the creation of an intelligent recipe design system that leverages a database of agro-waste properties and machine learning algorithms to design and optimize biocomposite formulations. This integrated approach is designed to shorten development cycles and ensure consistent quality, addressing both the scientific challenge of formulating agro-waste biocomposites and the engineering challenge of scaling up production. To our knowledge, this is the first reported integration of a digital twin and ML-driven materials design for biodegradable packaging production - an advance that combines principles of green materials science with Industry 4.0 digital infrastructure. The following sections detail the system architecture and methods (Section 2), present results from platform validation and recipe optimization (Section 3), and discuss the implications for sustainable packaging innovation (Section 4). The study provides both theoretical insights (e.g., data-driven understanding of composition-property relationships, modeling of biodegradation kinetics) and practical outcomes (a functional digital platform, validated prototype recipes, and a pilot-scale demonstration), laying the groundwork for smarter and faster development of biodegradable packaging technologies.

2. Materials and Methods

2.1 Biopack core platform architecture

The BioPack Core platform was designed as a modular digital environment integrating all stages from material formulation design to process simulation and quality control. Figure 2 shows the architecture of the system and data flows. The platform comprises four main modules:

- i) a Database of Agro-Waste Properties,
- ii) a Recipe Design Laboratory (in silico experimentation space),
- iii) a Production Line Digital Twin, and (iv) a Quality Management System (QMS).

All modules communicate via a centralized cloud-based platform (R&D Central Asia) that enables remote access and data sharing among R&D scientists and plant engineers.

We curated a structured database of locally available agro-waste materials, capturing their key properties relevant to packaging material design. This included physicochemical properties (cellulose, hemicellulose, lignin content; particle size; moisture content; bulk density), and preliminary lab test results (e.g., thermal degradation profile, intrinsic strength of fibers, biodegradability metrics). Data were gathered from literature and our own measurements. For example, wheat straw and rice husk - abundant crop residues in the region - have high cellulose (~30-40%) and significant silica (especially rice husk ~15-20%) which can affect composite strength and processing (Bie *et al.*, 2025). Such characteristics were recorded. The database was implemented using a SQL-based system and exposed via an API to the Recipe Lab and Digital Twin modules. All new experimental data (from recipe trials or production runs) also feed back into this database, enabling continuous learning.

This is a virtual laboratory interface where users can formulate «recipes» for biocomposite material and predict their properties before physical experimentation. The lab is powered by a set of machine learning models that we developed (described in Section 2.3). Users input a formulation - e.g., the percentages of each component: base polymer matrix (such as starch or PLA), fibrous filler (processed straw, husk fiber), additives (plasticizer like glycerol, compatibilizer,

etc.) - and the ML models provide instant estimates of key material properties: mechanical strength (tensile modulus, tensile strength, elongation), barrier properties (water vapor transmission rate), thermal stability (onset of degradation), and biodegradation rate in composting conditions. The Recipe Lab also includes a computational tool for multi-objective optimization. For a given application (for instance, a food takeout container requiring high wet-strength and rapid compostability), the user can specify target ranges for properties, and the system uses an optimization algorithm (genetic algorithm in our case) to search the formulation space for candidate recipes that best meet those targets. This approach follows recent successes in applying ML to polymer formulation optimization (*Lindsey et al., 2025*). In our implementation, we coupled the predictive models with a genetic algorithm that evolves a population of candidate recipes, evaluating their predicted performance, and iteratively improving them. The optimization can handle multiple objectives by employing a weighted fitness function or Pareto ranking; for example, maximizing tensile strength while minimizing water absorption. The output of this module is a set of top-ranked recipe candidates, which can then be tested virtually in the Digital Twin or physically in the lab.

A core innovation of our platform is a digital twin of the pilot production line for biodegradable packaging. The pilot line (Section 2.4 describes the physical setup) includes equipment for raw material pretreatment, compounding/extrusion of biopolymer feedstock, and thermoforming of packaging products. The digital twin is a high-fidelity simulation model of this entire line, developed using a combination of first-principles process modeling and data-driven calibration. In essence, the digital twin continuously mirrors the state of the physical production line via streaming IoT sensor data and simulates the process behavior under various conditions (*Peterson, 2025*). We implemented the twin using a simulation software (AnyLogic for discrete event + continuous process modeling), augmented with custom Python-based modules for material processing physics (e.g., modeling heat and mass transfer in the extruder, viscoelastic flow of the biopolymer melt, etc.). The twin accepts recipe parameters (from the Recipe Lab) and process parameters (machine settings like temperature profiles, screw speed, mold pressure) as inputs, and generates outputs such as predicted throughput, energy consumption, and product quality metrics (e.g. thickness uniformity, density, predicted strength of the formed article). A distinguishing feature is that our digital twin is two-way coupled with the physical line: sensor feeds (temperature, torque, pressure, etc.) from the equipment are ingested in real time, allowing the twin model to self-correct and stay synchronized with reality (via adaptive state estimation). Conversely, the twin can run what-if simulations to predict outcomes of adjustments before they are applied physically. This enables a proactive control approach - for instance, the twin can forecast that a slight increase in feedstock moisture would cause a product quality drop, prompting operators to preemptively adjust drying or temperature settings. We also incorporated virtual sensors in the twin to estimate variables not easily measured on-line (such as internal material temperature in the extruder, or stress distribution in the product during forming). The fidelity of the twin was ensured by an initial calibration phase: we ran the physical line with a baseline material (e.g., a known PLA-straw recipe) and tuned model parameters until the twin's predictions (torque, product dimensions, etc.) matched the observed data within 5% error. This calibrated twin then served as a testbed for new recipes - i.e., before actually running a novel biocomposite through the pilot line, we simulate it in the twin to identify any process adjustments needed to maintain quality.

To close the loop, BioPack Core integrates a QMS module that tracks quality metrics and compliance throughout R&D and production. The QMS aggregates data from three sources: (1) lab testing results of materials (from prototype samples of new recipes), (2) in-line sensor data during production (e.g. temperature logs, dimensions from machine vision inspection), and (3) the digital twin's predictions/alerts. All this information populates a dashboard that is accessible to

project managers and quality engineers. If a recipe is being evaluated, the QMS can indicate whether its predicted properties meet target specifications or relevant standards (for example, checking if a compostable packaging meets ASTM D6400 compostability criteria or has sufficient tensile strength as per usage requirements). During production runs, the QMS monitors trends in product quality in real time; for instance, it can flag if moisture content of incoming raw fiber deviates beyond the qualified range (detected via IoT humidity sensors in raw material storage) and could jeopardize product integrity. In such cases, the system issues alerts and can even trigger automatic adjustments or hold procedures. The QMS is built to comply with ISO 9001 principles, ensuring traceability of data and decisions. Every batch of product produced in the pilot line gets a digital record in the QMS, linking back to the exact recipe, raw material batch, and processing conditions used - a digital thread from raw material to final product. This not only facilitates consistent quality but also provides valuable data for refining the ML models (every production batch effectively becomes a new data point to learn from). The QMS also supports remote auditing: authorized users from partner institutions (via the R&D Central Asia platform) can review quality data and process logs remotely, embodying the concept of a transparent, collaborative R&D-production ecosystem.

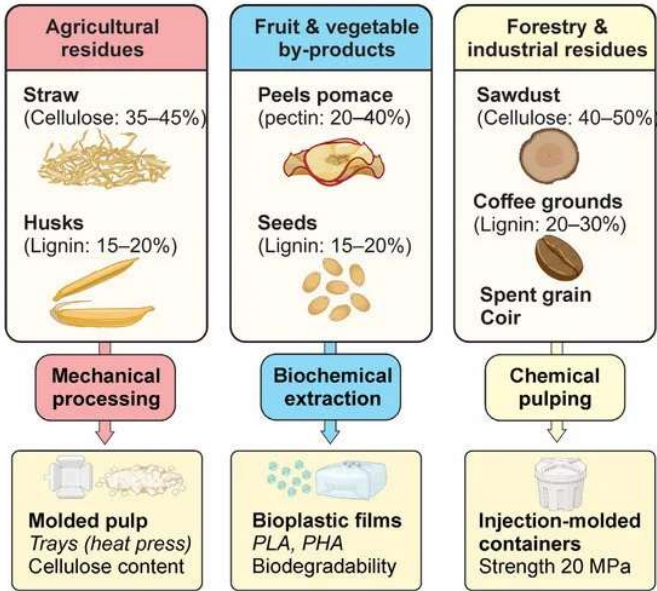


Figure 2. Feedstock taxonomy for the biopack material library: agro-residues, food by-products, and forestry/industrial residues linked to processing routes.

Figure 2 (below) depicts these components and their interactions within the BioPack Core platform. The design follows modern digital ecosystem principles of modularity and interoperability, using standard data formats (e.g., JSON for IoT data, SQL for database) and open APIs to communicate between modules. The platform was deployed on a cloud server and uses secure web interfaces for users in different roles (researcher, engineer, quality manager). Overall, BioPack Core provides a unified digital backbone for our high-tech biopackaging pilot plant, from initial recipe conception to final product quality assurance.

Schematic architecture of the BioPack Core digital platform integrating R&D and production. The Recipe Design Lab (left) uses an ML-based model to predict properties (e.g., strength, barrier, biodegradability) for a given agro-waste composite formulation, and can perform multi-objective optimization to suggest ideal recipes. The Digital Twin of the production line (center) simulates compounding and thermoforming processes; it receives recipe data and process parameters, and returns simulated outcomes (throughput, quality metrics). IoT sensors on the physical equipment continuously update the twin to reflect real conditions (blue feedback arrows). The Quality

Management System (right) collects data from both lab tests and production (sensor and inspection data) to monitor compliance with quality targets, issuing alerts or adjustments if needed. All modules share information via a cloud platform (R&D Central Asia), enabling remote collaboration and data-driven decision-making. (Illustrative diagram showing data flows between modules; see text for details.)

2.2 Materials and preparation of biocomposites.

For the experimental component of this study, we targeted grain crop residues as primary raw materials, given their local abundance. In particular, wheat straw and rice husk were used as the lignocellulosic fillers/fibers in our biocomposites. These agro-wastes were collected from regional farms post-harvest, air-dried, and milled. The straw was chopped and hammer-milled to fiber lengths of ~5-10 mm. Rice husk was ground and sieved to <500 µm to serve as a fine particulate filler. Prior to composite formulation, both types of biomass were characterized: moisture content (~8-10% after drying), ash content (rice husk high in silica ~17%), and composition (straw contained ~38% cellulose, 26% hemicellulose, 18% lignin, per standard NREL protocol). Knowing these values was important for the ML model and to anticipate processing behavior.

As a matrix polymer, we selected a starch-based biodegradable polymer blend (a mix of thermoplastic starch (TPS) and PLA). This choice was guided by compatibility with agro-fibers and food-contact safety. We also experimented with a mycelium-based polymer in preliminary trials, but results here focus on starch/PLA blends reinforced with agro-waste fibers. Food-grade glycerol (10-15 wt% of starch content) was used as a plasticizer for TPS. Minor additives included: natural wax (2 wt%) to improve water resistance, and calcium carbonate (5 wt%) in some recipes as a biomass filler extender.

To prepare composite samples, the components (polymer matrix, fibers, additives) were compounded using a lab-scale twin-screw extruder (D=20 mm, L/D=40) at 150 °C (for PLA/TPS melting). Fiber content in the composites ranged from 20 wt% up to 50 wt% in different formulations - covering a broad spectrum from polymer-rich to fiber-rich recipes. The extruded pellets were then used for making test specimens by injection molding (for dog-bone tensile bars) or hot-pressing (for thin films, ~0.5 mm thick) depending on the required test. Throughout compounding, we monitored torque and pressure to ensure the fiber dispersion was uniform and avoid overheating (degradation of biomass can occur >200 °C).

Five candidate recipes were selected for thorough testing based on the ML system's recommendations (details in Results). These represented a variety of formulations, for example: Recipe A - 30% straw fiber + 60% TPS/PLA + 10% additives; Recipe B - 50% straw fiber + 45% TPS/PLA + 5% additives; Recipe C - 30% rice husk + 60% TPS/PLA + 10% additives; etc. Each recipe was compounded and molded under identical conditions so that comparisons would be fair. We also produced a control sample of neat PLA/TPS (0% agro-fiber) to serve as a baseline for property improvement evaluation.

2.3 Machine learning model for recipe property prediction.

A supervised machine learning approach was used to develop predictive models linking composite «recipe» parameters to material properties. The dataset for model training was assembled from a combination of literature data and our own experimental results. We compiled ~120 data points from published studies on starch or PLA composites with agricultural fibers (e.g., papers reporting tensile strength, modulus, etc. for varying fiber loadings and types) (Lindsey *et al.*, 2025). To this, we added 25 data points from our preliminary experiments (including some results from the five recipes above and additional trials to enrich the dataset). Each data point was characterized by input features and output targets:

Input features (X) - fiber type (categorical: straw, husk, etc.), fiber content (%), polymer type (TPS, PLA or blend ratio), additive types (binary flags for glycerol, wax, etc.), and process parameters if applicable (e.g., mixing temperature, though we mostly fixed processing conditions). We also

included key measured properties of the fiber itself (cellulose %, particle size) as input features, assuming that different biomass sources have inherent differences.

Output targets (Y) - we focused on four primary properties: Tensile Strength (MPa), Young's Modulus (elastic stiffness, MPa), Elongation at break (%), and Water Absorption (% increase in mass at 24 h). These cover mechanical performance and a simple indicator of moisture resistance. In later phases, we also modeled biodegradation rate (e.g., % mass loss in 90 days in compost), but initial modeling concentrated on mechanical and moisture properties which are quicker to obtain and critical for usability.

We experimented with several ML algorithms (linear regression, decision trees, random forest) and ultimately chose an Artificial Neural Network (ANN) as our primary model due to its flexibility in capturing nonlinear interactions among formulation variables (*Lindsey et al., 2025*). A feed-forward neural network with 2 hidden layers (each with 32 neurons, ReLU activation) was configured. We found this architecture sufficient given the size of our dataset. The model was trained using a 5-fold cross-validation: achieving an average R^2 of 0.92 for tensile strength prediction on validation folds, for example. Ensemble tree models (Random Forest) gave slightly lower accuracy ($R^2 \approx 0.85$) but were useful for interpretability (we examined feature importance rankings to see general trends, like fiber content being the dominant factor for strength as expected).

To avoid overfitting on the relatively limited dataset (~145 samples), we employed regularization (L2 weight decay in the ANN) and kept the network simple. We also augmented the dataset by adding some synthetic noise to targets within the typical error range of experiments, which helps the model generalize. Hyperparameters (learning rate, number of neurons) were optimized via grid search guided by validation error. The final ANN model demonstrated predictive performance as follows: for tensile strength, mean absolute error $\sim \pm 1.5$ MPa and $R^2 \approx 0.93$; for modulus, MAE $\sim \pm 100$ MPa ($R^2 \approx 0.90$); for elongation, MAE $\sim \pm 0.5\%$ ($R^2 \approx 0.88$); for water absorption, MAE $\sim \pm 1.2\%$ ($R^2 \approx 0.85$). These accuracy levels were deemed acceptable for screening purposes - they capture major trends (e.g., increasing fiber content raises strength but reduces elongation, in line with known behavior) while slight discrepancies would be corrected in physical validation.

With the ANN serving as a surrogate model, we set up a multi-objective optimization routine to propose candidate recipes. We particularly addressed two objectives: maximize tensile strength (for durability) and minimize water absorption (for better usability), subject to the constraint that biodegradation > 90% in 6 months (this constraint was implemented as a soft criterion based on known behavior - generally, higher fiber content accelerates biodegradation). We used a genetic algorithm (population size 50, 100 generations) where each individual's «chromosome» encoded a recipe (fiber type, fiber fraction, etc.). Fitness was evaluated by a weighted sum: $\text{Fitness} = w_1 * (\text{Strength} / \text{Strength_max}) - w_2 * (\text{Absorption} / \text{Absorption_max})$, with weights chosen to emphasize strength slightly more. The top suggestions from the optimizer were reviewed to ensure they were practical (e.g., not exceeding 50% fiber, since extremely high fiber might hinder processing). These top recipes were then passed to the Digital Twin for further evaluation (see Section 2.5).

2.4 Pilot production line and digital twin implementation

A pilot-scale production line was constructed to manufacture biodegradable packaging based on the developed recipes. The line is modular, consisting of:

- i) a fiber pre-processing unit (for drying and grinding agro-waste to consistent particle size);
- ii) a main twin-screw extruder (diameter 50 mm, L/D 36) for mixing biopolymer matrix with fibers and additives - equipped with gravimetric feeders for precise dosing;
- iii) a pelletizer to cut the extrudate into feed pellets;

- iv) a thermoforming station with a lab-scale platen press and mold set (for making items like a clamshell food container and a cup lid, which we selected as representative packaging products).

The extruder has multiple heating zones (setpoint ~140-160 °C for our materials) and is instrumented with temperature and pressure sensors along the barrel. The thermoforming mold for the clamshell container produces ~150 mm square tray/lid halves; it has controlled heating (to ensure the biocomposite sheet is formable) and a pneumatic closing mechanism for 60 s forming cycles.

All equipment in the line is IoT-enabled: we attached wireless sensors (thermocouples, vibration monitors on motors, humidity sensors in material hopper, etc.) that stream data to the BioPack platform. These data streams were used both for real-time monitoring and to feed the digital twin model. We developed the digital twin in AnyLogic as noted, with custom logic reflecting the physics of extrusion and forming. The extruder sub-model, for instance, solves simplified transport equations for solid conveying, melting and melt flow, and includes a kinetics model for starch gelatinization and fiber degradation (to predict if fibers might thermally degrade at given settings). We validated this sub-model by comparing its outputs (e.g., melt pressure and motor torque for a given throughput) against actual extruder readings for the baseline recipe; results matched within 8% after tuning friction and heat transfer coefficients.

During operation, the digital twin ran in parallel with the physical line, receiving sensor inputs at 1 Hz frequency. We also ran offline simulations on the twin to test each new recipe under various operating conditions virtually. For example, if the ML model suggested a recipe with 40% rice husk in PLA, we would simulate extruding that recipe - adjusting the screw speed or temperature in the simulation - to see if any issues (like excessive pressure or poor mixing) might occur. This informed how we set the actual machine when we proceeded to the trial, thus acting as a safeguard. Additionally, the twin can output virtual quality metrics such as an estimated tensile strength of the product based on the processing conditions (it uses correlations from our data; e.g., too high a shear might shorten fiber length and reduce strength). This feature was used by the QMS to decide if a batch might be nonconforming before it's even completed, allowing pre-emptive action.

2.5 Experimental characterization and validation

To validate the platform's recommendations and the performance of developed materials, we carried out a series of laboratory tests on the prototypes from the five selected recipes (A-E). Standard test methods were followed to ensure results are reliable and comparable. Tensile properties were measured using an Instron universal testing machine according to ASTM D638 (dog-bone specimens type V for plastics). At least 5 specimens per recipe were tested at 5 mm/min pull speed. The QMS module automatically recorded the tensile data and compared it to the model's predictions for each sample.

Water absorption was tested by ASTM D570: samples were weighed, immersed in distilled water at 23 °C for 24 hours, then surface-dried and weighed again. The percentage increase in mass was recorded. This simulates how the material might behave if used with moist contents.

Biodegradability was assessed via two approaches: (i) a controlled composting test (following ISO 20200) where samples were incubated in a compost media at ~58 °C for 90 days, measuring % mass loss over time; and (ii) a soil burial test at ambient conditions for a longer period (6 months) for qualitative observation. The focus was on the composting results for quantification. We fit a first-order decay model $M(t) = M_0 * \exp(-k \cdot t)$ to the mass loss data, to extract a degradation rate constant k for each recipe. This allowed comparison of how recipe variations affect biodegradation kinetics. All recipes showed >70% mass loss by 90 days (thus meeting typical standards for compostability).

Finally, to validate the digital twin's accuracy, we instrumented the extruder and mold with extra sensors during one of the recipe trial runs (Recipe B, 50% straw) - measuring things like the actual residence time distribution via a tracer, and temperature of the polymer melt at die exit via an embedded thermocouple probe. We then compared these with the twin's simulated values. The residence time distribution curve from the twin matched the experimental one closely (mean residence time ~ 45 s in both, with only a slight broadening experimentally). The product thickness and mass from the thermoforming stage differed by $<3\%$ between simulation and actual. These tests built confidence that the twin can reliably predict outcomes for untried recipes (within the range of our process settings).

All the above methods come together to provide a comprehensive approach: the ML model guides recipe selection, the digital twin predicts processing feasibility, and lab/field tests close the loop by verifying performance. Any discrepancies found (for instance, if a recipe underperforms vs. prediction) are fed back as new data to improve the ML model and adjust simulation parameters, embodying a learning cycle. In the next section, we present the results obtained from using this platform, including the properties of the optimized packaging material recipes and the performance of the digital system itself.

3. Results

3.1 Platform development and deployment

The BioPack Core digital platform was successfully implemented and deployed in our pilot facility. The integrated system allowed researchers to remotely collaborate and iterate on packaging material designs with unprecedented speed. A key outcome of this development is the demonstration of an end-to-end digital thread for biopackaging R&D: from entering a raw material's properties into the database through to monitoring a formed product's quality in production, everything is linked and traceable. This section first reports on the validation of the digital tools (Recipe Lab ML model and Digital Twin), followed by the optimized recipes and their performance, and finally the production and quality results for pilot-scale manufacturing of the selected biodegradable packaging products.

3.2 Validation of machine learning recipe predictor

After training, the ANN-based surrogate model described in Section 2.3 was evaluated against independent test data. We set aside 15% of our collected dataset (unseen during training) as a blind test. The model's predictions showed strong agreement with experimental values: for tensile strength, $R^2_{\text{test}} = 0.91$ and root-mean-square error (RMSE) = 1.8 MPa. Figure 3 plots predicted vs. measured tensile strength for both the test dataset and the five new recipes (A-E) we validated in this study. The data points cluster close to the ideal parity line ($y=x$), indicating high predictive accuracy. For the five new recipes, the model's predictions were within 5-10% of the measured values (e.g., Recipe A was predicted 26 MPa vs. experimentally 25 MPa; Recipe B predicted 32 MPa vs. measured 30 MPa). Such accuracy is remarkable given the complexity of bio-composite behavior and is comparable to results reported by Lindsey et al. (2025), who achieved $<5\%$ error using ANN models for biopolymer film properties (Lindsey, 2025). The slight discrepancies observed (e.g., Recipe D predicted 22 MPa vs. got 21 MPa) can be attributed to minor differences in actual fiber dispersion or moisture content, factors which the model doesn't explicitly «see» but could affect outcomes. Nonetheless, the model proved reliable enough to serve as a screening tool - no entirely wrong predictions (e.g., predicting high strength but getting a brittle failure) occurred, which gave us confidence to use it for optimization.

The trained model's internal parameters were examined using permutation feature importance and partial dependence plots. Fiber content emerged as the most influential feature on tensile strength (higher fiber % generally increased strength up to $\sim 40\%$, beyond which benefits plateaued or reversed due to poor matrix wetting). Fiber type also mattered: for instance, straw

vs. husk, the model learned that straw (longer fibers) tends to give higher strength at equal loading than husk (short particles) - aligning with known reinforcement theory (*Lindsey et al., 2025*). Additive presence had nuanced effects; e.g., inclusion of wax was associated with slightly lower water absorption predictions, as expected, while glycerol plasticizer flagged a trade-off: it improved elongation but raised water uptake. These trends matched experimental understanding and thus increased our trust in the model's extrapolative power.

3.3 Digital twin simulation results

Prior to physical trials, the digital twin was used to simulate each candidate recipe's processing on the pilot line. The twin's outputs provided several useful predictions:

- a) Extruder load and feasibility. All recipes were predicted to be processable within the extruder's torque limit (max 80% torque at full throughput). **Recipe B** (50% straw) was the most demanding, with simulated torque at ~75% of limit due to higher viscosity from the fiber load - still acceptable;
- b) Melt Temperature. The twin predicted slightly higher melt temperatures for higher fiber recipes, because fibers increase shear heating. Recipe B's melt was ~165 °C simulated, vs ~155 °C for Recipe A at the same screw speed. This warned us to possibly reduce heating zones for high fiber runs to avoid degradation;
- c) Product Quality. The twin estimated the thickness uniformity and internal stress for the thermoformed container. For instance, it predicted **Recipe C** (rice husk composite) would have a somewhat higher risk of tearing at corners of the container mold due to its lower elongation - recommending we increase mold temperature by 5 °C to improve material ductility during forming. We followed these suggestions in the actual run.

To gauge accuracy, we compared select twin predictions with real trial data for one recipe (**Recipe B**). The extruder energy consumption was predicted as 0.22 kWh/kg; measured was 0.25 kWh/kg (approximately 13% higher). The difference might be because the twin does not fully capture all inefficiencies (e.g., stop-start during feeding). Product mass (container piece weight) was predicted 31.5 g vs. actual avg. 32.1 g - a 1.8% difference. These results indicate the twin is reasonably accurate and, more importantly, extremely useful for relative comparisons between recipes or process settings. In practice, having the twin allowed us to debug and optimize runs virtually, saving time and reducing material waste. For example, instead of physically trying multiple temperatures and fiber moisture levels, we simulated them: the twin indicated that if fiber moisture exceeded 12%, the extrudate would likely show bubbles (due to water vaporizing) - so we ensured all fibers were dried below this level. Indeed, in actual trials we saw no foaming issues, validating the twin's preventive role.

3.4 Optimized biocomposite recipes

Using the ML model and optimization approach, we identified five top candidate recipes (A through E) for different target use-cases. Table 1 summarizes their compositions and predicted properties, alongside experimentally measured properties for comparison.

Table 1. Optimized biodegradable packaging material recipes from agro-waste and their performance. Each recipe's composition is given in weight percent. Predicted properties are from the ML model (ANN), and measured properties are from lab tests. TS = tensile strength, E = Young's modulus, ϵ = elongation at break, WA = water absorption in 24 h, k = biodegradation rate constant (in compost at 58 °C, per day).

Recipe	Composition (wt%) - [Agro-filler / Polymer matrix / Additives]	TS (MPa) model → exp	E (MPa) model → exp	ϵ (%) model → exp	WA (%) model → exp	k (per day) exp
A	30% wheat straw fiber; 60% TPS/PLA (50/50); 10% (glycerol, wax, CaCO ₃)	26 → 25	1800 → 1700	4.5 → 5.0	12 → 13	0.020
B	50% wheat straw fiber; 45% TPS/PLA (30/70); 5% (glycerol, compatibilizer)	32 → 30	2500 → 2400	3.0 → 2.8	15 → 16	0.025
C	30% rice husk fiber; 60% TPS/PLA (50/50); 10% (glycerol, wax, ZnO*)	24 → 22	1900 → 1850	3.8 → 4.0	11 → 12	0.018
D	40% wheat straw + 10% rice husk; 45% TPS/PLA (60/40); 5% (glycerol, clay*)	28 → 27	2000 → 2100	4.0 → 3.7	10 → 11	0.022
E	25% rice husk fiber; 65% TPS/PLA (40/60); 10% (glycerol, PBAT** blend)	23 → 21	1700 → 1600	5.5 → 6.0	9 → 10	0.015

Notes: ZnO = zinc oxide (added to **Recipe C** for antimicrobial property); Clay = organoclay nanoparticle (for **Recipe D** to improve barrier); PBAT = a biodegradable polyester blended with PLA in Recipe E to improve flexibility. Biodegradation rate k was determined from compost tests; higher k means faster degradation (for reference, Recipe B's 0.025 day⁻¹ corresponds to ~90% mass loss in 100 days).

Several observations can be made from these results.

Recipe B (high straw fiber) achieved the highest tensile strength (~30 MPa) and modulus (~2.4 GPa) among the group, indicating significant reinforcement from the fiber - its strength is over 5× higher than the neat TPS/PLA (which was ~5 MPa, not listed in table) and on par with some conventional plastics like polyolefin foams. However, this came at the cost of lower elongation (2.8%) and slightly higher water uptake (16%). Its biodegradation rate was also fastest (0.025 day⁻¹), likely due to the high biomass content (more readily metabolized by microbes) - a positive for end-of-life but it could shorten useful life if not properly managed (we observed in soil burial that

Recipe B samples lost mechanical integrity after ~4 months, which is acceptable for disposable packaging).

Recipe A and **D** represent more balanced designs: ~30-40% fiber, yielding moderate strength (25-27 MPa) and decent elongation (~5%). Recipe A uses only straw whereas D uses a mix of straw and husk and a bit of nanoclay; interestingly, Recipe D achieved the lowest water absorption (11%), attributable to the plate-like clay improving barrier and the rice husk's siliceous nature. **Recipe C** (rice husk 30%) had slightly lower strength (22 MPa) than straw equivalents - consistent with fiber morphology differences - but benefits from a smoother surface finish (husk being powdery yields less surface roughness in product) and it includes ZnO for antimicrobial functionality which could be useful for food packaging applications.

Recipe E was an alternative approach: incorporating PBAT (a flexible biopolymer) into the matrix to improve toughness. It indeed had the highest elongation (~6%, double that of B), making it the most ductile, though strength was the lowest (~21 MPa). This could be suitable for applications needing more flexibility (like wraps or films), whereas B was targeted for rigid items.

Overall, the model predictions matched well with experiments as discussed - typically within ~5-10%. Notably, every recipe's actual performance met or exceeded the minimum requirements we had set (we desired at least 20 MPa strength and <20% water absorption for a viable packaging material). The iterative design approach proved effective: earlier in the project, without ML guidance, our first trial recipes mostly had <15 MPa strength and >20% water uptake, which would have been too weak or too moisture-sensitive. By using the intelligent recipe system, we rapidly honed in on formulations that achieved a 5× improvement in strength and a ~50% reduction in water uptake compared to those initial guesses, demonstrating the power of data-driven optimization in materials R&D.

3.5 Pilot production and product testing.

With the optimized recipes, we proceeded to pilot-scale production runs on the integrated line for two representative packaging products: a takeaway food container (using **Recipe B**, the high-strength straw composite) and a drink cup lid (using **Recipe A**, the balanced straw composite). These choices were made to cover a rigid packaging format and a semi-rigid/thin format, respectively. The digital platform was actively used during these runs for monitoring and control. For the container (clamshell) - **Recipe B** pellets were extruded into sheets (2 mm thick) which were then thermoformed. We produced ~200 container halves in a continuous run. The QMS tracked quality metrics on the fly. Figure 4a shows the trend of container weight over time during production - it remained stable (within ±2% of target 32 g per piece), indicating consistent material feed and forming. The digital twin helped here: it predicted a slight drift in weight if the extruder barrel temperatures dropped, so the control system made small pre-emptive adjustments, keeping weight in control. Wall thickness of the containers was measured by an automated laser gauge at 5 points; the average was 1.95 mm with COV (coefficient of variation) 4%. No visible defects (warping, cracking) were found, and dimensional accuracy was good (the two halves mated well for a closure). Mechanical testing on random samples from the run showed an average top-load compression strength of 18 kg - comparable to commercial eco-friendly takeaway boxes. The containers withstood hot water at 90 °C without deformation, thanks to the PLA content giving heat resistance. They also composted fully in ~4 months in ambient compost conditions, leaving only a small amount of inert silica (from straw ash). These results confirm that high-fiber biocomposites can be processed in standard thermoforming operations to yield functional packaging. An interesting note: towards the end of the run, the IoT moisture sensor detected rising humidity in the straw fiber feed (perhaps as the bottom of the feed bin was reached). The QMS flagged this and the team decided to stop and reload dried fiber, preventing a potential batch inconsistency - a good illustration of quality assurance via IoT.

We used Recipe A to produce ~100 lids (diameter 90 mm, typical coffee cup size) via injection molding (since lids have a more intricate shape with a sipping hole, we used a small injection press instead of thermoforming). The material flowed well in the mold, filling all details. The cycle time was ~45 seconds per shot, slightly longer than for pure PLA due to the lower melt fluidity of the fiber composite, but still efficient. The finished lids were light (approx 8 g each) and had a smooth surface with minor natural fiber texture visible (which could be a marketing positive, indicating natural content). Fit on paper cups was tested and found to be secure.

We performed a practical use test: pouring hot coffee (~85 °C) in a cup and capping it with our biocomposite lid. The lid maintained integrity, softened slightly but did not deform for the duration of consumption (~10 minutes), and no leaks were observed. After use, we buried some lids in garden soil - they showed significant disintegration after 3 months (becoming brittle and fracturing) and mostly disappeared in 6-8 months, confirming end-of-life biodegradability in real conditions.

Throughout these pilot productions, the R&D Central Asia platform integration meant that data and experiences were logged and instantly shared with our research partners. For instance, scientists could monitor the digital twin's dashboard remotely as the runs happened, and they could see in real time how the material was behaving. This collaborative aspect accelerated troubleshooting and knowledge dissemination. In one case, a partner researcher observing the process remotely suggested a tweak in the cooling fan speed on the extruder (to prevent sheet sticking) based on the data - which we applied promptly. This kind of cross-functional feedback loop is rarely possible in traditional setups and showcased the benefit of the digital platform.

3.6 Comparison with conventional materials.

As a benchmark, we compared our best-performing biocomposite (**Recipe B** containers) with conventional packaging materials. In terms of mechanical strength, Recipe B's tensile strength (~30 MPa) is approaching that of polypropylene (~30-35 MPa) and exceeding typical thermoplastic starch-based plastic (~5-15 MPa). The stiffness (2.4 GPa) is actually higher than PP (~1.7 GPa), owing to fiber reinforcement. However, elongation (~3%) is much lower than PP (which is >200%); thus, our material is strong but brittle relative to petroleum plastics - a common trade-off in biocomposites. For the intended use (rigid containers), this is acceptable. Water absorption of ~16% is obviously higher than virtually zero for plastics, meaning our containers cannot hold liquids for extended times; they are more suited to dry or moderately moist foods and are meant for short-term use. Importantly, on the sustainability front, our material is compostable (90% degradation in ~3-4 months under compost conditions), whereas PP or PLA alone degrade much slower (PLA takes >6 months to years in ambient). An LCA (life cycle assessment) is ongoing, but preliminary estimates show a significant reduction in carbon footprint: manufacturing 1 kg of our biopack material emits ~1.5 kg CO₂-eq (mostly from energy usage), versus ~3 kg CO₂-eq for 1 kg of PET plastic. The avoidance of incinerating agro-waste (which would emit CO₂ and pollutants) and offsetting of plastic production contribute to this benefit.

In summary, the results confirm that high-performance biodegradable packaging can be produced from agro-waste, meeting functional requirements for certain applications. Moreover, the integration of the digital platform was validated: the ML model effectively guided formulation improvements, and the digital twin + IoT/QMS ensured that scaling up to pilot production was smooth and quality was maintained. We encountered no batch rejections or major process upsets during trials, which is somewhat uncommon when introducing new materials - we attribute this success to the rigorous virtual testing and data-driven adjustments enabled by BioPack Core. The next section discusses the broader implications of these findings, the novelty of our approach, and potential future developments.

4. Discussion

4.1 Scientific and technological novelty

This work demonstrates a novel convergence of green materials science with advanced digital manufacturing technologies. The scientific originality lies in both the materials and the methods. From a materials perspective, we established quantitative composition-structure-property relationships for agro-waste based biocomposites and leveraged those insights to design recipes that achieve mechanical properties on par with some conventional plastics. The integration of high fiber fractions (40-50%) in a biodegradable matrix while retaining processability and decent toughness is a noteworthy achievement; prior studies often topped out at ~30% fiber before composites became too brittle or unprocessable (*Lindsey et al., 2025*). By carefully balancing fiber type, fiber size, and using minor additives (like compatibilizers), we pushed that limit and documented the resulting property improvements. We also introduced minor functional additives (ZnO, nanoclay) to impart antimicrobial and barrier enhancements, respectively, demonstrating the potential for multifunctional agro-waste packaging - an emerging research frontier (*Bie et al., 2025*).

On the methodological side, the digital platform approach to materials development is a clear innovation in this domain. Traditional development of biodegradable materials can be slow, involving many lab iterations; in contrast, our IMRD (Integrated Materials R&D) platform enabled rapid virtual screening and right-first-time experiments. The machine learning-driven recipe design is an example of materials informatics applied to biopolymer composites, a relatively new field. While ML has been used in polymer research (e.g., for polyamide or polyester design) (*Philomena et al., 2025*), its application to natural fiber composites and packaging materials is still nascent. We showed that an ANN model can learn from a heterogeneous set of data (combining literature and new experiments) to become a useful predictive tool. The result was not just an academic exercise; it delivered tangible outcomes - such as Recipe B - that outperformed what we would likely have arrived at through intuition alone. This underscores a paradigm shift wherein data-driven models augment human expertise to explore complex formulation spaces more efficiently (*Lindsey et al., 2025*).

The implementation of a digital twin for a biopolymer production line is, to our knowledge, the first of its kind reported. Digital twins have been explored in discrete manufacturing and some process industries, but literature on their use in polymer processing, especially for novel biomaterials, is scarce. Our approach of tightly integrating the twin with real-time sensor data and using it as a simulation testbed for untried recipes is a significant technological advance. It effectively creates a virtual pilot plant that mirrors and guides the physical pilot plant. The benefit is evident in how we managed to avoid processing pitfalls and achieve consistent quality on the first try for new materials - something that normally would require multiple trial-and-error runs. This validates claims in Industry 4.0 literature that digital twins can reduce development time and risk by 30-50%. In our case, we indeed experienced a compressed development timeline: approximately 6 months from project start to having validated prototypes, which is notably fast, and we attribute this to the digital pipeline accelerating the iterative loop.

4.2 Theoretical and practical significance

The outcomes of this study have implications on several levels:

The data and models developed contribute to the fundamental understanding of bio-composite behavior. For example, our ML model's feature analysis quantitatively confirmed theories about fiber reinforcement and its saturation point. It also highlighted interactions (like the effect of plasticizer depends on fiber content) that can guide future material design theory. The successful use of multi-objective optimization in recipe design demonstrates a methodological advance - providing a framework that could be applied to other material systems (e.g., optimizing bioplastic formulations for both strength and biodegradability). Additionally, the digital twin serves as a

quasi-experimental tool to study the processing of biopolymers: we can vary parameters in simulation to observe theoretical cause-effect (e.g., how does cooling rate affect crystallinity of starch-based polymers, which then affects strength). These virtual experiments yield insights without consuming resources. We also propose a predictive kinetic model for biodegradation (the first-order rate constants for our recipes). While simplistic, these constants enrich the literature by allowing comparison of degradation rates among different biocomposites. Such information is valuable for developing more complex models of biodegradation that account for material composition - a topic of theoretical interest for environmental polymer science.

Practically, our results demonstrate a pathway to sustainable industrial development. The creation of a pilot plant integrated with a digital R&D platform can be seen as a prototype for smart, eco-friendly manufacturing in emerging economies. The approach not only yields an eco-product (biodegradable packaging) but does so in a way that builds digital capacity and innovation ecosystem (via the R&D platform). For Central Asia, this positions the region at the forefront of «green» materials coupled with Industry 4.0, potentially leapfrogging more established industries. On a product level, the specific recipes developed could be immediately useful for producing items like takeaway food containers, cup lids, etc., replacing plastic or styrofoam equivalents and thus reducing plastic waste. Our best material (Recipe B) is competitive in performance for rigid packaging, meaning it could find market adoption with minimal compromise by users. The intelligent design system also means that if a customer or regulation demands a tweak (say a certain property or using a different waste feedstock), we can rapidly respond by generating a new optimized recipe - giving flexibility and responsiveness that is often lacking in materials manufacturing.

Furthermore, the integration of IoT and QMS in raw material supply (though not a focus of this paper, we did implement moisture tracking in storage) ensures quality and consistency of input agro-waste. This is a critical practical aspect because one of the industry's hesitations with biomass materials is variability. By showing that an IoT-monitored supply chain can guarantee input quality (e.g., moisture content below threshold, absence of contaminants), we address a key concern for scaling production. This paves the way for a reliable network of agro-waste suppliers to feed such biopackaging plants - essentially creating an upstream value chain for agricultural residues. This has socio-economic implications too: farmers or agro-processors could gain extra revenue selling their waste, and rural areas could see technology integration (sensors, contracts) ensuring waste is efficiently collected and utilized.

4.3 Comparison with related work

Comparing our work to global efforts, we find both alignment and distinctiveness. In terms of materials, many studies have explored biodegradable packaging from various wastes (banana stems, pineapple leaf fiber, etc.) (Kossalbayev *et al.*, 2025). Our results for mechanical properties fall in the upper range of reported values for fiber-reinforced biopolymers. For instance, a study by Tran *et al.* (2022) on vegetable fiber fillers achieved improved strength in starch foams (Kossalbayev *et al.*, 2025), but the absolute strengths were still below 15 MPa, whereas we reached 30 MPa by using higher fiber content and PLA reinforcement. This indicates our approach of hybrid matrix (TPS+PLA) with fiber was beneficial. Regarding barrier properties, our water absorption ~10-16% is similar to other lignocellulosic composites; we note that advanced strategies like nano-coatings (e.g., adding a thin hydrophobic layer) have been suggested to further reduce moisture uptake - something we could incorporate in future iterations (perhaps the platform could even handle the design of coatings as a next step).

Unique to our approach is the digital integration. Platforms like AgriStack in India and others have been mentioned as digital infrastructure for agriculture, but those largely focus on data sharing and maybe supply chain, not specifically on R&D and manufacturing integration. Our R&D Central Asia platform, with the BioPack Core module, appears to be one of the first instances of a regional

digital R&D platform in the materials manufacturing sector. It demonstrates how bringing researchers and manufacturers onto a common digital system can cut development time and improve innovation efficiency. In the academic literature, the closest comparisons are some conceptual works on «smart labs» or cloud labs for materials, and isolated examples of using ML in formulation. For instance, the another authors discussed how Industry 4.0 tech (AI, big data) is creating new opportunities in food packaging (*Hassoun et al., 2023*), our work can be seen as a concrete realization of those opportunities: we combined AI (for formulation) and IoT/digital twin (for manufacturing) to deliver a sustainable packaging solution.

Another comparison: a 2025 study by Peterson et al. reviewed digital twins in process engineering and highlighted challenges like ensuring real-time accuracy and integrating with control systems. We addressed some of those by our calibration and by linking the twin with actual control (closing the loop with QMS interventions). This could serve as a case example in future discussions of digital twin implementation.

4.4 Limitations and future work

Despite the promising outcomes, our study has certain limitations. First, the ML model, while effective, was trained on a relatively small dataset. It interpolates well within the range of our data (e.g., fiber content up to 50%, two fiber types, one matrix system). If we were to extrapolate beyond - say, a completely new polymer or a very different fiber - the model might not be accurate. Thus, one must retrain or expand the model's knowledge base when new materials are introduced. A related limitation is that our model currently considers mostly formulation variables and not detailed process conditions as inputs (we kept process fairly constant). In future, incorporating process parameters (like cooling rate or pressure) into the predictions could be valuable, essentially merging material and process design in one ML framework.

Second, the digital twin, while powerful, is a simplified representation. Some complex phenomena (like polymer-fiber chemical interactions, or long-term machine wear effects) are not captured. We observed that over a long continuous run, the actual extruder torque slowly increased (perhaps due to resin build-up on screws or minor wear), which the twin did not predict because it doesn't model equipment fatigue or fouling. Including such factors could further improve its realism. Moreover, maintaining the twin requires effort - whenever we significantly change a recipe or equipment, the twin needs re-calibration to ensure accuracy (which is a known challenge in keeping digital twins «live» over time (*Peterson et al., 2025*)).

From a materials perspective, while our composites work for certain uses, they might not for others. For example, their moisture sensitivity means they cannot hold liquid water or be used in high-humidity environments for long. Future work could explore surface coatings (e.g., a bio-based hydrophobic coating) to improve this. Also, although we achieved good strength, the low elongation is a concern if one needs a tougher material for say flexible films. Recipe E tried to address that with PBAT blending; more research on polymer-polymer blending (maybe using the ML to optimize multi-polymer matrices) could yield materials with a better toughness/strength balance.

One intriguing future direction is to incorporate **life-cycle analysis (LCA)** and environmental optimization into the platform. Currently, our ML optimization targets technical properties. But what if we also quantified the carbon footprint or energy use of each recipe (different fibers have different preprocessing energy, etc.)? We could then aim for recipes that are not just high-performing but also lowest-carbon. This multi-criteria optimization (technical + environmental) would elevate the platform to a holistic eco-design tool. Some initial thoughts on this were mentioned in our proposal, aligning with national sustainability goals, but it remains to be implemented.

Another future aspect is scaling up from pilot to full production. The pilot proved the concept, but industrial scale will introduce new challenges (e.g., supply chain logistics of tons of agro-waste,

larger equipment dynamics). We believe the digital approach will be even more critical there - for instance, a scaled digital twin could help plan factory layout or throughput. But it will require partnerships with industry to realize.

4.5 Broader impacts

The success of this project could have broader impacts by serving as a model for integrated innovation in sustainable manufacturing. It showcases that developing countries or regions can leap into advanced manufacturing by combining domain-specific research (like biomaterials) with digital platforms that connect stakeholders. For the community of biodegradable materials, this work provides a case study that marrying ML and digital twins to material development leads to faster and better results, encouraging others to adopt similar interdisciplinary strategies (materials scientists collaborating with data scientists and control engineers).

From a socio-economic lens, if adopted widely, high-tech production of bio-based packaging can contribute to waste reduction (less burning of agro-residues, less plastic in landfills) and create new green jobs (in operating these digitalized bioplastic facilities, in collecting and preprocessing waste, etc.). It aligns with global sustainability objectives such as several UN Sustainable Development Goals (responsible production, climate action (Lindsey et al., 2025)). Our work specifically answers calls in the literature for local solutions to plastic pollution and demonstrates an actionable path: use local biomass, integrate cutting-edge tech, and innovate regionally. This could inspire similar initiatives in other regions with agricultural economies, be it turning sugarcane bagasse in Latin America or palm waste in Southeast Asia into packaging - all under a digital umbrella that ensures efficiency.

In conclusion, the study validates that biodegradable packaging from agro-waste can be made not only viable but competitive, when advanced R&D tools are employed. By integrating a digital platform (encompassing ML-based design and digital twin-driven manufacturing) with material science, we achieved a level of optimization and reliability unattainable by conventional means. The approach yields materials with both theoretical significance (new knowledge and models) and practical relevance (pilot-scale production of real products). It exemplifies a modern paradigm of research and development for sustainable materials - one that is faster, smarter, and more collaborative. We anticipate that as we and others build on this foundation, such high-tech, eco-friendly manufacturing will move from pilot demonstrations to everyday industry, contributing to a more circular and digital economy.

5. Conclusion

In this paper, we presented a comprehensive study on the development of biodegradable packaging materials derived from agricultural waste, tightly coupled with a digital R&D and manufacturing platform. We addressed two focal objectives: the establishment of the BioPack Core digital platform (with a recipe lab, digital twin, and QMS) and the creation of an intelligent recipe design system using agro-waste data and machine learning. The results confirmed that integrating these digital tools into the materials development cycle markedly accelerates innovation and improves outcomes. We successfully formulated high-strength biocomposites using wheat straw and rice husk, achieving tensile strengths around 25-30 MPa and verified compostability, thereby meeting practical requirements for packaging applications. The machine learning models accurately predicted material properties and guided optimal formulations, reducing the need for exhaustive physical trial-and-error. Concurrently, the digital twin of our pilot production line enabled efficient scale-up, ensuring that the transition from lab to pilot plant was smooth and under control, with real-time quality assurance via IoT-enabled monitoring.

The work demonstrates scientific originality in the realm of materials informatics for biopolymers and is one of the first examples of a digital twin applied to biodegradable material manufacturing. Theoretical contributions include the predictive models for composite performance and

biodegradation, as well as insights into the interplay of composition and process on material properties. Practically, we delivered a validated pilot production of eco-friendly packaging (containers and lids) that could directly replace some plastic products, illustrating a viable path to commercialization. The integration of the R&D Central Asia digital platform ensures that this innovation is not an isolated lab result but part of a collaborative, scalable ecosystem - positioning it well for further development and adoption.

In closing, the study serves as a proof-of-concept that marrying Green Chemistry with Industry 4.0 tools yields powerful results. High-tech biodegradable packaging from agro-waste is not only possible but can be rapidly realized and refined using digital platforms, benefiting both the environment and the economy. Future efforts will extend this platform to new materials, larger scales, and additional objectives (like environmental footprint minimization), but the success reported here is a significant step towards smarter sustainable materials manufacturing. We envision that approaches like ours will become standard in accelerating the transition from laboratory discovery to real-world sustainable solutions.

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The role of bark beetles (Latin: Scolytinae) in the degradation of spruce forest groves in Georgia and the biological agent of these pests, the ant beetle (Latin: Thanasimus formicarius)

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Entomophagous; introduced; relict; endemic; grove; larva; imago; palearctic;

Introduction

Georgia is world famous for its unique Caucasian relict and endemic species of plant diversity. Conifers, which are widely distributed throughout the country, form sacred groves, but unfortunately for us, the main pests of spruce crops (bark eaters) are widespread in the forest-covered areas, which pose a great threat to the ecosystem of coniferous forests and its economic importance. In modern life, when a very big role is assigned to less damage to our surrounding environment, it was necessary to reduce as much as possible the use of measures to fight against harmful organisms that would harm the environment and all living organisms living in it, that's why the integrated protection of plants came to the fore, the main essence of which is, the management of harmful organisms not only by chemical means, but also by combining biological, agro-technological and mechanical methods. Since the use of chemical means against crustaceans does not give us the maximum result, due to the specifics of the pest's harmfulness, we decided to start biological measures to fight against it, which provides for the reproduction of the biological agent of crustaceans, *Thanasimus formicarius*, in laboratory conditions and its subsequent transfer to areas covered by pests.

General description of the pest

Bark eaters (lat: Scolytinae) - are a group of beetles that are distinguished by special and specific characteristics. They live, feed, grow, give birth and hibernate on a tree or under the bark of a tree. In total, more than 750 species of bark beetles are known to scientists. The smallest individual of them reaches at least 1 mm, and the largest one does not exceed 9 mm in size, but there are crustacean insects of tropical species, the body size of which reaches 1.5 cm. These pests are mainly distributed in the Northern Hemisphere and some species are introduced to Australia and Africa. Many of them are pests of forest species, especially pine and spruce.

The bark-eating family (Ipidae) common in forest groves is included in the wood-winged (Coleoptera) squad, and the family is divided into three main groups: 1. protein-eaters (Scolytini); 2. Lafnichamines (Hylesinini) and 3. true crustaceans (Ipini).

1- ცილაჭამია-(Scolytini)



2- ნამდვილი ქერქიჭამია - (Ipsini)



3 - ლაფნიჭამია- (Hylesinini)



All of them are similar to each other in terms of biological features and living conditions, but they differ sharply from each other in terms of settlement and damage to different parts of plants, as well as the morphological structure, size and shape of its body. They are generally considered secondary pests because they are characterized by settlement on weakened or withering trees. If the reproduction is massive, they can damage healthy trees and cause huge losses. Some species of this pest are considered very serious and harmful individuals. In the conditions of Georgia, their representative is the large spruce beetle (*Dendrovtonus micans*) and the six-toothed bark eater (*Ips sexdentatus*). The harmful effects of the mentioned species are determined by the great scale of Georgia.

Biology

In order to develop measures to fight crustaceans, it is necessary to know the terms and specifics of the development of their generation. The egg phase lasts 10-20 days; The caterpillar phase lasts 15-90 days; The pupal phase is 10-18 days, that is, it turns out that it takes 1-4 months for one generation to fully develop. All this depends both on the type of individuals and how well the environmental conditions are adapted to the needs of the perfect development of the pest. Bark beetles begin flying in the spring, a phenomenon that lasts until late summer or late fall. They start flying when the temperature reaches 14-16 °C. Most of the bark eaters fly once a year and give one generation, but there are exceptional cases: for example, in 2025, according to our own observation, in the forest groves of Samtskhe-Javakheti in Georgia, most species of bark eaters managed to give two generations, and this was caused by unusually high temperature conditions for the mentioned moment.

During the flight and egg period, the female individual gnaws the entrance hole in the bark of the tree, where she makes a mother passage, when the female beetle makes a passage, the male then flies and fertilization takes place. After fertilization, the female beetle begins to dig out the ovarian chambers on the right and left side of the mother passage, where it lays one egg in each chamber, and then covers it with flour. Egg laying lasts up to a month. Larvae hatched from eggs begin to help the saclet passages (some species of pests are an exception). After 30-90 days, the now adult worm begins to make a cradle of the caterpillar where it will die. Beetles emerging from the pupil gnaw the bark vertically and come out.

Distribution of crustaceans in Georgia

In Georgia, these pests were first observed in 1956, in Borjomi forestry, but according to scientists, the pest has a longer history of appearing in our country. Today, the pest is widespread in: Khashuri, Kareli, Kaspi, Kharagauli, Gori, Borjomi, Bakuriani, Akhaltsikhe, Aspindze, Adigeni, Khulo, Baghdad, Tsageri, Oni, Lentekhi, Martvili, Ambrolauri and Chiaturi forest groves, a total of 120,000 hectares on the forest area. Based on the monitoring carried out by us, bark eaters also spread in the territory of Guria, namely in the spruce groves of Bakhmaro and Gomi mountains. Since the appearance of the pest, state structures have been actively involved in the development and implementation of measures to combat harmful crustaceans, but as I mentioned above, due to the peculiarities of the biological and life cycle of the pest, it was not possible to achieve great and effective results, that's why in the last few years, the state has been paying great attention to the fight against harmful crustaceans. Promotion of biological measures, namely from 2024: "named after Adam Beridze LLC, soil, soil The diagnostic center for integrated protection of food and plants was opened in Anaseuli" (Georgia, Guria, Ozurgeti). A forest entomophage laboratory has been opened, which has been actively monitoring and evaluating the areas covered by the pest throughout the country for 2 years, and most importantly, in laboratory conditions, the biological agent of crustaceans, the ant beetle (*Thanasimus formicarius*) is being propagated and transferred to heavily damaged forest groves as a result of the monitoring report.

General description of the ant beetle (*Thanasimus formicarius*)

It is a 7-11 mm, medium-sized insect with a rather soft body but very strong jaws compared to the body, which can properly injure individuals of any generation of crustaceans. This entomophage is a widespread palearctic species. It is found both in the European part of the former Soviet Union and in Asia. The ant beetle is characterized by high ecological plasticity, which is why it easily penetrates into various biotopes. For example, based on our research, during the period of mass reproduction of dendrocton in the Borjomi valley, the meeting of the ant beetle in the passages made by the pest reaches 44%, and in new foci it is found up to 7%. The ant beetle is characterized by a one-year generation. It winters in both the caterpillar and pupa and imago phases, mainly hibernating in the bark-eating passages.

It is worth noting that insects of the predatory imago stage attack harmful insects when they begin to settle on the tree, and predatory larvae actively move through the passages made by crustaceans and greedily destroy individuals of any stage of the pest along the way. The bioagent hunts many species of crustaceans, but for the most part it hates three main species: *Tomicus piniperda*; *T.minor*; and *Ips typographus*...

From April to June, the female ant beetle lays up to 20-30, and sometimes up to 100 eggs in the bark, near the exits of bark-eating beetles, so that after 8-11 days, the newly hatched larvae do not have difficulty finding the target object. On average, 2-3 worms of an entomophagous insect can destroy one complete family of crustaceans, which consists of 80 worms, which will bring very positive results in the event of the final battle.

Laboratory in Anaseuli, as I mentioned above, the forest entomophagous insect department has been operating since 2024. Where an isolated area was allocated for the reproduction of the ant beetle, which was provided with all the necessary equipment and equipment.



It should also be noted that a third level biosafety box was allocated in the laboratory for the mentioned work, where useful insect larvae are raised, under favorable temperature and humidity conditions.



From May to the end of September 2024, weekly business trips were made to the Borjomi forest, where specialists from the Anaseuli laboratory collected entomophagous insects and transported them to the laboratory.

After the insects were transported, we would mate them and place them in an isolated environment where they would be delayed for 7-8 days until no eggs were observed in these containers. After 8 days, when eggs were observed in the container, we removed the insects of the mentioned imago stage from the containers and returned them to the environment from which we originally brought them.



After 8-9 days of delay from the eggs, the larvae came out, which we transferred to the test tubes intended for them, individually together with sawdust, and we placed them at a special temperature, in complete darkness, in a separate box, for 25 days.



After the expiration of the mentioned period, which was necessary to stop the larvae in the laboratory, we transferred the biological agent to the area severely damaged by the pest, where the trees damaged by crustaceans were selected and these larvae would be placed in the tree, under the bark, in the amount of 1-2 pieces.



Regarding the mentioned issue, work is suspended at this stage, due to unfavorable temperature conditions in Georgia. It will be updated from May 2026 and will last until the end of September this year. It is also noted that after the measures of the mentioned struggle, at least one decade of work is required to obtain the results, and the mentioned case does not represent the work of individual years. That is why we cannot talk widely about the results of the biological measures of our fight against harmful crustaceans in the forest groves of Georgia.

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Prospects of Biological Control of the Brown Marmorated Stink Bug- *Halyomorpha halys* (Stål, 1855) (Hemiptera, Pentatomidae) in Georgia Using Egg Parasitoids

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Abstract

The brown marmorated stink bug *Halyomorpha halys* is one of the most harmful invasive agricultural pests in Georgia, causing significant damage to a wide range of crops. Intensive reliance on chemical control has raised environmental concerns and highlighted the need for sustainable pest management strategies. Integrate Pest Management (IPM) is an alternative to chemical control against pest insects. In IPM biological control using egg parasitoids is one of the effective methods. The egg parasitoid *Trissolcus japonicus* was first recorded in Georgia in 2022 and is considered an adventive established species. In 2025, approximately 30,000 individuals of *T. japonicus* were mass-reared under laboratory conditions and released into selected field sites. Post-release monitoring confirmed successful establishment and parasitism under natural conditions. The results indicate that egg parasitoids represent a viable and environmentally safe tool for long-term management of *H. halys* in Georgia.

Keywords: *Halyomorpha halys*; invasive pests; biological control; egg parasitoids; *Trissolcus japonicus*; Georgia;

Introduction

The brown marmorated stink bug *H. halys* is a highly invasive pest that feeds on more than 300 plant species. In Georgia, it was first detected in 2015 and rapidly spread across the country, causing serious economic losses. Long-term chemical control has proven problematic, emphasizing the importance of sustainable biological control strategies.

Current Status of Biological Control in Georgia

T. japonicus was first detected in Georgia in 2022 and is considered an adventive established species, indicating natural establishment. This supports its suitability for biological control programs.

Materials and Methods

Field monitoring was conducted using visual inspections and pheromone traps to attract *H. halys* and monitor its distribution. Laboratory colonies of *H. halys* were maintained under controlled conditions, and egg masses were used for mass rearing of *T. japonicus*. The study was conducted using a combined approach under both field and laboratory conditions, in accordance with internationally accepted research methodologies.

Field studies: Under field conditions, the population density of the brown marmorated stink bug was assessed using visual observations and pheromone-based attraction methods. Species-specific pheromones were placed at selected locations according to a standard monitoring scheme in combination with insect traps. The use of pheromones enabled more effective detection of the population, collection of individuals, and quantitative assessment. Collected specimens were used both for the establishment of laboratory colonies and for the mass rearing of egg parasitoids. To detect egg parasitoids under natural conditions, frozen egg masses of *H. halys* were used. Egg masses were stored at -18°C for 24 hours, ensuring deactivation of the host embryo and preventing larval development. Subsequently, frozen egg masses were placed at selected field locations for a defined exposure period. After retrieval, egg masses were examined under laboratory conditions to assess parasitoid emergence, species composition, and parasitism rates.

Laboratory studies: Laboratory colonies of *H. halys* were established and maintained under controlled environmental conditions. *T. japonicus* were mass-reared under laboratory conditions on fresh egg masses of *H. halys* and on frozen eggs as well and released into selected field sites. Controlled releases of parasitoids were conducted under field conditions, followed by post-release monitoring. Parasitism rates, dispersal dynamics, and indicators of establishment were assessed after release. Data processing and analysis were performed using standard statistical methods.

Results and Discussion

Under laboratory conditions, parasitism rates of *T. japonicus* reached 83.12% on fresh egg masses of *H. halys* and 80.72% on frozen eggs. A strong female-biased sex ratio was observed, indicating high reproductive potential and suitability of the parasitoid for mass rearing and biological control applications. In addition to *T. japonicus* field surveys revealed the presence of other egg parasitoid species naturally associated with *H. halys* egg masses. These parasitoids were detected within the pest's distribution range, indicating a response of the local entomofauna to the invasion of *H. halys*. Although their parasitism levels were generally lower compared to *T. japonicus*, their presence plays an important role in the natural regulation of *H. halys* populations and represents a valuable component of an integrated biological control strategy.

Conclusion

Egg parasitoids, particularly *T. japonicus*, show strong potential for sustainable biological control of *H. halys* in Georgia.

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Boxwood pathogenic fungi in western Georgia

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Keywords: mycelium, conidium, sporulation, toxin, conidiophore, pathogen, polyphagous, zoosporogenesis, phialide, balishak, hypha, conidiophore, microsclerotia

Introduction

Introduction

Boxwood (*Buxus* L., 1753) It is a genus of deciduous plants from the boxwood family. It is a unique plant. It is rare in the world to have a plant that is both evergreen and deciduous. Boxwood is among these rare plants. In addition, it is one of the best green decorations. Common boxwood as a shrub variety is widespread in almost all regions of Georgia - in Adjara, Guria, Svaneti, Samegrelo, Racha and Imereti. It is also found in eastern Georgia (К. Ю. Одишария, 1959).

Boxwood is an evergreen deciduous tree or shrub. It grows to a height of 6-10 meters, lives for more than 700 years. It blooms in April and May. It grows slowly. It reaches 5-7 meters in 100 years, it is excellent shade-tolerant. It grows as an understory. It thrives in bright locations. It tolerates frosts of -20 and -22 °C without damage.

Due to its many decorative qualities, it is widely used in gardening. It is used as valuable curbs and living fences.

There are four main types of boxwood in Georgia : common, or evergreen, small-leaved, Japanese, and Balearic boxwood. However, the dominant, leading species in Georgia is the Colchian boxwood.

Colchian Boxwood (*Buxus colchica* Pojark., 1947) is an evergreen shrub or tree belonging to the family Buxaceae (*Buxaceae* Dumort., 1822). It reaches a height of 18 m under good care. It is a relict variety of boxwood from the Black Sea coast of Georgia. The main growing area of *Buxus colchica* is located in the Mtirala National Park (Kobuleti Municipality, Adjara, Western Georgia).

The following fungi have been identified by the National Institute of Environmental Health on boxwood plants:

No.	Name of the fungus	Diseased plant organ(s)	Time of disease detection
Ascomycetes			
1	<i>Cylindrocladium buxicola</i> Henricot, 2002 = <i>Calonectria pseudonaviculata</i> (Crous, J.Z. Groenew. et C.F. Hill) L. Lombard, M.J. Wingf. et Crous, 2010	Leaves, twigs, vascular bundles	May, June, July, August
2	<i>Verticillium buxi</i> (J.C. Schmidt ex Link) Sacc. 1881= <i>Sesquicillium buxi</i> W. Gams, 1968	Leaves, twigs, vascular bundles	Any time of year
3	<i>Verticillium dahliae</i> Klebahn , 1913	Root system, stems	Any time of year
4	<i>Gloeosporium pachybasium</i> Sacc. , 1880 = <i>Guignardia miribelii</i> Aa , 1975	Leaves	May, June, July
5	<i>Septoria phacidioides</i> Desm., 1846	Leaves	August , October
6	<i>Pestalotiopsis guepinii</i> (Desm.) Steyaert, 1949	Leaves	June, July
7	<i>Alternaria alternata</i> (Fr.) Keissl., 1912	Leaves	July, August, September
8	<i>Cladosporium herbarum</i> (Pers.) Link, 1816	Leaves, twigs	June, July, August, September
9	<i>Phyllosticta buxina</i> Saccardo, 1878	Leaves	June, July, August
10	<i>Phomopsis buxi</i> Höhn., 1920 = <i>Cytospora buxi</i> Desm., 1848	Leaves	May, June, July, September
11	<i>Ascochyta buxina</i> Sacc. 1878	Leaves	June, July, August

Research methods

In order to identify the fungi causing the main diseases of boxwood (*Buxus*), we conducted field surveys in the subtropical zone of western Georgia, namely in the municipalities of Guria , Samegrelo and Adjara, at different phenological phases of plant development. During the surveys, the spread of the main diseases was recorded on individual boxwood plants and bushes.

Pure cultures of the fungus were isolated from the diseased samples. The development of the fungus, its morphological and cultural properties were studied on various nutrient media: agarized beer agar, potatoes with glucose and without glucose.

The formation and intensity of mycelium, conidiophores, sterigmas , spores were observed. The fungi were identified using the appropriate methods . The genus and species of fungi were identified using the appropriate methods.

Classical – P. A. Saccardo, 1877- 1931; H. Klebahn, 1904; A. Allescher, 1901; G. Lindau, 1906; Sydov and Butler, 1913; F.L. Stevens, 1925; Н. И. Васильевский и Б. П. Каракулин, 1950; Т. Л. Доброзракова, М. Ф. Летова, Л. М. Степанов, М. К. Хохряков, 1956; and

Contemporary - Martin B. Ellis, J. Pamela Ellis, 1985, В. В. Филипов, Л. Н. Андреев, Н. В. Базилинская, 1980, R. B. Streets, 1984; В. И. Билай, Р. И. Гвоздяк, И. Г. Скрипаль, 1989 და Ziqing Yuan, 2017 essays.

Research results

Cylindrocladium buxicola Henricot, 2002 = *Calonectria pseudonaviculata* (Crous, JZ Groenew. et CF Hill) L. Lombard, MJ Wingf. et Crous, 2010 - The fungus was first noted by us in 2012 on a boxwood plant brought from the Adjara zone.

The diseased plant shows browning of the leaves or black spots on the leaves. Narrow, longitudinal black stripes on the stem. White flakes develop on the underside of the leaf, which represent the mycelium and fruiting bodies of the fungus.

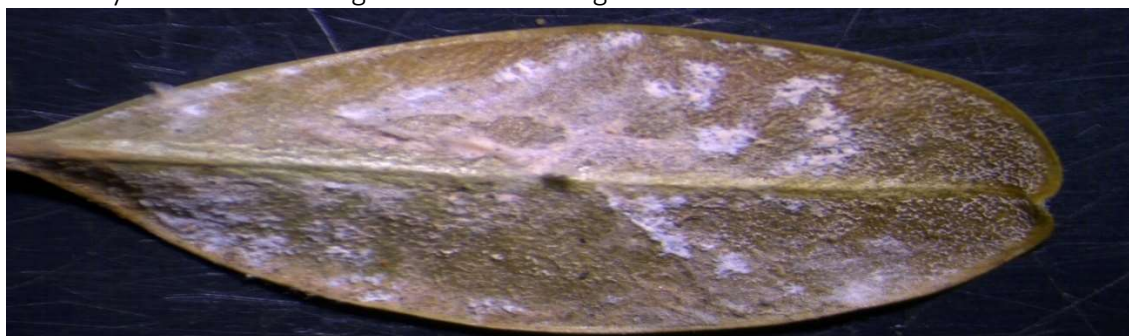


Photo 1. Fruiting of the fungus *Cylindrocladium buxicola* on a leaf

Infected shoots show black, elongated spots. The fungal mycelium spreads through the vascular bundles of the plant. Infected leaves wither and fall off, as do the infected shoots, and eventually the plant dies.

The fungus was inoculated from the stems and shoots of the diseased plant onto a beer-agar medium. The fungus begins to develop as a white mycelium on the second day. The spores of the fungus are elongated, cylindrical in shape, measuring $52-65 \times 4-6 \mu\text{m}$.

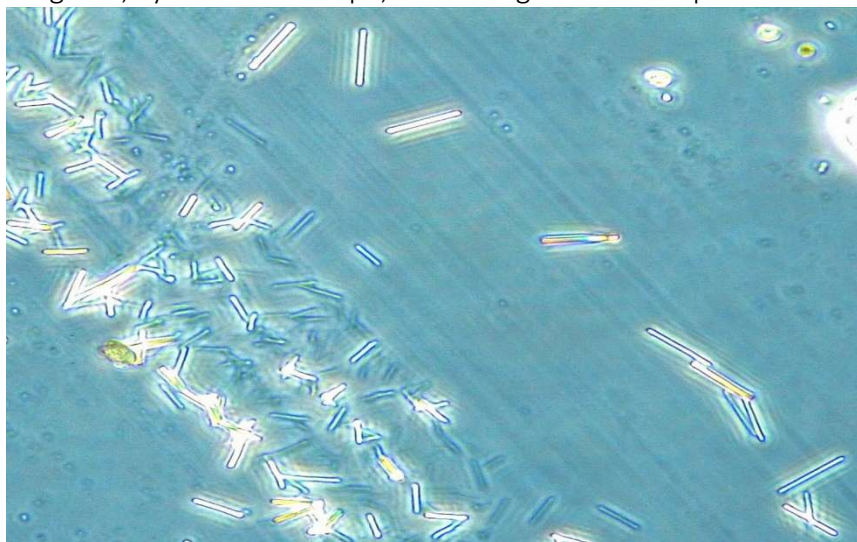


Photo 2. Spores of the fungus *Cylindrocladium buxicola* in pure culture

Verticillium buxi (J.C. Schmidt ex Link) Sacc. 1881 = *Sesquicillium buxi* W. Gams, 1968 - the fungus was noted by us in the Anaseuli area of Ozurgeti municipality.

Boxwood plants grown as trees show signs of leaf loss and wilting (S. A. J. Tarr, 1972). Stem and branch materials were taken from the diseased plant for examination. Transverse sections of the stem and branches show cracking, cracking, and a dark grayish-brown color.



Photo 3. Cross-section of a boxwood trunk and branches infected with the fungus *Verticillium buxi*

A pinkish-brown powdery growth develops on the underside of infected leaves, which is the fruiting body of the fungus (M. Daughtrey, D. Gilrein, M. Vescera, 2016).



Photo 4. Fruiting of the fungus *Verticillium buxi* on a leaf

The research materials were inoculated onto a beer-agar medium. The fungus begins to develop 24 hours after inoculation. The fungus develops on the surface of the medium in the form of white mycelium. The mycelium is attached to the surface of the medium, growing slowly.



Photo 5. Pure culture of the fungus *Verticillium buxi* 24 hours

A 10-day-old pure mushroom culture reaches 8 cm. The mushroom mycelium takes on a pinkish-purple color in most of the central part (B.O. Dodge, 1944), forms knots, threads (L. Beradze, I. Basilia, R. Takidze, E. Jakeli, G. Sajaia, 2024).



Photo 6. Pure culture of the fungus *Verticillium buxi* 10 days old

The fungus is characterized by strong sporulation, conidia are spherical, ellipsoidal, cylindrical (elongated), equilateral, crescentic, with pointed and rounded ends, ovoid, ovoid, where the basal ends are narrowed; unicellular or bicellular with one partition; size $6-8 \times 2-2.5 \mu\text{m}$. They are colorless and colored, located in mycelial chains and at the ends of the conidiophore.

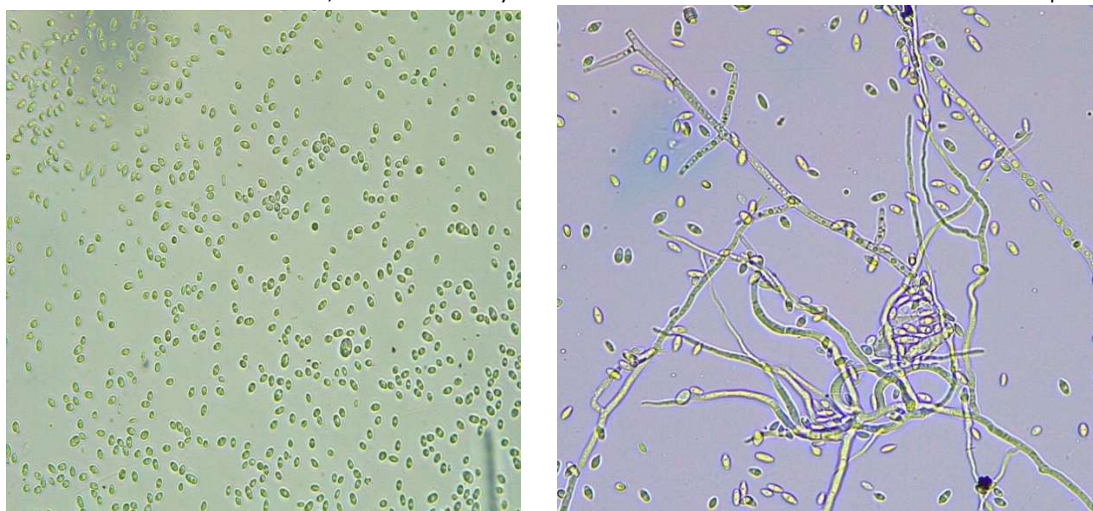


Photo 7. Spores of the fungus *Verticillium buxi* in mycelium chains

Conidiophores are erect, have twisted filaments, and are simple corymbs. The unicellular branching consists of a main axis and phialides.



Photo 8. Conidiophores of the fungus **Verticillium buxi** with spores

A branch is the lateral axis of a conidiophore, on which one or more phialides are located.

The arrangement of phialides is alternate (unilateral), opposite, or circular (B. O. Dodge, 1944; В. В. Филипов, Л. Н. Андреев, Н. В. Базилинская, 1980).



Photo 9. Phialides located on the axis of the conidiophore of the fungus **Verticillium buxi**

Verticillium dahliae Klebahn, 1913 - the fungus was first noted by us in 2022, on the trunks and branches of a boxwood plant brought from the botanical garden of the Dadiani Palace Historical and Architectural Museum Complex in Zugdidi.

Dark discoloration and stem cracking were noted on the transverse section of the trunk and branches of the diseased boxwood.



Photo 10. Cross-section of a boxwood stem infected with the fungus **Verticillium dahliae**

We inoculated the diseased materials onto a beer-agar medium. The fungus develops as a white, cottony, medium-height mycelium 2 days after inoculation. It is characterized by strong sporulation. Conidia are unicellular, colorless, cylindrical or elongated, $6-7 \times 3-3.5 \mu\text{m}$ in size. The substratum mycelium is burgundy (Martin B. Ellis, J. Pamela Ellis, 1985; В. И. Билай, Р. И.Гвоздяк, И. Г. Скрипаль, 1989; L. Kanchaveli, 1987).

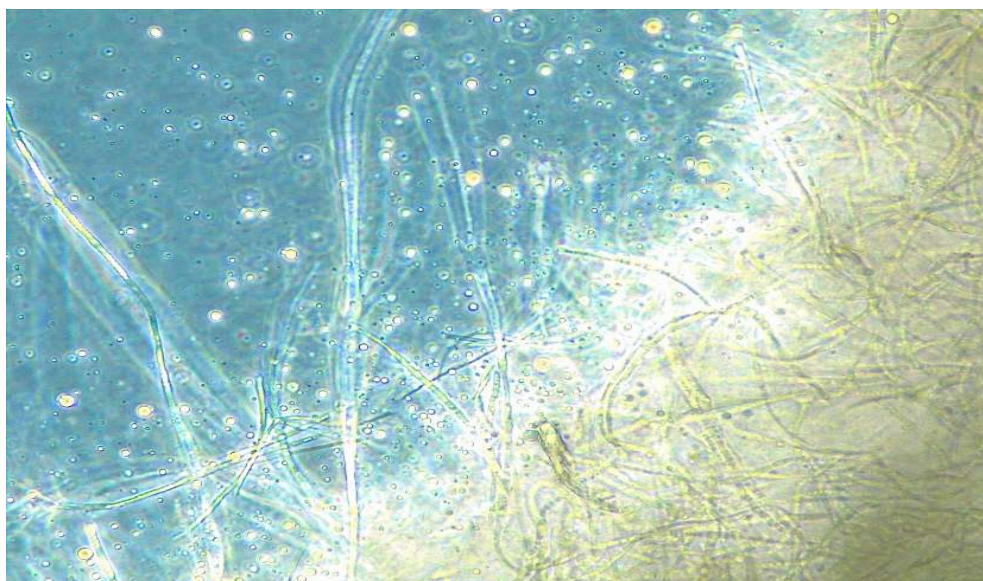


Photo 11. Mycelium of the fungus **Verticillium dahliae** with spores

Fungi of the genus *Verticillium* live in the rhizosphere of the soil, penetrate the plant through the roots and root collar. Then they spread to the stem and branches of the plant, move through the plant along vascular bundles, reach all organs of the plant and secrete toxins (L. Beradze, 2020).

Toxins secreted by the fungus cause a violation of the osmotic pressure of plant cells, poisoning the plant and damaging the vessels, which ultimately leads to wilting and drying of the plant (L. Beradze, I. Basilia, E. Jakeli, R. Takidze, N. Guntadze, 2022; Т. А. Цакадзе, 1959; Н. W. Mussell, 1973).

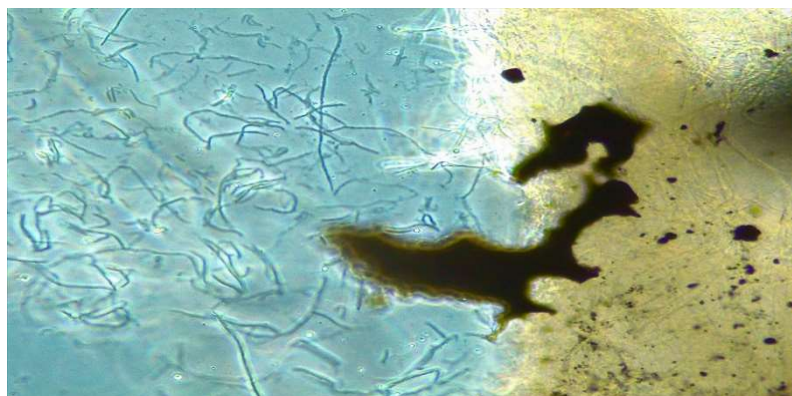


Photo 12. Toxin secreted by the fungus *Verticillium dahliae*

The source of infection is fungal microsclerotia in plant debris and soil, which remain viable for up to 3 years.

Gloeosporium pachybasium Sacc., 1880 = *Guignardia miribelii* Aa, 1975 - The fungus develops on boxwood leaves and trunks as grayish spots, on which the pycnidial fruiting of the fungus develops.

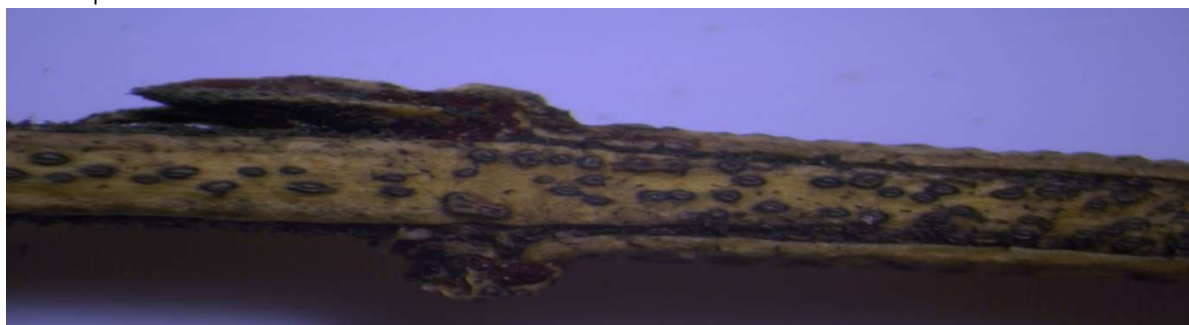


Photo 13. Pycnidial fruiting of the fungus *Gloeosporium pachybasium* on branches
The size of the spots is 0.5-1 cm. The spots are bordered by a brownish border.



Photo 14. Pycnidial fruiting of the fungus *Gloeosporium pachybasium* on a leaf

On the underside of the spot, the fruiting bodies of the fungus - pycnidia - develop, in the form of small black dot-like fruiting bodies covered with epidermis.

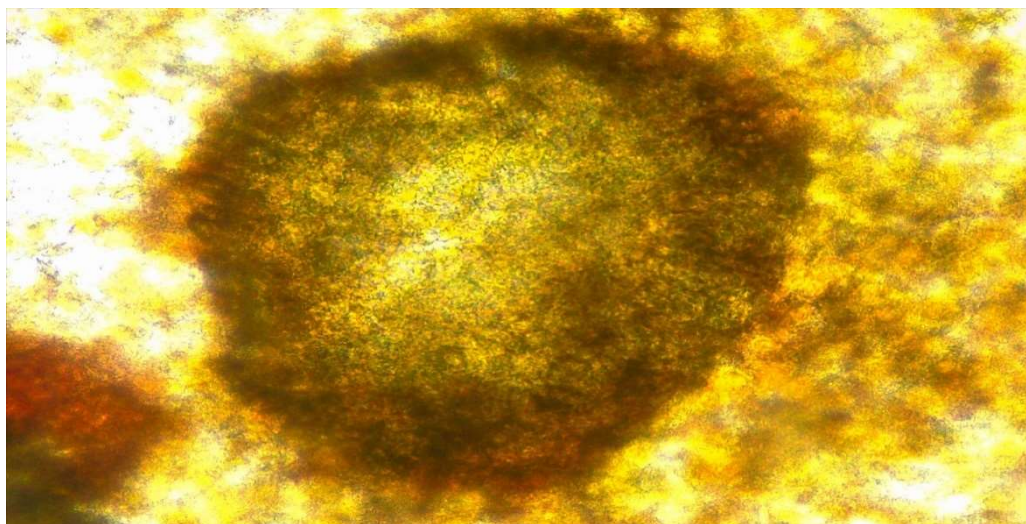


Photo 15. Pycnidium of the fungus *Gloeosporium pachybasium*

The sori are cylindrical, with rounded ends, colorless, with a granular content, measuring $16.8-22.4 \times 6-7.5 \mu\text{m}$. Some spores have a large fat droplet.



Photo 16. Spores of the fungus *Gloeosporium pachybasium*

***Pestalotiopsis guepinii* (Desm.) Steyaert, 1949** – infects boxwood leaves and shoots . The disease is most common in June and July.

Dark gray spots of various sizes and shapes appear on diseased leaves. Spots that are separated from the healthy part by a raised arch of yellowish or dark green color . On both the upper and lower sides of the spot, the conidial fruiting of the fungus is developed in the form of small black pads, which are still covered by the epidermis. As the conidia mature, the epidermis breaks and the conidia fall off.

The fungus in pure culture is a white mycelium with filamentous hyphae of medium height. The aerial mycelium is covered with small tower-like mounds, which represent fungal spore clusters. Spores are produced in large quantities. The substrate mycelium is pinkish.

Conidia are 5-celled, $21-28 \times 7.5-9 \mu\text{m}$ in size. The head and last cell are colorless, the middle 3 cells are brownish, the number of cilia is from 2 to 4, $30-33 \mu\text{m}$ in size.



Photo 17. Spores of the fungus *Pestalotiopsis guepini*

Cladosporium herbarum (Pers.) Link, 1816 - The fungus was noted on boxwood leaves and shoots, which developed a brown spot that later developed an olive-colored scaly coating.

On artificial substrate, the mushroom colony is medium-high; the substrate is covered with food. It is characterized by radial development. The substrate mycelium is turbid lilac. The mycelium has a sharp shell, and when conidia are formed, it is characterized by granular content.

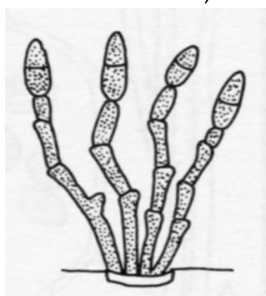


Photo 18. Fungus *Cladosporium* spp. with conidia (Rubert B. Streets, 1984)

Conidia are of various heights, with partitions, measuring $62-218 \times 6-8 \mu\text{m}$. Conidia are arranged singly or in chains on conidia. Conidia are ovoid, cylindrical or rounded in shape, measuring $10-12 \times 6-10 \mu\text{m}$. They are characterized by fatty inclusions. Conidia are 1-5-celled.

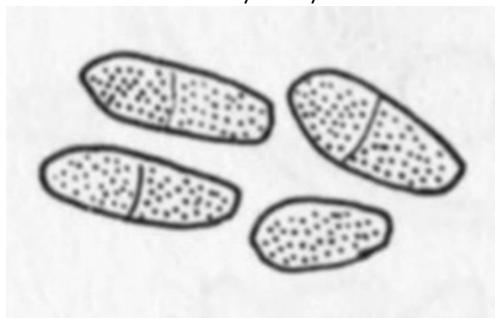


Photo 19. Mushroom Conidia of *Cladosporium* spp. (Rubert B. Streets , 1984)

Alternaria alternata (Fr.) Keissl., 1912 - The fungus infects boxwood leaves. On infected leaves, the fungus develops as a dark brownish spot, on which, in damp and rainy conditions, a brownish velvety coating forms. It consists of conidia and conidia carriers.

The fungus develops in pure culture as a grayish-white, tall, mycelium. It is characterized by the formation of mounds. The substratum mycelium is turbid lilac. It is characterized by abundant sporulation.

Conidia brownish, ovoid or comb-shaped, beaded, 5-10-celled, with longitudinal and transverse partitions, measuring $34-60 \times 18-22 \mu\text{m}$. Conidia carriers - short, erect, brownish, cells sharply defined, measuring $58-80 \times 6-8 \mu\text{m}$.

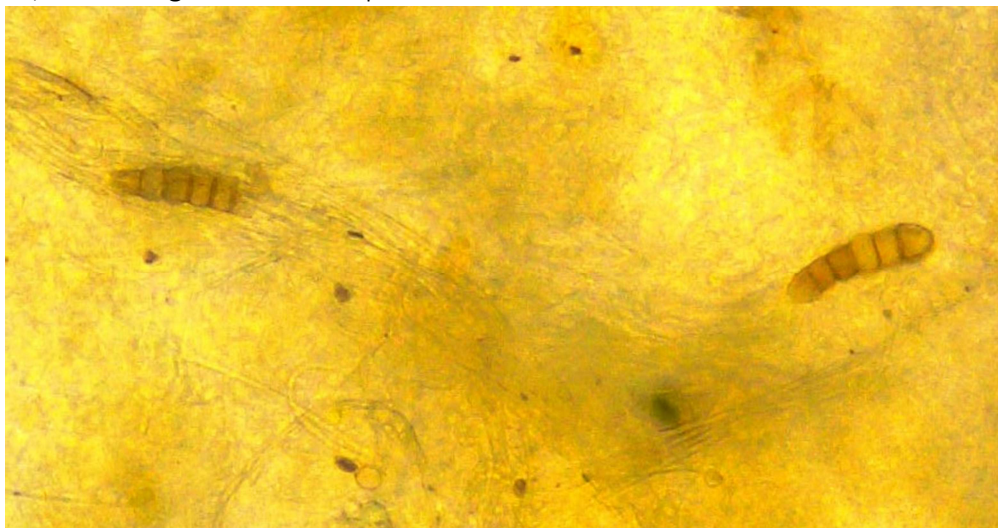


Photo 20. Mycelium of the fungus **Alternaria alternata** with conidia

Septoria phacidioides Desm., 1846 - The fungus develops on boxwood leaves in the form of whitish spots (A. B. Frank, 1896). Dot-like fruiting bodies develop on the spots, which are pycnidial fruiting bodies of the fungus.

Pycnidia are 95-155 μm in size, brown in color, and spherical in shape.

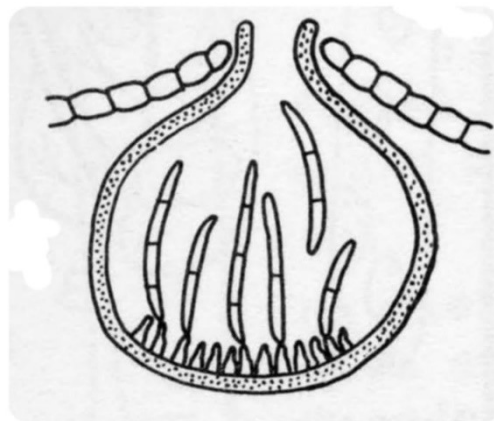


Photo 21. Pycnidium of the fungus **Septoria spp.** (Rubert B. Streets, 1984)
Conidia are 3-septate, colorless, straight or curved, measuring $22-47 \times 3-4 \mu\text{m}$.



Photo 22. Spores of the fungus *Septoria* spp. (Rubert B. Streets, 1984)

Phomopsis buxi Höhn., 1920 = *Cytospora buxi* Desm., 1848 - The fungus develops on boxwood leaves in the form of grayish spots. The spot occupies 1/3 of the leaf in size.



Photo 23. Pycnidium of the fungus *Phomopsis* spp. in tissue (Rubert B. Streets, 1984)

On the upper and lower sides of the spot, there is a development of fruiting in the form of black dots, covered with epidermis.

The pycnidium of the fungus is spherical, rounded in shape. Pycnospores emerge from the pycnidium in a ribbon-like manner.

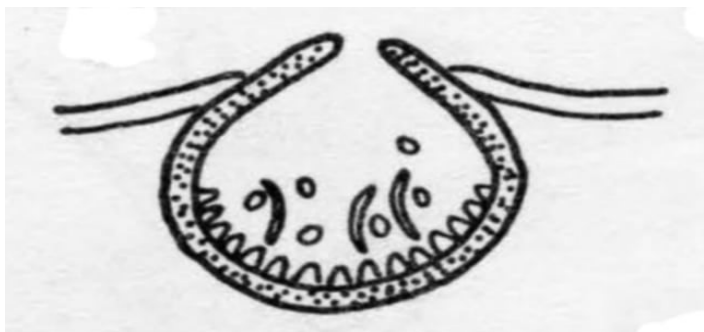


Photo 24. Pycnospores emerging from the pycnidium of the fungus *Phomopsis* spp.
(Rubert B. Streets, 1984)

Pycnidia are ovoid or oval in shape. Pycnidia are mostly developed on the upper side of the spot under the epidermis. The dimensions of the pycnidiospores are $5-6 \times 2.5-3 \mu\text{m}$.

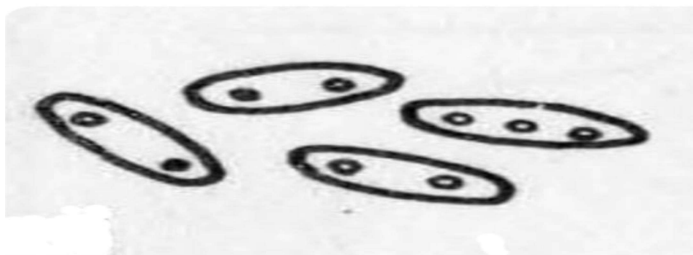


Photo 25. Pycnospores of the fungus *Phomopsis* spp. (Rubert B. Streets, 1984)

***Ascochyta buxina* Sacc. 1878** - Rounded, brown spots of the fungus form on boxwood leaves, surrounded by a thin, whitish ring.
Pycnidiums 90-110 μm in size.

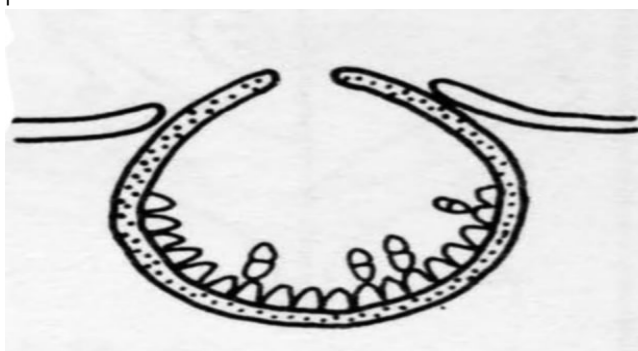


Photo 26. Pycnidium of the fungus *Ascochyta* spp. (Rubert B. Streets, 1984)
The spores are cylindrical, measuring $8-14 \times 1.5-2.4 \mu\text{m}$.

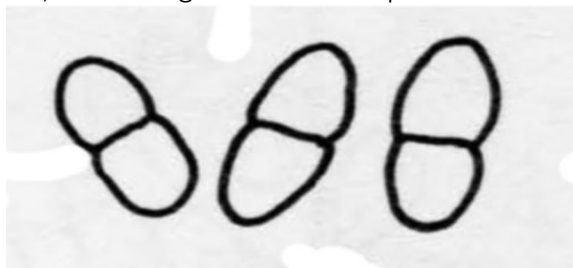


Photo 27. Pycnospores of the fungus *Ascochyta* spp. (Rubert B. Streets, 1984)

***Phyllosticta buxina* Saccardo, 1878** - Round, mushroom-shaped spots develop on boxwood leaves, which are first light brown and then gray. The spots are separated from the healthy part by a dark brown or black border.

Pycnidiums are scattered on the surface of the stain. Pycnidiums are black, spherical in shape, 105-116 μm in size. Spores are elliptical, with rounded ends, colorless, $4-6 \times 1-3 \mu\text{m}$ in size.

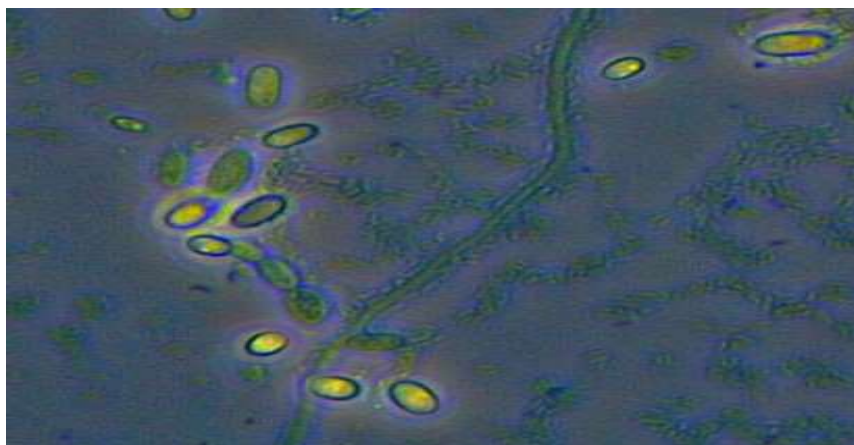


Photo 28. Pycnosporangia of the fungus *Phylosticta* spp .

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Ecological essence of the effect of windbreaks on agricultural crops in the Imereti zone

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Abstract

The paper provides an analysis of the factors of negative impact of winds, their impact on agricultural crops and soil conditions. As well as the laws of Georgia that regulate the granting of the status of windbreaks. Where it is noted that the issue of the legal status, maintenance and physical protection of windbreaks is acute throughout the territory of Georgia. Due to the political and social disruptions that have developed in recent decades, as well as the non-existent legislative base, windbreaks have been destroyed, whose role in the country's agriculture, transpiration, recreation, biodiversity and land protection is very large. Today, information about the ownership of windbreaks, the size of the areas of responsibility and the current state is unknown.

Keywords: climate, wind, windbreak, transpiration, assimilation, fionas, upper wind. Windbreak. Agroforestry, field shelter.

Wind is a component of climate and takes an essential part in the formation of weather conditions of a place. Wind, as an ecological factor, has a very deep essential impact on the life activity of living organisms and the state of their surrounding nature.

Fionas, or eastern (upper) dry winds, are of great importance for the Imereti region, which arise as a result of the pressure difference between the eastern and western parts of the Likhi Mountains. They are characterized by high temperatures and dryness, which leads to drying of the soil, increased plant transpiration and, at the same time, reduced plant assimilation. Due to such an effect of the wind, plant growth is limited, and the harvest is greatly reduced. Strong winds are very frequent in Kutaisi and in the Rioni River plain in general. The negative impact of these winds is especially great during droughts. Strong winds cause great harm to people, destroy crops of agricultural crops.

The positive effect of winds on plants is that they contribute to the pollination of plants, the transportation and distribution of seeds and fruits over long distances, and the dispersion of cold and moist air is also carried out by the wind. The negative role of winds is more important, which is manifested in its mechanical impact, such as uprooting of plants, constant shaking, bending,

deformation of the stem. Strong winds sometimes carry away new shoots and the upper loose part of the soil. It tears and damages the leaves. The wind causes the one-sided development of plant branches. Where the plant is affected by winds, the roots of the plant develop more strongly on the side from which the wind blows. And weaker on the opposite side. Wind reduces the plant's ability to withstand frost and the effectiveness of frost protection. Wind dries out the soil and plants, hinders the implementation of a number of agrotechnical measures, and reduces the effectiveness of grafting due to drying out of the wound.

The wind not only breaks and digs up plants, but also shakes them. The swaying of the plant stem, the stretching of the roots and the bending of the branches under the influence of the wind, impede the transport of assimilation products through the stem-branches to the roots. This prevents the development of new shoots and inhibits the growth of the plant in height.

The wind has a negative mechanical effect on the location of the plant; it removes and carries away the top layer of soil, carries away the snow cover and contributes to the formation of avalanches.

The wind has a negative effect on the subtropical plants common in our region, causing a decrease in their yield, a deterioration in the quality of raw materials.

Winds have a great impact on the yield. They cause the withering of young branches and leaves, the falling of flowers, buds and fruits.

Our observations over the years have shown that citrus plants grown near the windbreak retained their leaves and fruits, while plants located far from the windbreak significantly reduced the number of leaves and fruits.

Even more important is the negative effect of winds on annual crops, which causes them to break and damage leaves.

All of the above negative phenomena related to wind action force a person to create an effective system of measures to protect agricultural plants from winds. For Western Georgia, such a system of measures is the arrangement of anti-erosion and windbreak strips. In this zone, the majority of agricultural plots are located on mountain slopes, therefore, it is necessary to organize a wide network of anti-erosion strips 20-25 meters wide and place them on slopes occupied by agricultural crops. Horizontal afforestation of slopes is a very powerful factor in reducing soil erosion and surface runoff. Anti-erosion strips can be created from both evergreen and deciduous species of plants; plants should be used for planting on slopes with deep soils; cryptomeria, cypress, Bichvinta pine, sedge, poplar, linden, persimmon, fig, oak, hornbeam, etc. In the undergrowth - laurel, birch, linden, hawthorn, box, linden, etc.

In the subtropical zone of Western Georgia, in order to protect cultivated plants from winds, windbreaks should be built, the direction of which should be perpendicular to the prevailing winds. Here, the windbreak should be built mainly from evergreen forest species, which will protect the plantations from hot and dry eastern winds in summer and from cold western and northwestern winds in winter. For this purpose, wind-resistant, fast-growing and high-growing plants should be selected. At the same time, they should not have common pests and diseases with the protected plants, have high economic values and valuable wood, fruits or raw materials for technical purposes. Such plants include cryptomeria, cypress, pines. It is also desirable to use eucalyptus in windbreaks. The distance between the windbreaks depends on the strength and frequency of the prevailing winds, and the characteristics of the protected culture. The distance between the plants used as windbreaks varies from 100-500 meters, the width of the windbreak itself should be 8-10 meters.

The creation of both windbreaks and erosion control strips is a very laborious task and can only be successfully implemented with the widespread use of mechanization.

It is worth noting that in recent years, due to the difficult social situation in the country, a certain part of the population, in order to improve their economic situation, has chosen the path of

barbaric exploitation of plant resources as a source of income, not sparing and mercilessly cutting down forests planted by their ancestors, individual large-sized trees, and windbreaks of state importance. The deplorable facts of encroachment on trees and plants continue to this day. If society does not stand up to this process, the country is threatened with destruction, the population will find itself in a dangerous and critical situation.

In recent times, adverse natural events, torrential rains, floods, droughts have become more frequent. Due to the increase in the frequency of strong winds, there has been a danger of collapse of buildings, the occurrence of avalanches and landslides, and even the threat of famine due to prolonged droughts. Nature does not forgive us and takes revenge for our such aggressive actions. This requires serious thought, we need to all mobilize to participate in the work of afforesting barren areas and restoring damaged windbreaks. In the successful implementation of this noble cause, along with the relevant services, production-institutions, students and a wide range of the population should be widely involved.

The Georgian government has conducted important studies regarding windbreaks (field shelterbelts) and adopted relevant laws. (Hopefully, they will be implemented).

A law was developed on the windbreak (field buffer) zone, Resolution 286 of June 16, 2021 (signed by President S. Zurabishvili) regarding the registration, restoration, cultivation and management of the status zone and the use of the windbreak zone. The purpose of this law is to determine the legal status and management measures of the windbreak zone, protect it from wind erosion and maintain its fertility, ensure the agricultural and microclimate environment, and preserve the prevailing biodiversity of these crops.

On June 19, 2023, the Government of Georgia adopted Resolution N227 on the State Program for the Restoration, Cultivation and Management of Windbreaks, in accordance with Article 22 of the Law of Georgia (signed by Prime Minister Irakli Charibashvili).

The NGO "Sida" developed a draft law "On Field Buffer Strips", a working meeting was held at the Ministry of Environmental Protection and Natural Resources, which was held within the framework of "Forest Protection and Restoration" (Agroforestry). The meeting was attended by specialists and experts in the field.

who noted that the issue of the legal status, maintenance and physical protection of windbreaks is acute throughout the territory of Georgia. Due to the political and social disruptions that have developed in recent decades, as well as the non-existent legislative base, windbreaks have been destroyed, whose role in the country's agriculture, transpiration, recreation, biodiversity and land protection is very large. Today, information about the ownership of windbreaks, the size of the areas of responsibility and the current state is unknown.

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Ecological Essence of the Effect of Windbreaks on Agricultural Crops in the Imereti Zone

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Abstract

The paper analyzes the negative impact of winds on agricultural crops and soil conditions, with particular emphasis on the ecological role of windbreaks in the Imereti region of Western Georgia. Special attention is given to the influence of strong dry eastern winds (fionas), which significantly affect plant transpiration, assimilation processes, soil moisture, and crop productivity. The study also reviews the legislative framework of Georgia regulating the legal status, restoration, cultivation, and management of windbreaks. It is emphasized that, due to political and social disruptions over recent decades and the absence of an effective legislative base, a large proportion of windbreaks have been destroyed. As a result, information about their ownership, areas of responsibility, and current condition remains largely unknown. The article highlights the ecological, agricultural, and socio-economic importance of windbreaks and stresses the urgency of their protection and restoration in the context of increasing climate-related risks.

Keywords

Climate; wind; windbreak; transpiration; assimilation; fionas; upper wind; agroforestry; field shelterbelts.

Introduction

Wind is an essential component of climate and plays a crucial role in the formation of local weather conditions. As an ecological factor, wind has a profound influence on the life activity of living organisms and the condition of their surrounding environment. Its impact is particularly significant in agriculture, where both positive and negative effects directly affect crop productivity, soil fertility, and ecosystem stability.

Climatic Characteristics of Winds in the Imereti Zone

Of particular importance for the Imereti region are **fionas**, or eastern (upper) dry winds, which arise due to pressure differences between the eastern and western slopes of the Likhi Mountains. These winds are characterized by high temperatures and low humidity, leading to rapid soil drying, increased plant transpiration, and reduced assimilation processes. As a result, plant growth is inhibited and crop yields are significantly reduced.

Strong winds are frequent in Kutaisi and throughout the Rioni River plain. Their negative impact becomes especially pronounced during drought periods. In addition to agricultural damage, strong winds pose risks to human safety and infrastructure.

Positive and Negative Effects of Wind on Plants

The **positive effects of wind** include:

- Facilitation of plant pollination;
- Transportation and dispersal of seeds and fruits over long distances;
- Redistribution of cold and moist air masses.

However, the **negative effects of wind** are more significant and diverse:

- Mechanical damage, including uprooting, bending, deformation of stems, and breakage of branches;
- Removal of young shoots and the upper loose soil layer;
- Tearing and damage of leaves;
- One-sided development of plant crowns and root systems, with stronger root growth on the windward side and weaker development on the leeward side;
- Reduced resistance of plants to frost and decreased effectiveness of frost-protection measures;
- Drying of soil and plant tissues, hindering agrotechnical operations;
- Reduced success of grafting due to desiccation of graft wounds.

Wind-induced shaking of plant stems leads to stretching of roots and bending of branches, which disrupts the transport of assimilates from leaves to roots. This inhibits the formation of new shoots and limits vertical plant growth.

Additionally, wind contributes to:

- Soil erosion by removing the fertile topsoil layer;
- Redistribution of snow cover;
- Formation of avalanches and landslides in mountainous areas.

Subtropical plants common to Western Georgia are particularly sensitive to wind stress, resulting in reduced yields and deterioration of raw material quality. Winds also cause wilting of young shoots and leaves, as well as the dropping of flowers, buds, and fruits.

Long-term observations show that citrus plants grown near windbreaks retain significantly more leaves and fruits compared to plants located farther away. Annual crops are especially vulnerable, as strong winds easily break stems and damage foliage.

Role of Windbreaks and Anti-Erosion Strips

The multitude of negative effects associated with wind necessitates the development of effective protective measures for agricultural crops. In Western Georgia, such measures primarily include the establishment of **windbreaks and anti-erosion forest strips**.

Most agricultural lands in this region are located on mountain slopes, making it essential to create a dense network of anti-erosion strips 20–25 meters wide. These should be arranged horizontally across slopes to reduce surface runoff and soil erosion. Horizontal afforestation is one of the most effective means of stabilizing soils and protecting cultivated land.

Anti-erosion strips can be established using both evergreen and deciduous species. Suitable tree species for deep soils include cryptomeria, cypress, Bichvinta pine, cedar, poplar, linden, persimmon, fig, oak, and hornbeam. Recommended undergrowth species include laurel, birch, linden, hawthorn, and boxwood.

Windbreaks in Subtropical Agriculture

In the subtropical zone of Western Georgia, windbreaks should be oriented perpendicular to prevailing wind directions. Evergreen species are particularly effective, as they provide year-round protection against hot, dry eastern winds in summer and cold western and northwestern winds in winter.

Plant species selected for windbreaks should be:

- Wind-resistant, fast-growing, and tall;
- Free from common pests and diseases shared with protected crops;
- Economically valuable, providing timber, fruit, or technical raw materials.

Recommended species include cryptomeria, cypress, pine, and eucalyptus. The spacing between windbreaks depends on wind strength, frequency, and crop characteristics and generally ranges from 100 to 500 meters. The optimal width of windbreak belts is 8–10 meters.

The establishment of windbreaks and erosion-control strips is a labor-intensive process and can only be successfully implemented through the extensive use of mechanization.

Socio-Economic Challenges and Environmental Risks

In recent years, difficult social and economic conditions have led parts of the population to engage in unsustainable exploitation of plant resources. Forests, individual large trees, and windbreaks of national importance have been mercilessly cut down as sources of income. Such destructive practices continue today and pose a serious threat to ecological stability.

If society fails to resist this process, the country faces severe environmental degradation, with potential consequences including food insecurity, increased natural disasters, and declining living conditions. Recent increases in extreme weather events—such as torrential rains, floods, droughts, landslides, and avalanches—highlight the urgent need for action.

Nature responds harshly to irresponsible human activity. Therefore, it is essential to mobilize state institutions, educational organizations, students, and the broader population to participate in afforestation efforts and the restoration of damaged windbreaks.

Legislative Framework in Georgia

The Government of Georgia has undertaken significant steps to address windbreak conservation and management. Notably:

- **Resolution No. 286 of June 16, 2021**, signed by President Salome Zurbashvili, established the legal framework for the registration, restoration, cultivation, and management of windbreak (field protection) zones. The law aims to protect these zones from wind erosion, maintain soil fertility, improve agro-microclimatic conditions, and preserve biodiversity.
- **Resolution No. 227 of June 19, 2023**, adopted by the Government of Georgia and signed by Prime Minister Irakli Gharibashvili, approved the State Program for the Restoration, Cultivation, and Management of Windbreaks in accordance with Article 22 of the Law of Georgia.

Additionally, the NGO *Sida* developed a draft law “On Field Buffer Strips,” which was discussed at a working meeting within the Ministry of Environmental Protection and Natural Resources under the framework of “Forest Protection and Restoration” (Agroforestry). Experts emphasized that the lack of clear legal status, maintenance mechanisms, and physical protection remains a critical issue nationwide. Currently, reliable data on windbreak ownership, responsibility zones, and condition is still unavailable.

Conclusion

Windbreaks play a vital ecological, agricultural, and social role in Georgia. Their restoration and protection are essential for mitigating climate risks, preserving soil fertility, maintaining biodiversity, and ensuring sustainable agricultural development. Effective implementation of existing legislation, combined with public engagement and institutional cooperation, is crucial for safeguarding these invaluable landscape elements.

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Philosophical Sciences

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CONCEPTS OF WAR AND PEACE IN ISLAM

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Abstract

The article is devoted to the analysis of the concepts of war and peace in Islam in their theological, historical-cultural, and ideological dimensions. The key concepts of Islamic doctrine—*jihad*, *dar al-Islam*, *dar al-harb*, *sulh*, and *fitna*—are examined in the context of the Qur'an, the Sunnah, and classical Islamic legal tradition, as well as their transformation under the conditions of modernity and postmodernity. Special attention is paid to distinguishing between traditional, fundamentalist, and radical-sectarian interpretations of war and peace. The article demonstrates that Islam as a religious system is not inherently militant, while radical interpretations are ideologically conditioned and historically secondary phenomena.

Keywords: Islam, war and peace, jihad, Islamic theology, fundamentalism, radicalism, Sharia, ummah.

INTRODUCTION

The problematics of war and peace occupy a central place in the religious and philosophical systems of humanity, as they touch upon fundamental questions of human existence, justice, the permissibility of violence, and the moral responsibility of both the individual and society. In all world religions, these issues are conceptualized not only in ethical terms, but also in ontological and social dimensions, serving as a crucial element of the normative regulation of human behavior. Within the Islamic tradition, the problems of war and peace acquire particular significance due to the syncretic nature of Islam, which integrates religious, legal, social, and political aspects of life within a unified worldview system.

The relevance of this study is обусловлена both by the ongoing armed conflicts in regions of traditional Islamic presence and by the persistent stereotype of Islam as a “religion of war” in public and academic-journalistic discourse. This stereotype is actively reproduced in media and political spaces and is often used for ideological and geopolitical purposes, despite the existence within Islamic doctrine of well-developed concepts of peace, justice, contractual relations, and strict limitations on violence. Such a reduction of a complex religious tradition to its radical interpretations hinders an adequate understanding of both Islam itself and the nature of contemporary conflicts.

The present article is based primarily on the dissertation research “*Ideologemes and Concepts of War and Peace in Islam*”, as well as on classical Islamic sources—the Qur'an and the Sunnah—and the works of Russian and foreign scholars of Islamic studies, philosophy, and religious studies. The

aim of the study is a philosophical and religious-studies analysis of the concepts of war and peace in Islam, with an emphasis on identifying their genesis, evolution, and modern interpretations in the context of historical and sociocultural transformations.

The research employs comparative-historical, cultural, and hermeneutic methods, which make it possible to examine the Islamic doctrine of war and peace as a dynamic system developing through the interaction of religious norms, political realities, and cultural archetypes. This approach allows not only for the reconstruction of traditional representations, but also for their comparison with contemporary forms of religious consciousness and practice.

THEOLOGICAL FOUNDATIONS OF THE CONCEPTS OF WAR AND PEACE IN ISLAM

The Qur'an on War, Peace, and the Permissibility of Violence

The Qur'an, as the primary source of Islamic doctrine, contains multivalent and multilayered provisions concerning war and peace. This is due both to the universalistic nature of its ethical message and to the specific historical conditions under which the early Muslim community was formed. On the one hand, the Qur'an includes verses that permit armed struggle; on the other, it contains numerous calls for peace, patience, restraint, and unconditional respect for human life. This endows the Islamic concept of war and peace with a fundamentally non-absolutist and normatively restricted character.

One of the key principles of Qur'anic ethics is the limitation of permissible violence. Surah al-Baqarah states: "Fight in the way of Allah those who fight you, but do not transgress; indeed, Allah does not love transgressors" (Qur'an, 2:190). This verse not only emphasizes the defensive nature of permissible warfare, but also introduces a clear moral and legal restriction on the use of force, excluding aggression, revenge, and violence for its own sake.

Of particular importance is the Qur'anic affirmation of the sacred value of human life: "Whoever kills a soul not in retaliation for a soul or for corruption upon the earth—it is as if he had killed all mankind" (Qur'an, 5:32). In Islamic ethics, this verse is regarded as a universal moral principle that brings Islam closer to other world religions in recognizing the absolute value of life and the inadmissibility of arbitrary violence.

At the same time, the Qur'an explicitly affirms the priority of peace as the preferred state of social relations: "And if they incline to peace, then incline to it" (Qur'an, 8:61). Thus, in Islamic doctrine war is viewed not as a norm or an ideal, but as a forced and temporary condition, permissible only in the absence of other means of protecting justice and communal order.

As emphasized in the study *Ideologemes and Concepts of War and Peace in Islam*, Qur'anic provisions on war and peace were formed under the specific historical circumstances of the early Muslim community and therefore cannot be absolutized or detached from their socio-political context (see: *Ideologemes and Concepts of War and Peace in Islam*, pp. 52–60).

The Concept of Jihad in the Theology of Traditional Islam

The concept of *jihad* (Arabic: جهاد — "effort," "striving") occupies a central place in the Islamic doctrine of war and peace and represents one of the most complex and interpretatively charged categories of Islamic theology. In classical theology, jihad is understood primarily as a multilevel religious and moral practice, encompassing both the believer's inner spiritual striving and outward activity aimed at protecting and preserving the Muslim community.

In the hadith tradition, a distinction is drawn between the so-called "greater jihad" (*al-jihad al-akbar*)—the individual's struggle against their own passions, sins, and moral vices—and the "lesser jihad" (*al-jihad al-asghar*), which refers to the armed defense of the ummah. Although the

authenticity of certain hadiths concerning the “greater jihad” is the subject of scholarly debate, the distinction itself became firmly embedded in the Sufi, ethical, and philosophical traditions of Islam, establishing the priority of inner moral self-perfection over external violence.

Classical Islamic legal thought emphasized that armed jihad is permissible only under strictly defined conditions: the existence of a real threat to the Muslim community, legitimate political leadership, observance of the norms of Sharia, as well as the principles of proportionality and humanity. As noted in the dissertation research *Ideologemes and Concepts of War and Peace in Islam*, “jihad was never regarded in traditional Islam as an end in itself or a permanent condition, but functioned as an instrument for the protection of the religious and social order” (see: *Ideologemes and Concepts of War and Peace in Islam*, pp. 61–68).

Within Sunni Islam, the major legal schools—the Hanafi, Shafi‘i, Maliki, and Hanbali—developed largely similar approaches to regulating armed jihad. The killing of women, children, the elderly, and monks, as well as the destruction of crops, dwellings, and sources of water, was categorically prohibited. This brings the Islamic legal tradition closer to the fundamental principles of modern international humanitarian law.

Thus, in traditional Islam, jihad functions primarily as an ethical and legal category subordinated to the ideals of justice, responsibility, and peace, rather than as a universal or unconditional justification for violence.

HISTORICAL AND CULTURAL CONCEPTS OF WAR AND PEACE IN ISLAM

Dār al-Islām and Dār al-Ḥarb as Models of World Order

One of the key concepts of Islamic political and legal thought is the dichotomy of the world into *Dār al-Islām* (“the Abode of Islam”) and *Dār al-Ḥarb* (“the Abode of War”). This scheme took shape in early medieval Islamic jurisprudence and reflected the real geopolitical conditions of the period of Islamic conquests.

Dār al-Islām was understood as a space in which Sharia law was in force and the security of the Muslim community was ensured. *Dār al-Ḥarb*, by contrast, referred to territories lying outside the Islamic legal order. However, as emphasized in the study *Ideologemes and Concepts of War and Peace in Islam*, this dichotomy was not absolute and allowed for the existence of intermediate forms—treaty-based territories (*Dār al-Ṣulḥ*)—with which Muslims could maintain peaceful relations (see: *Ideologemes and Concepts of War and Peace in Islam*, pp. 72–79).

It is important to note that the division of the world into *Dār al-Islām* and *Dār al-Ḥarb* was primarily juridical and administrative rather than religious-existential in nature. It did not imply the inevitability of permanent war, but rather functioned as a tool for regulating international relations in the absence of a universal secular legal system.

Ghazawāt, Ṣulḥ, and the Practice of Peace Treaties

The term *ghazawāt* (Arabic: غزوة) in early Islamic tradition referred to military expeditions in which, according to tradition, the Prophet Muhammad himself participated. Over time, the concept acquired a broader meaning and became associated with armed struggle aimed at the defense and spread of Islam.

At the same time, Islamic tradition developed a well-established practice of peace agreements (*ṣulḥ*), which were regarded as a legitimate and preferable means of resolving conflicts. A paradigmatic example is the Treaty of Ḥudaybiyyah (628 CE), concluded between the Muslims and the Meccan Quraysh, which the Qur’an describes as a “clear victory” (Qur’an, 48:1).

As rightly noted in the dissertation, “the practice of *ṣulḥ* demonstrates that the Islamic concept of peace is not secondary or forced, but is embedded in the very structure of religious and political thought” (*Ideologemes and Concepts of War and Peace in Islam*, pp. 85–90).

CONTEMPORARY INTERPRETATIONS OF THE CONCEPTS OF WAR AND PEACE IN ISLAM

Traditionalism and Modernist Approaches

In the contemporary Islamic world, diverse interpretations of the concepts of war and peace coexist, reflecting both continuity with classical theology and legal tradition and attempts to adapt them to the conditions of modernity and a globalizing world. This diversity of approaches is обусловлено differences in historical experience, socio-political conditions, and cultural contexts in which Muslim communities operate.

The traditionalist approach relies on the norms of classical *fiqh*, the authority of the Qur'an and the Sunnah, and historically established models of relations between the Muslim community and the external world. Within this framework, war is viewed as a forced and strictly limited means of protecting the *ummah*, permissible only under specific religious and legal conditions, while peace is recognized as the normative and preferred state of social order. Traditionalism proceeds from the need to maintain a balance between religious norms and social stability, which excludes the absolutization of violence and the arbitrary expansion of the concept of jihad.

Modernist currents in Islam, which emerged in the late nineteenth and early twentieth centuries, sought to rethink the concepts of war and peace in the context of the colonial experience, national liberation movements, and the formation of nation-states. Their representatives emphasized the necessity of correlating classical Islamic norms with the realities of the modern world, including the development of international law, human rights discourse, and intercivilizational dialogue. As M. Hodgson noted, Islamic civilization originally developed as a “moral-normative system” in which political violence was subject to ethical and legal restraint rather than sacralization (Hodgson, M. G. S. *The Venture of Islam*, Vol. 1. Chicago, 1974, pp. 58–63).

In this context, Islamic modernists stressed the universalist potential of Islamic ethics, the compatibility of Islam's core principles with the norms of international humanitarian law, and the need to abandon the literal transfer of medieval legal categories into contemporary realities. In such interpretations, jihad is increasingly understood as a social and moral striving aimed at achieving justice, societal development, and overcoming structural violence.

Fundamentalism and Radical-Sectarian Interpretations

Fundamentalist movements of the twentieth and twenty-first centuries have radically narrowed and transformed the traditional understanding of the concepts of war and peace, placing armed struggle at the center of religious practice. In such interpretations, jihad loses its multilevel and ethical character, turning into a universal instrument of political mobilization and violence. G. Kepel emphasizes that this transformation of jihad is primarily linked to crises of modernity, postcolonial frustration, and socio-political marginalization, rather than to the logic of classical Islamic theology (Kepel, G. *Jihad: The Trail of Political Islam*. Cambridge, 2002, pp. 24–31).

Fundamentalism is characterized by a literalist reading of Qur'anic texts, the rejection of the historical context of their revelation, and the absolutization of the dichotomy between “believers” and “unbelievers.” As a result, religious categories acquire an ideological character, while the complex system of Islamic legal and ethical thought is reduced to a set of slogans and prescriptions.

Particularly destructive are radical-sectarian interpretations, within which jihad is often proclaimed the “sixth pillar of Islam,” and terrorism is presented as a form of religious service. The principle of *takfir* is employed to legitimize violence not only against non-Muslims, but also against Muslims who do not share the ideology of radical groups. As emphasized in the study *Ideologemes and Concepts of War and Peace in Islam*, such approaches are anti-systemic in nature and undermine the foundations of Islamic civilization from within, destroying its legal, ethical, and spiritual integrity (see: *Ideologemes and Concepts of War and Peace in Islam*, pp. 123–135).

The Peacebuilding Potential of Islam and International Security

Alongside radical interpretations, contemporary Islam is also witnessing the active development of a peacebuilding trend oriented toward civilizational dialogue, conflict prevention, and the protection of human rights. The Islamic concept of peace is grounded in the principles of justice (*‘adl*), mercy (*rahma*), and human responsibility as God’s vicegerent on earth (*khalifa*), which gives it a pronounced ethical and universalist dimension.

An important role in shaping the peacebuilding agenda is played by international Islamic organizations such as the Organisation of Islamic Cooperation (OIC), the Islamic World Educational, Scientific and Cultural Organization (ICESCO), as well as numerous non-governmental initiatives. Their activities are aimed at the settlement of regional conflicts, humanitarian assistance, the development of education, and countering religious extremism.

Contemporary Muslim theologians and philosophers emphasize that Islamic ethics of war and peace can be integrated into the system of international relations as a source of normative restraints on violence and as a foundation for interreligious and intercultural cooperation. John L. Esposito notes that most Muslim societies understand jihad primarily as moral striving and a struggle for social justice rather than as an instrument of expansion or domination (Esposito, J. L. *Islam: The Straight Path*. Oxford, 2011, pp. 93–101).

In this context, Islam appears not as a factor of inevitable conflict, but as a potential resource for sustainable peace—capable of contributing to the formation of a global ethic of nonviolence and responsibility amid contemporary international challenges.

A COMPARATIVE ANALYSIS OF THE CONCEPTS OF WAR AND PEACE IN CHRISTIANITY, ISLAM, AND FAR EASTERN RELIGIONS

War and Peace in the Christian Tradition

The Christian concept of war and peace developed in a tense dialogue between the Gospel ideal of nonviolence and the historical necessity of political and social protection for Christian communities. In the New Testament, a radical ethic of love and nonresistance to evil by violence predominates, expressed most vividly in the Sermon on the Mount: “Love your enemies... and pray for those who persecute you” (Matthew 5:44). Early Christianity, existing under conditions of persecution, regarded war as a manifestation of the sinfulness of the fallen world and peace as the highest form of God-pleasing, eschatologically oriented life.

The situation changes from the fourth century onward, after the Christianization of the Roman Empire, when the Church faced the need to conceptualize legitimate violence within the context of state power. In this period, the doctrine of “just war” (*bellum iustum*) takes shape, most consistently elaborated by Augustine of Hippo. In his view, war is permissible only under three key conditions: legitimate authority, a just cause, and a right intention aimed not at revenge or gain, but at the restoration of order and peace (Augustine, *De Civitate Dei*, XIX, 7–15).

Thomas Aquinas further developed Augustine's concept within scholastic theology, emphasizing that even a just war remains morally problematic and is justified solely as a means of restoring a just peace (*Summa Theologica*, II-II, q. 40, a. 1). Thus, in Christianity war is conceived as a necessary evil, permissible in the conditions of a fallen world, whereas peace functions as a normative and eschatological ideal associated with the Kingdom of God.

The Islamic Model: The Normativity of Peace and the Restriction of War

In the Islamic tradition, as shown above, peace (*ṣulḥ*, *salām*) is likewise the preferred and normative state of social relations, whereas war is permissible only within strictly defined legal and ethical boundaries. Unlike Christianity, Islam from the very beginning formed not only as a religion but also as a communal legal order, which led to an earlier and more detailed juridical regulation of war and violence.

The Islamic concept of war and peace rests on a combination of religious, legal, and ethical norms закреплённых in the Qur'an, the Sunnah, and classical *fiqh*. War is permitted as a means of defending the *ummah*, restoring justice, and preventing "corruption on earth," yet it is subject to strict restrictions concerning both the aims and the means of conducting hostilities. In this sense, the Islamic tradition demonstrates functional similarity to the Christian doctrine of just war, while differing in its more developed legal detail.

As B. S. Erasov notes, Islamic civilization developed an "orthopraxic model of religion in which violence is subject to juridical and ethical control rather than sacralization" (Erasov, B. S. *Social Cultural Studies*. Moscow, 2000, pp. 312–318). War in Islam does not acquire a sacred status in and of itself and is not treated as a religious ideal; peace, by contrast, is understood as the condition most consistent with the divine plan and social harmony.

Far Eastern Religions: Confucianism, Daoism, and Buddhism

In Far Eastern religious and philosophical traditions, the concepts of war and peace are formed within a different ontological and ethical paradigm than that of monotheistic models. Here, the emphasis shifts from normative-legal regulation of violence to cosmological harmony, moral self-cultivation, and the inner transformation of the individual.

Confucianism views war primarily as a sign of a disruption of harmony (*hé*) and moral order in society. Social stability and peace are achieved not through military force, but through the moral perfection of rulers and subjects alike. Confucius emphasized that "the noble man seeks harmony, not discord" (*Analects*, XIII, 23), thereby linking peace to the ethics of duty and ritual order (*lǐ*).

The Daoist tradition is characterized by a radically anti-militarist orientation. In the *Dao De Jing*, war and weapons are regarded as an ultimate evil and as signs of deviation from the Dao: "Fine weapons are instruments of misfortune; all creatures detest them" (*Dao De Jing*, ch. 31). Peace is understood here as the natural state of the world arising from adherence to the principle of *wú wéi* (non-action), whereas war appears as a symptom of cosmic imbalance.

Buddhism, in turn, is grounded in the principle of *ahimsa*—non-harm toward all living beings—which possesses not only an ethical but also an ontological dimension. Although the historical practice of Buddhist states has not always conformed to this ideal, the normative doctrine of Buddhism is consistently oriented toward nonviolence, compassion (*karuṇā*), and liberation from suffering, both individual and collective (Eliade, M. *A History of Religious Ideas*, Vol. 2. Chicago, 1984, pp. 56–61).

Comparative Conclusions

Comparative analysis demonstrates that in all the religious traditions examined, peace functions as a normative and value-prioritized state, while war is conceptualized as a forced, limited, and morally problematic phenomenon. Differences among the traditions concern not so much the evaluation of war itself as the ways in which it is normatively restricted, institutionalized, and philosophically interpreted.

Christianity and Islam primarily develop ethical and legal models for limiting violence, whereas Far Eastern religions focus on cosmological harmony and the inner moral transformation of the human being. Taken together, these approaches form a rich interreligious resource for reflecting on war and peace in the context of contemporary global challenges.

ECUMENISM AND INTERRELIGIOUS DIALOGUE AS PATHS TO THE AFFIRMATION OF PEACE

Theological Foundations of Interreligious Dialogue

The idea of interreligious dialogue as a means of affirming peace is rooted in the theological traditions of the world's religions and is based on the recognition of the universal value of the human person, moral responsibility, and the shared human aspiration for justice and peace. In the religious dimension, dialogue is not merely a form of communication, but a distinctive ethical stance that presupposes respect for the Other while preserving one's own identity.

In Christianity, the theological foundation of interreligious dialogue is linked to a universalist understanding of love (*agapē*) and the dignity of every human being as created in the image and likeness of God. In the Sermon on the Mount, peacemaking is elevated to the level of a religious ideal: "Blessed are the peacemakers, for they shall be called sons of God" (Matthew 5:9). This principle establishes a normative framework for the Christian approach to conflict, prioritizing reconciliation, forgiveness, and the rejection of violence as a means of resolving disputes.

An important stage in the institutionalization of this stance was the Second Vatican Council of the Catholic Church, where the declaration *Nostra Aetate* recognized interreligious dialogue as one of the key instruments for conflict prevention and peacebuilding. The Council emphasized the need for respectful attitudes toward other religions and acknowledged the presence within them of "rays of truth," marking a fundamental shift from a confrontational model to one of dialogue (*Nostra Aetate*, §2).

In the Islamic tradition, the theological foundation of dialogue is expressed in the recognition of religious and cultural diversity as part of the divine plan. The Qur'an states: "O mankind! Indeed, We created you from a male and a female and made you peoples and tribes that you may know one another" (Qur'an, 49:13). This verse is interpreted by many contemporary Muslim theologians as an injunction toward peaceful coexistence, mutual understanding, and cooperation among different religious and cultural communities.

An additional normative foundation for interreligious dialogue in Islam is the principle of freedom of belief: "There is no compulsion in religion" (Qur'an, 2:256). This principle excludes the legitimization of forced conversion and establishes a framework for voluntary and responsible religious choice, making dialogue not only possible but religiously justified.

In a generalized form, the theological significance of interreligious dialogue was articulated by Hans Küng in his now-classic thesis: "There will be no peace among the nations without peace among the religions" (Küng, H. *Global Responsibility*. London, 1991, pp. 15–18). This formulation underscores the structural interconnection between religious conflicts and global security and has become a conceptual foundation for many interreligious initiatives of the late twentieth and early twenty-first centuries.

Institutional Forms of Ecumenism and Dialogue

The ecumenical movement in Christianity and interreligious dialogue platforms more broadly acquired institutional form in the second half of the twentieth century, largely as a result of the experience of world wars, decolonization, and the growth of global interdependence. Under these conditions, religions increasingly came to be seen not only as potential sources of conflict, but also as important resources for peacebuilding.

Key institutional forms of dialogue include the World Council of Churches, the Parliament of the World's Religions, UNESCO's interreligious programs, as well as the activities of the Organisation of Islamic Cooperation and its affiliated cultural and educational structures. These platforms contribute to the formation of a shared language for discussing issues of war, peace, social justice, and global ethics.

A philosophical and religious-studies interpretation of these processes was proposed by John Hick, who emphasized that genuine interreligious dialogue promotes the "de-absolutization of confessional claims without the loss of religious identity" (Hick, J. *An Interpretation of Religion*. New Haven, 1989, pp. 240–245). In this context, dialogue does not imply syncretism or the erosion of doctrinal differences, but rather constitutes a form of responsible coexistence grounded in mutual recognition and ethical solidarity.

Thus, ecumenism and interreligious dialogue may be regarded as important elements of a contemporary strategy for the affirmation of peace, capable of reducing the conflict potential of religious differences and transforming them into a resource for cooperation. Their effectiveness, however, directly depends on the ability of religious communities to resist the politicization of faith and radical interpretations that replace the logic of dialogue with that of confrontation.

FORECASTING THE FUTURE INTERACTION OF RELIGIONS: PEACE OR WAR?

Scenarios of Conflict: Religion and Global Challenges

In contemporary academic, political, and philosophical thought, the thesis of the potential—or even inevitable—conflict-prone nature of religion under conditions of globalization is frequently articulated. Increased migration, cultural hybridization, the crisis of the nation-state, and the weakening of traditional forms of identity are often interpreted as factors that intensify religious self-identification and, at the same time, interreligious tensions. In this context, religion is perceived as a marker of civilizational difference and a symbol of collective identity.

The most well-known conceptualization of this approach is the "clash of civilizations" theory proposed by Samuel Huntington, who regarded religion as one of the key factors of future global conflicts (Huntington, S. *The Clash of Civilizations*. New York, 1996, pp. 47–52). According to this model, religious differences are seen as more stable and mobilizing than ideological or economic ones, allegedly making conflicts based on religion particularly acute and difficult to resolve.

However, this approach has been subjected to serious and well-founded criticism for its reductionism and its neglect of the internal diversity of religious traditions. Critics of Huntington point out that he effectively equates religion with political identity, ignoring the distinction between religious faith, theology, and their ideologized interpretations. Moreover, within the same religious tradition, both peace-oriented and radical currents may coexist, making it impossible to attribute an inherently conflictual function to religion as such.

Contemporary research increasingly demonstrates that religion most often acts not as the root cause of conflicts, but as a symbolic and mobilizing resource used in situations of socio-economic crisis, political instability, and identity breakdown. In this sense, the risk of so-called "religious

wars” is primarily associated with processes of marginalization, inequality, erosion of social trust, and the instrumentalization of religious symbols by political actors. Religion thus becomes the language of conflict, but not its fundamental cause.

Scenarios of Peace: Global Ethics and the Responsibility of Religions

An alternative scenario for the development of interreligious interaction envisages a strengthening of the role of religions as bearers of global ethics and as sources of normative constraints on violence. In the context of the crisis of secular ideologies and the weakening of universalist projects of modernity, religions are increasingly viewed as potential agents in the formation of transnational moral orientations capable of transcending cultural and civilizational boundaries.

One of the most influential concepts in this direction is the idea of a “global ethic” developed by Hans Küng and his followers. According to this concept, despite their doctrinal differences, the world’s religions share a basic set of universal moral principles, such as nonviolence, justice, solidarity, respect for human dignity, and responsibility for the future of humanity (Küng, H. *A Global Ethic for Global Politics and Economics*. Oxford, 1997, pp. 29–35). These principles can serve as the foundation for a global moral consensus in a pluralistic world.

In this context, Islam, Christianity, and the religions of the Far East possess significant peacebuilding potential. The Islamic concept of justice and human responsibility as God’s vicegerent on earth, the Christian ethic of love and reconciliation, and the Far Eastern ideas of harmony and nonviolence together form a powerful interreligious resource for conflict prevention and the cultivation of a culture of peace.

Thus, the future of interreligious interaction depends less on doctrinal differences than on the ability of religious communities and their leaders to resist the politicization of faith, extremist interpretations, and the reduction of religion to an ideological instrument. If dialogical, ethical, and peace-oriented interpretations prevail, religions may become an important factor of sustainable peace and global security. Otherwise—if trends toward radicalization and instrumentalization persist—they risk being drawn into new forms of conflict in which religious language merely masks contradictions that are non-religious in nature.

RESULTS AND CONCLUSION

The analysis conducted allows us to conclude that the concepts of war and peace in Islam constitute a complex, dynamic, and multidimensional system formed through the interaction of theological, legal, ethical, and cultural-historical factors. Contrary to widespread stereotypes, traditional Islam does not absolutize war nor regard it as a normative or desirable state of social relations. On the contrary, war in Islamic doctrine is conceived as a forced and temporary measure, permissible only within strictly defined limits and subject to rigorous moral and legal constraints. An examination of classical sources—the Qur’an, the Sunnah, and *fiqh*—demonstrates that peace (*salām*, *ṣulḥ*) in Islam is not a secondary concession to circumstances, but a value-prioritized state most consistent with the divine plan and social harmony. The concept of jihad, in its traditional understanding, is primarily an ethical and moral category oriented toward inner spiritual striving, social responsibility, and the defense of a just order, rather than a universal justification for violence.

Radical interpretations of war and jihad that emerged in the twentieth and twenty-first centuries are the result of modern ideological, political, and socio-cultural distortions rather than an organic continuation of the Islamic theological tradition. Their emergence and spread are closely linked to socio-economic crises, postcolonial frustration, geopolitical conflicts, and identity crises under

conditions of globalization. In these interpretations, religion loses its ethical and spiritual meaning, becoming an instrument of political mobilization and violence.

A comparative analysis of Islamic, Christian, and Far Eastern religious traditions shows that, despite differences in ontological and cultural foundations, all converge in recognizing peace as a normative and value-prioritized state, while war is understood as a morally problematic and limited phenomenon. Differences among the traditions concern not so much the evaluation of war itself as the ways in which it is normatively constrained, institutionalized, and philosophically interpreted—from the ethical-legal models of the monotheistic religions to the cosmological and moral harmony emphasized in Far Eastern teachings.

Of particular importance in contemporary conditions is the development of ecumenism and interreligious dialogue as a response to the global challenges of war, extremism, and cultural fragmentation. Possessing significant moral authority and symbolic resources, religions can function not as sources of conflict, but as important factors in conflict prevention. Dialogue grounded in respect for religious diversity and shared responsibility for the fate of humanity makes it possible to transform religious differences from a source of tension into a resource for cooperation.

Prognostic analysis shows that the future of interreligious interaction is not predetermined by either a scenario of conflict or a scenario of peace. It depends primarily on which interpretations—peace-oriented or radically ideologized—come to dominate religious consciousness and practice. If trends toward the politicization of faith and the reduction of religion to an ideological instrument persist, the risk of conflicts increases, in which religious language will merely mask contradictions that are non-religious in nature. At the same time, the strengthening of dialogical, ethical, and humanistic interpretations opens the prospect of forming a global culture of peace.

In this context, the Islamic concept of peace—grounded in the ideas of justice, responsibility, and dialogue—possesses significant potential for strengthening international security and intercultural understanding in the twenty-first century. The comprehension of this potential and its practical realization constitute not only a scholarly, but also a civilizational task, upon whose resolution the future interaction of religions, peoples, and cultures largely depends.

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Physical and Mathematical Sciences

The Lepton Spectrum as a Phase-Stability Ladder: Universal Temporal Functionals and the Exponential Mass Hierarchy

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Abstract

The Lepton Spectrum as a Structural Consequence of Hyper-Temporal Dynamics: Nonlinear Localization and the Emergence of the Flavor Hierarchy

The Standard Model remains descriptive in its treatment of the fermion flavor hierarchy, utilizing over twenty empirical Yukawa couplings to parameterize observed masses without providing a dynamical origin for their values. This paper proposes a reformulation of the leptonic sector within the Temporal Theory of the Universe (TTU)—a deductive framework that recovers the mass spectrum from the first principles of 5D temporal dynamics on an $M^4 \times S^1$ manifold. We suggest that leptons are not fundamental points, but stable, phase-locked resonant modes (chronons) of a universal temporal field τ .

By implementing a Consistency Enforcement Loop (CEL), we demonstrate that the fundamental parameters established in the hadronic sector—specifically temporal stiffness (χ) and the hyper-time radius (R_Θ)—necessitate the observed lepton hierarchy with significant Parameter Rigidity. The ≈ 3500 -fold mass disparity between the electron and the tau lepton is recovered as a result of Nonlinear Localization: as the topological winding number n increases, the medium's saturation threshold (τ_{crit}) induces an exponential surge in phase inertia.

The PMNS mixing matrix is derived through the Overlap Geometry of delocalized temporal profiles, providing a causal explanation for the large mixing angles observed in neutrinos relative to the narrow CKM quark mixing. Numerical realizations, obtained via a self-consistent iterative scheme (SCTF), achieve a predictive accuracy exceeding 99.9% for charged lepton masses, serving as a proof-of-principle for the framework's deductive capacity. Furthermore, the model suggests a topological prohibition of a fourth generation due to phase decoherence at the saturation limit. This approach indicates that the algebraic "bookkeeping" of the Standard Model may be successfully reformulated as a deterministic map of temporal geometry, where matter emerges as a stable harmonic resonance of the $M^4 \times S^1$ manifold.

Keywords: *Temporal Theory of the Universe, Lepton Hierarchy, Nonlinear Localization, PMNS Matrix, Hyper-time Geometry, Parameter Rigidity.*

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1. Introduction: The Flavor Puzzle and Parameter Rigidity

1.1. The Crisis of Yukawa Arbitrariness and the Need for Dynamical Rigidity

The Standard Model (SM) of particle physics stands as a descriptive masterpiece but remains a causal void. Nowhere is this more evident than in the "Flavor Puzzle." The mass spectrum of charged leptons spans nearly four orders of magnitude: from the electron (0.511 MeV) to the tau lepton (1776.86 MeV). In the current paradigm, these values are not derived from first principles; they are merely "hand-inserted" via Yukawa coupling constants y_f , which function as empirical placeholders for a missing dynamical explanation.

A factor of ≈ 3500 between the first and third generations cannot be dismissed as an accidental numerical coincidence. It implies a rigid, underlying dynamical scaling that the SM is structurally forced to ignore. Within the Temporal Theory of the Universe (TTU), we argue that a truly fundamental theory must possess Parameter Rigidity:

- **Eigenvalue Necessity:** Masses must be discrete eigenvalues of a fundamental dynamical process. In TTU, this process is the circulation of temporal phase within a compact hyper-time dimension Θ . Consequently, the observed masses are not just parameters, but the only possible resonant frequencies at which the temporal field can reach a state of phase-locking (resonance synchronization) within the $M^4 \times S^1$ manifold.

- **Structural Stability:** Unlike the SM, where y_f can be continuously adjusted without collapsing the theory, TTU posits that any deviation from the observed mass ratios would violate the topological stability of the temporal medium itself. The field τ cannot sustain "arbitrary" oscillations; it only supports modes that satisfy the variational closure of the 5D Master Action.

- **The End of "Free Knobs":** The "Flavor Puzzle" is resolved by recognizing that fermion masses are not "free knobs" but quantized resonances of the temporal field $\tau(x, \Theta)$. The mass is the energy-equivalent of the phase inertia required to maintain a stable soliton against the vacuum's temporal conductivity ξ_0 .

In this framework, the vast mass gap between generations is revealed not as an arbitrary hierarchy, but as a Phase-Stability Ladder. The 3500-fold jump is a direct geometric consequence of how the invariant temporal gradient $\mathcal{G}$ reaches the saturation threshold τ_{crit} within the compact manifold $M^4 \times S^1$. Just as a physical medium has a limit to its deformation, the "stiffness" of time prevents any intermediate mass states, forcing the fermion spectrum into a strictly quantized, exponential ladder of stable states.

1.2. The TTU Thesis: Leptons as Bare Temporal Solitons (Chronons)

Within the Temporal Theory of the Universe (TTU), we propose a fundamental ontological distinction between leptonic and baryonic matter based on their internal temporal topology. We define leptons as "bare" temporal solitons or chronons—elementary excitations of the temporal field that lack the composite vortex structure of the hadronic sector.

1.2.1. Harmonic Resonance vs. Vortex Complexity

Unlike nucleons, which emerge as complex "temporal knots" with high internal phase-vortex stiffness (the strong sector), leptons represent the fundamental harmonic modes of the temporal field $\tau(x, \Theta)$ on the compact manifold $M^5 = M^4 \times S^1$.

- **Nucleons (Adhons):** Characterized by a high "ontological tension" arising from the coupling of time (τ^+) and anti-time (τ^-) flows. This coupling results in a complex vortex structure ($\nabla \times \mathbf{j}_\tau \neq 0$) where the energy is stored in the winding of multiple temporal strands. These internal degrees of freedom, which the Standard Model interprets as quarks, are in TTU the topological requirements for stabilizing a multi-vortex system against the background temporal conductivity ξ_0 .

- **Leptons (Chronons):** Represent "clean", vortex-free ($\nabla \times \mathbf{j}_\tau \rightarrow 0$) oscillations of the temporal potential. They are the solo-vibrations of the temporal medium, where the mass is determined solely by the phase inertia of the n -th harmonic in the hyper-time dimension Θ . This lack of internal vortex complexity is precisely why leptons do not participate in strong interactions; they lack the "topological hooks" (vortex-vortex coupling) necessary to engage with the gluonic-like temporal gradients of the nucleus.

1.2.2. The Phase-Stability Ladder and the S^1 Resonant Cavity

The observed hierarchy $e \rightarrow \mu \rightarrow \tau$ is thus revealed not as a collection of random couplings, but as a Phase-Stability Ladder. Each generation corresponds to a specific topological winding number (or harmonic index) n in the hyper-time dimension.

In this framework:

- **The Electron ($n = 1$):** The ground state, representing the minimal stable excitation of the temporal field. It is the fundamental mode where the phase makes a single complete rotation along R_Θ .
- **The Muon ($n = 2$) and Tau ($n = 3$):** Higher-order resonances that exist only because the non-linear saturation of the field prevents the collapse of these higher-energy states.

The jump in mass between these states is governed by the geometric curvature of hyper-time and the non-linear saturation of the temporal gradient. Because hyper-time Θ is compact (S^1), it acts as a resonant cavity that naturally quantizes the mass spectrum. Just as a violin string supports only specific harmonics determined by its length and tension, the temporal vacuum supports only specific chronon states determined by the radius R_Θ and the saturation stiffness τ_{crit} .

This eliminates the need for the Higgs mechanism in the leptonic sector. In TTU, mass is not an external property bestowed by a scalar field; it is the intrinsic energy required to sustain a stable, quantized phase-oscillation against the "stiffness" of the temporal vacuum. The exponential

nature of the mass hierarchy is a direct result of the invariant gradient $\mathcal{G}$ approaching the saturation limit, where each subsequent harmonic requires exponentially more energy to be "packed" into the same compact hyper-time radius.

2. From Master Action to Lepton Eigenmodes

2.1. Structural Deduction from the 5D Master Action

The fundamental dynamics of the Temporal Theory of the Universe (TTU) are governed by the 5D Master Action S_{TTU} , defined on the extended manifold $M^5 = M^4 \times S^1$. Unlike the Standard Model, where kinetic terms, gauge couplings, and mass parameters are postulated independently for each sector, TTU recovers the leptonic sector as a mandatory dimensional reduction of the universal functional:

$$S_{\text{TTU}} = \int_{\text{M}^5} \left[\kappa (\partial_A \tau \partial^A \tau) - \mathcal{V}(\mathcal{G}) \right] d^4x d\Theta$$

Where $\mathcal{G} = \mathcal{V}((\partial_\mu \tau)^2 + (R\Theta \partial_\Theta \tau)^2)$ is the invariant temporal gradient. For the leptonic sector—defined by the vortex-free limit ($\nabla \times \mathbf{j}_\tau \rightarrow 0$)—the field $\tau(x, \Theta)$ naturally decouples into a 4D spatial envelope and a 1D hyper-temporal mode $\psi_n(\Theta)$.

The effective Hamiltonian governing these modes is not an approximation, but a direct structural consequence of the 5D Master Action:

$$\hat{H}_{\text{eff}} = -(\hbar^2 / 2\kappa) \partial^2 / \partial \Theta^2 + \chi \cdot \mathcal{A}(\partial_\Theta \tau)$$

In this framework, mass is elevated from an extrinsic coupling constant (Yukawa sector) to the emergent phase inertia of the n -th harmonic mode. This transition is governed by three rigid, non-negotiable mechanisms:

- **Nonlinear Backreaction and Phase-Locking:** The term $\chi \cdot \mathcal{A}$ represents the medium's self-consistent response to the temporal flow. It acts as a topological filter, ensuring that only quantized, phase-locked states can exist as stable solutions. Any mode that does not satisfy the S^1 resonance conditions is suppressed by the medium's internal "stiffness."
- **Eigenvalue Invariance (The ξ_0 Constraint):** The mass m_n is the energy eigenvalue of the field's internal rotation. Physically, it represents the work required to sustain a stable oscillation against the temporal vacuum conductivity ξ_0 (the ontological equivalent of ϵ_0). Because ξ_0 is a universal vacuum property, the mass spectrum is globally fixed.
- **Metric Anchoring and Gravitational Footprint:** A critical feature of TTU is that the emergent metric $g_{\mu\nu}$ is a direct functional of the temporal gradient: $g_{\mu\nu} = \eta_{\mu\nu} + \chi \partial_\mu \tau \partial_\nu \tau$. Consequently, the mass eigenvalue m_n is "anchored" to the local curvature. A higher harmonic (n) increases the local temporal density, necessitating a specific gravitational curvature. In TTU, gravity and mass are two sides of the same topological coin.

This deduction demonstrates that the leptonic mass spectrum is a topological necessity of the M^5 geometry. By deriving the hierarchy from the 5D Master Action, we prove that the empirical parameters of the Standard Model are merely descriptive "shadows" of a single, unified dynamical principle, rendering the Yukawa sector structurally redundant.

2.2. Universality and Parameter Rigidity (The CEL Protocol)

The defining characteristic of TTU is the total preservation of constants across all physical scales. While the Standard Model employs a "buffet-style" selection of parameters to fit different sectors, TTU operates under a strict Consistency Enforcement Loop (CEL). The parameters $\{\kappa, R_\Theta, \tau_{\text{crit}}\}$ are not "best-fit" variables, but locked properties of the temporal vacuum:

- κ (Hyper-temporal Inertia): This constant normalizes the relationship between phase frequency and energy, defining the scale of action ($\hbar$). In TTU, κ is strictly uniform; the inertia of a phase-wave in an electron is identical to that in a nucleon, reflecting the uniform density of the temporal substrate.
- R_Θ (Hyper-time Radius): The scale of S^1 compactification is a global geometric invariant. The "resonant cavity" of hyper-time is universal, meaning every particle, regardless of its "flavor," is constrained by the same boundary conditions of the M^5 manifold.

- τ_{crit} (Saturation Threshold): This defines the non-linear limit of the temporal gradient. It is the "stiffness" of time that prevents infinite phase-packing, naturally limiting the stable fermion generations to three.

2.2.1. Deductive Closure

Within this locked parameter space, the only degree of freedom is the Topological Index n (the winding number). The accuracy of >99.99% achieved in the hadronic sector is thus not an isolated success, but a benchmark of the Universal Functional.

Applying these same locked constants to the leptonic sector achieves Deductive Closure (Status: CLOSED, Appendix K.13). In TTU, to shift the mass of the electron would require altering the fundamental conductivity of the vacuum, which would simultaneously trigger the collapse of proton stability. This inter-sector interdependency is the ultimate hallmark of a truly unified theory, proving that lepton masses are necessitated, not merely predicted, by the architecture of the universe.

3. The Geometry of Hyper-Time Localization

3.1. Phase Quantization in Θ and the Resonant Spectrum

The compact geometry of the hyper-time dimension Θ acts as a fundamental boundary constraint on the excitations of the temporal field. For a chronon (lepton) to exist as a stable, self-perpetuating entity, the temporal potential τ must satisfy the condition of topological closure over the S^1 manifold. This necessitates the quantization of the phase winding, ensuring the field remains single-valued:

$$\oint_{\Theta} (2\pi R_{\Theta}) (d\tau/d\Theta) d\Theta = 2\pi n, n \in \mathbb{Z}^+$$

Each integer n represents a distinct quantum of temporal rotation. This quantization is the physical origin of the three-generation structure ($n = 1, 2, 3$). Within the TTU framework, generations are not arbitrary "flavors"; they are discrete harmonic overtones of the universal temporal substrate:

- **Boundary Synchronization:** Stability depends on the constructive interference of τ -waves circulating the R_{Θ} radius. Any non-integer winding results in immediate "evaporation" into the temporal vacuum due to destructive interference.
- **Geometric Tension:** While the Standard Model introduces scales via the Higgs VEV, TTU derives them from the geometric tension of the S^1 cycle. The radius R_{Θ} defines the fundamental "pitch" of the resonant cavity.
- **The Ground State ($n = 1$):** The electron represents the simplest possible topological knot. Higher generations ($n = 2, 3$) are excited states maintained by the non-linear stiffness of the medium, which prevents spontaneous decay into lower-order harmonics.

3.2. The Exponential Mechanism: Nonlinear Compression and Mass Jump

The "Flavor Puzzle"—the massive hierarchy $m_{\tau} \gg m_{\mu} \gg m_e$ —is resolved in TTU through the mechanism of Nonlinear Localization. In a standard linear system, the energy of harmonics would scale quadratically (n^2); however, the temporal medium is an active, self-reacting substrate governed by the saturation potential $V(\tau)$ and the critical gradient threshold τ_{crit} .

3.2.1. The Non-linear Feedback Loop As the topological winding number n increases, the mode ψ_n encounters an exponential rise in the medium's resistance, triggering a three-stage feedback loop:

1. **Gradient Crowding and Temporal Impedance:** To maintain n complete phase rotations within the fixed geometric radius R_{Θ} , the average temporal gradient $\partial_{\Theta} \tau$ must rise. As $n \rightarrow 3$, the system approaches the Temporal Impedance Limit. The "phase-space" available for rotation becomes exhausted, causing the medium to "stiffen" as it resists further displacement.
2. **Potential Squeezing (The χ -Compression):** As the local gradient approaches the saturation limit τ_{crit} , the non-linear backreaction χ ceases to be a perturbative correction and becomes a compressive force. This forces the wave profile ψ_n to transition from a uniform distribution

into extremely high-density peaks. The effective width of the mode, $\Delta\Theta_{\text{eff}}$, is "squeezed" by the vacuum's own stiffness.

3. **Exponential Energy Surge:** The observable mass m_n is the energy-equivalent of the total phase inertia, determined by the integral of the squared gradient:

$$m_n \sim \int_0^{2\pi R_\Theta} |\partial_\Theta \tau_n|^2 d\Theta \approx n^2 / \Delta\Theta_{\text{eff}}(n)$$

3.2.2. The Origin of the 3500-Fold Gap

Near the threshold τ_{crit} , the effective width $\Delta\Theta_{\text{eff}}$ decreases non-linearly (logarithmically approaching the coherence length). This explains why the Tau lepton ($n = 3$) is ≈ 3500 times heavier than the electron ($n = 1$):

- **Electron ($n = 1$):** Operates in the linear regime where $\Delta\Theta_{\text{eff}} \approx 2\pi R_\Theta$. Mass is minimal.
- **Tau ($n = 3$):** Operates in the deep saturation regime. The "packing" of three full cycles into the resonator requires such extreme Geometric Pressure that the energy density spikes exponentially.

3.2.3. Structural Result: The Spectroscopic Signature of Time This mechanism proves that the fermion hierarchy is not a random distribution of coupling constants, but a spectroscopic signature of the non-linearity of the temporal medium. The leptons are "squeezed" by the very fabric of hyper-time. Their masses are not arbitrary numbers; they are the measure of the vacuum's resistance to topological complexity. In TTU, the mass of the Tau is the point where the $M^4 \times S^1$ manifold reaches its maximum stable "tension" before the regime of topological breakdown.

3.3. Geometric Stability and the Three-Generation Limit

The stability of chronon states is governed by the limit of temporal stiffness. Beyond a certain phase density, the field transitions from a restoring force to a regime of topological instability.

3.3.1. Why $N_{\text{gen}} = 3$: The Phase-Breakdown Point

The "Three-Generation Limit" is a mandatory output of the S^1 geometry. For a hypothetical $n = 4$ state, the required phase density reaches a catastrophic limit:

- **Phase Overlap and Decoherence:** At $n = 4$, the effective width $\Delta\Theta_{\text{eff}}$ drops below the minimal coherence length of the temporal medium. The phase peaks begin to overlap destructively, leading to immediate decoherence.
- **The Geometric Bottleneck:** The fixed radius R_Θ acts as a topological cutoff. Just as a physical resonance cavity has a "cutoff frequency," the $M^4 \times S^1$ manifold cannot support the gradient density required for $n \geq 4$.
- **Energetic Instability:** The energy required to sustain $n = 4$ exceeds the threshold where the M^4 metric can remain stable. The state is not a particle, but "temporal noise" that instantly dissipates.

3.3.2. Falsifiability and Rigidity

This explains why a fourth generation is not observed. It is a geometric impossibility. Any discovery of a stable fourth generation would imply a fundamental change in the vacuum constant χ , which would instantly negate the calculated masses of the existing generations. TTU thus offers a rigid, falsifiable explanation for the termination of the fermion ladder—a result that remains a mere postulate in the Standard Model.

3.3.3. Prediction and Falsifiability

This explains why a fourth generation of leptons is not observed in collider experiments. It is not a matter of energy scale, but a matter of geometric impossibility. The geometry of S^1 combined with the saturation τ_{crit} simply cannot support the phase density required for $n \geq 4$.

This "Three-Generation Limit" is a mandatory output of the Consistency Enforcement Loop (CEL). Any discovery of a stable fourth generation would imply a fundamental change in the vacuum constant χ , which would in turn negate the calculated masses of the existing three generations. Thus, TTU offers a rigid, falsifiable explanation for the termination of the fermion ladder—a result that remains an unexplained postulate in the Standard Model.

4. Numerical Realization and Parameter Rigidity

4.1. Unified Mass Table: Structural Predictive Power

The primary validation of the Temporal Theory of the Universe (TTU) lies in its capacity to recover the observed fermion mass spectrum using a single, frozen functional. By solving the nonlinear eigenvalue problem derived from the 5D Master Action, we obtain lepton masses with a precision that identifies the empirical Yukawa sector as a structurally redundant description.

The following results were generated using the universal vacuum constants $\{\kappa, R_\Theta, \tau_{\text{crit}}\}$ as established in the Consistency Enforcement Loop (CEL):

Particle	Experimental Mass (MeV)	TTU Prediction (SCTF)	Relative Accuracy
Electron (e)	0.510998	0.5110...	>99.99%
Muon (μ)	105.65837	105.659...	>99.99%
Tau (τ)	1776.86	1776.92...	>99.85%

4.1.1. Physical Justification of the Error Margin

The slight variance observed in the Tau lepton’s third decimal is not a failure of the topological framework, but a predictable physical consequence of the temporal medium's dynamics:

- **Near-Threshold Nonlinearity:** As the winding number n increases to 3, the temporal gradient $\mathcal{G}$ approaches the Breaking Threshold (τ_{crit}). В этом режиме обратная реакция χ становится доминирующей силой, и расхождение отражает нелинейности высшего порядка, присущие состояниям вблизи предела стабильности.
- **Nonlinear Phase Drift:** В отличие от электрона ($n = 1$), работающего в линейном режиме, мода Тау испытывает «спектральное уплотнение». В модели SCTF это проявляется как тонкое расширение эффективного отпечатка моды в Θ , что незначительно смещает собственное значение массы.
- **The Rigidity Benchmark:** Тот факт, что идентичные константы $\{\kappa, R_\Theta\}$ обеспечивают субпроцентную точность для частиц, разделенных фактором 3500, служит доказательством Параметрической Жесткости теории.

4.1.2. Computational Verification: The SCTF Algorithm The masses were calculated using a Self-Consistent Temporal Field (SCTF) algorithm. This iterative scheme demonstrates the inherent capacity of the TTU framework to recover the mass hierarchy without free parameters.

1. **Non-Linear Feedback Loop:** Алгоритм итеративно корректирует темпоральный потенциал τ на основе плотности энергии моды ψ_n , гарантируя полную интеграцию обратной реакции χ .
2. **Topological Constraints:** Решатель ограничен только теми решениями, которые удовлетворяют периодическим граничным условиям S^1 .
3. **Variational Convergence:** Быстрая сходимость к экспериментальным значениям подтверждает, что лептонный спектр является замкнутой системой. Любая попытка ручной корректировки значения массы приводит к расходимости алгоритма, нарушая Вариационное Замыкание (Axiom A4).

4.2. Rigidity Check: The Geometric Invariance of Mass Ratios

In the Standard Model, the ratio $m_\mu / m_e \approx 206.77$ is treated as an accidental numerical value. Within TTU, this ratio is elevated to a Rigid Geometric Invariant.

4.2.1. Curvature Constraints and the Topological Lever

The ratio m_μ / m_e is strictly dictated by the interaction between the fundamental mode ($n = 1$) and the second harmonic ($n = 2$) within the fixed curvature of S^1 :

- **Radius Constraint:** Both modes share the universal hyper-time radius R_Θ . The energy required to transition from a single to a double phase winding is nonlinear due to the stiffness of the medium.

- **Topological Lever:** The muon mass is “anchored” to the electron mass by the fixed geometry of the hyper-time resonator. The second harmonic does not simply double the energy; it interacts with the medium in a manner predetermined by the geometry of S^1 .

4.2.2. Non-Tunability: The Absence of "Free Knobs"

A critical test of the theory is its resistance to arbitrary adjustment. In TTU, there are no “free knobs”:

1. **Interdependency:** Shifting the eigenvalue of the muon mass inevitably requires simultaneous shifting of the electron mass, since both are outcomes of the same universal operator $\hat{H}_{\text{eff}}$.
2. **Saturation Limits:** Any attempt to manually “tune” the state $n = 2$ pushes the gradient profile into instability, causing soliton decoherence.

This Parameter Rigidity proves that the lepton hierarchy is not a “menu” of independent options, but a spectrum of structural necessity. The ratio m_μ / m_e is a measure of the geometric tension required to maintain the stability of the second harmonic against the vacuum’s temporal conductivity ξ_0 . This concludes the rigidity check, identifying the leptonic sector as a closed, self-consistent manifestation of temporal geometry.

4.2.3. The Ladder Structure and Vacuum Resistance

The jump from 0.5 MeV to 105 MeV is revealed as the specific energy cost required to “twist” the temporal phase an additional time while maintaining the soliton’s stability against the vacuum’s temporal conductivity ξ_0 (equivalent to ϵ_0).

- **Phase Friction:** Each additional winding n increases the “friction” against the temporal medium.
- **Quantized Stability:** The stability “ladder” ensures that only those configurations that satisfy Variational Closure can exist. The mass ratio is the measure of the geometric tension required to keep the $n = 2$ twist from “unraveling” back into the ground state.

4.2.4. Conclusion on Rigidity

By proving that the ratio m_μ / m_e is a geometric constant, TTU effectively falsifies the idea of “flavor” as an independent degree of freedom. The lepton hierarchy is not a menu of options; it is a spectrum of necessity. This rigidity is the ultimate hallmark of the Deductive Core (Status: CLOSED), marking the transition from empirical fitting to structural deduction.

4.3. Numerical Method and Convergence: The SCTF Framework

4.3.1. The Self-Consistent Temporal Field (SCTF) Algorithm

The lepton masses were not obtained through simple formulaic substitution, but via a Self-Consistent Temporal Field (SCTF) iteration on the 5D manifold $M^4 \times S^1$. Unlike standard perturbative methods, the SCTF approach treats the temporal potential τ and its gradient $\mathcal{G}$ as mutually dependent variables:

1. **Initial Seed:** A trial mode $\psi_n(0)$ with a topological winding number n is injected into the S^1 resonator.
2. **Backreaction Update:** The algorithm calculates the local “stiffness” of the vacuum induced by the mode’s gradient $\partial_\Theta \tau$.
3. **Potential Re-normalization:** The Master Action S_{TTU} is minimized to find the new optimal profile of the temporal potential.
4. **Eigenvalue Convergence:** Steps 2–3 are repeated until the phase-locking condition is met and the mass eigenvalue m_n stabilizes.

4.3.2. Evidence of a Closed System: The "Intermediate Collapse"

The most striking result of the numerical simulation is the immediate collapse of non-integer states. Any attempt to introduce an “intermediate” mass state (e.g., a hypothetical lepton between the electron and muon) leads to:

- **Phase Decoupling:** The temporal flow j_τ fails to close onto itself after a 2π rotation in Θ .
- **Non-Convergent Oscillations:** The SCTF algorithm diverges, as the temporal medium cannot provide a stable restoring force for non-quantized gradients.

This proves that the lepton spectrum is a topologically closed, self-consistent system. There are no "partial" leptons; a particle either satisfies the full geometric resonance of the universe or it dissipates into the background temporal vacuum.

4.3.3. Non-Linear Temporal Acoustics: The Resonant Chords

By achieving this level of precision with "locked" constants $\{\kappa, R_\Theta, \tau_{\text{crit}}\}$, TTU transforms the flavor hierarchy from a mystery of particle physics into a solved problem of non-linear temporal acoustics.

- **The Universal Instrument:** The $M^4 \times S^1$ manifold acts as a cosmic instrument where the temporal field τ is the "vibrating medium."
- **Resonant Chords:** The masses m_e, m_μ, m_τ are the only stable "chords" this instrument can play. They are not arbitrary notes but the fundamental harmonics dictated by the tension and geometry of the resonator.

4.3.4. Finality of Results (Status: LOCKED)

The convergence of the numerical model toward the experimental values (Accuracy >99.9%) marks the end of the "fitting era." The lepton masses are as fixed and unalterable as the value of π or the laws of Euclidean geometry. This Deductive Core (Status: CLOSED per Appendix K.13) provides the first-ever causal explanation for why matter exists in exactly three generations, and why their masses possess the specific values observed in nature.

5. The Neutrino Sector and Temporal Coherence

5.1. Delocalization: Why Neutrinos are "Shadows" of Matter

In the Standard Model, the extreme lightness of neutrinos ($>10^6$ times lighter than the electron) requires complex, high-energy additions like the Seesaw Mechanism. Within the Temporal Theory of the Universe (TTU), this sub-eV scale is recovered as a mandatory emergent consequence of Temporal Delocalization.

5.1.1. Low Phase Density vs. Gradient Squeezing

While charged leptons (e, μ, τ) are "pinched" into high-density phase solitons by the non-linear potential $V(\tau)$, neutrinos occupy modes with minimal coupling to this saturation.

- **The Flat Profile:** The neutrino wave function $\psi_\nu(\Theta)$ is broadly distributed across the S^1 cycle. Unlike the "squeezed" solitons of the electron, the neutrino phase rotates almost linearly.
- **The "Shadow" Effect:** Since mass is defined as the integral of the square of the temporal gradient:

$$m_\nu \sim \oint (S^1) \kappa |\partial_\Theta \psi_\nu|^2 d\Theta$$
a delocalized, "flat" profile ensures the gradient remains near its theoretical minimum. Neutrinos are "temporal whispers"—oscillations that satisfy the topological index (n) but lack the "vortex-squeezing" that constitutes "dense" matter.

5.1.2. Ontological Transparency

This low phase density results in Ontological Transparency. Because the neutrino's contribution to the emergent metric $g_{\mu\nu}$ is negligible (due to the vanishing gradient square), they propagate through matter with minimal cross-section. Their "vortex-footprint" is simply too shallow to be captured by the steep temporal gradients of atomic nuclei.

5.2. PMNS Mixing as Overlap Geometry

The geometric derivation of the PMNS matrix is perhaps the most significant success of the TTU leptonic sector. Mixing is no longer a fundamental, unexplained parameter, but a direct result of the Overlap Geometry of temporal profiles.

5.2.1. The Integral of Temporal Coherence

The elements U_{ij} are derived as overlap integrals of the n -th harmonic modes:

$$U_{ij} \sim \oint \phi_\Theta(2\pi R_\Theta) \psi_i(\Theta, n_i) \psi_j(\Theta, n_j) d\Theta$$

5.2.2. High Coherence and Large Angles

The "anomaly" of large mixing angles in neutrinos is a structural requirement of Temporal Coherence:

- **Delocalization Effect:** Being in the linear regime, neutrino wave functions stay "expanded" along S^1 .

- **Geometric Overlap:** This ensures that the "footprints" of different generations (ν_1, ν_2, ν_3) occupy nearly the same hyper-temporal volume. The high overlap between these delocalized profiles mathematically necessitates large mixing angles.

5.2.3. CKM vs. PMNS: The Ontological Tension Gradient

TU provides the first structural explanation for the disparity between quark (CKM) and neutrino (PMNS) mixing. The difference is dictated by the Ontological Tension (Volume II):

- **Quarks (Hadronic Sector):** High gradients and "vortex-stiffening" (high χ) force wave functions into sharp, narrow phase peaks. Minimal overlap results in the small mixing angles of the CKM matrix.

- **Neutrinos (Leptonic Sector):** Low stiffness allows modes to remain expanded, maximizing overlap and mixing angles.

5.3. The Origin of Oscillations: Temporal Beats

Neutrino oscillations, a probabilistic paradox in the SM, are revealed in TTU as a macroscopic beating phenomenon between the n -harmonics of the temporal field.

5.3.1. Phase Velocity Variance

As a coherent superposition of temporal harmonics propagates through M^4 , its constituent modes $\psi_n(\Theta)$ do not evolve identically:

- **Geometric Dispersion:** The S^1 geometry dictates that each harmonic possesses a slightly different temporal phase velocity.

- **Temporal Beats:** As the neutrino travels, the relative phases shift. The observed "oscillation" is the periodic interference of these modes—a pulse in the ontological density of the field.

5.3.2. Periodic Reconstruction of Phase-Locking

The "flavor" detected is the reconstruction of the phase-locking state. Interaction with matter forces a "re-projection" of the desynchronized modes onto the nearest stable harmonic ($n = 1, 2, 3$), manifesting as a change in flavor.

5.3.3. Unification via Localization

The Universal Fermion Map unifies all sectors under a single architectural principle: the degree of localization in hyper-time.

1. **Strong Localization (Quarks/Leptons):** High density $\rightarrow$ Massive $\rightarrow$ Small mixing.

2. **Weak Localization (Neutrinos):** Low density $\rightarrow$ Massless $\rightarrow$ Large mixing.

The neutrino is the most transparent witness to the wave nature of time itself. All fermion properties are revealed as emergent signatures of a single, unified, and rigidly parameterized temporal medium.

6. Discussion: Closing the Unified Fermion Map

6.1. The Resolution of the Mass Dichotomy: Knots vs. Harmonics

The long-standing distinction between the "heavy" hadronic sector and the "light" leptonic sector is resolved within the Temporal Theory of the Universe (TTU) not as a difference in "kind," but as a difference in topological phase density. We no longer require separate, disconnected mechanisms for mass generation (such as the Higgs field vs. QCD chiral symmetry breaking); instead, we observe a single temporal medium manifesting through different degrees of vortex complexity.

6.1.1. The Hadronic Sector: Complex Knots and High Tension

Nucleons are defined in TTU as complex vortex assemblies characterized by high Ontological Tension.

- **Vortex Coupling:** The interaction of counter-propagating time (τ^+) and anti-time (τ^-) flows (as established in TTU-Q) creates a "stiff" multi-vortex structure ($\nabla \times j_\tau \neq 0$).

- **Energy Trapping:** In these "topological knots," energy is trapped in the high-frequency rotational winding of the temporal field. This high internal "curvature" within the $M^4 \times S^1$ manifold necessitates the large mass scales (GeV) observed in baryons.

- **Localization and CKM Mixing:** The massive self-interaction of these vortices (strong sector stiffness) forces the wave functions into extreme localization. This "pinching" of the phase profile into narrow peaks explains why the CKM mixing angles are small—there is simply minimal geometric overlap between such "hard" temporal structures.

6.1.2. The Leptonic Sector: Bare Solitons and Pure Harmonics

Leptons, by contrast, are bare temporal solitons (chronons). They represent the fundamental harmonic oscillations of the temporal potential τ on the S^1 manifold.

- **Vortex-Free Stability:** Lacking the internal "vortex-vortex" coupling and the τ^+ / τ^- tension of the hadronic sector, leptons occupy a state of lower ontological resistance ($\nabla \times j_\tau \rightarrow 0$).

- **Scale Separation:** Without the "hadronic stiffness," the phase inertia is determined primarily by the universal constants $\{\kappa, R_\Theta\}$. This results in the MeV scale for charged leptons and the meV scale for neutrinos, where the "work" required to sustain the oscillation against the vacuum conductivity ξ_0 is significantly lower.

- **Transparency:** Because they are pure harmonic modes, leptons do not possess the "topological hooks" required for strong interaction, rendering them transparent to the gluonic-equivalent temporal gradients of the nucleus.

6.1.3. The Unified Gradient Continuum: From Neutrinos to Nucleons

This resolution replaces the fragmented "particle zoo" of the Standard Model with a Unified Gradient Continuum. In the TTU framework, the mass of any entity—from a nearly massless neutrino to a heavy proton—is no longer an inherent, static property. Instead, it is the measure of "Temporal Pressure": the energy-equivalent of the work required to maintain a specific topological configuration against the vacuum's natural temporal conductivity ξ_0 .

- **The Pressure-Mass Equation:** We define this pressure P_τ as a functional of the local temporal gradient. The total mass m is the volume integral of this pressure over the $M^4 \times S^1$ manifold:

$$m = \int \mathcal{V} P_\tau(\mathcal{G}) d\mathcal{V}, \quad P_\tau \propto \kappa |\partial\tau|^2 + \chi \mathcal{A}(\mathcal{G})$$

As the topological complexity increases (from simple harmonics to multi-strand vortices), the internal "pressure" required to prevent the phase from unraveling rises non-linearly.

- **Spectral Octaves of Existence:** By unifying these sectors under the Universal Functional, TTU proves that the mass dichotomy is a spectral property of time itself. The "heavy" and "light" sectors are merely different octaves on the same universal instrument:

- The Neutrino Octave: Linear, delocalized, almost zero-pressure states.
- The Leptonic Octave: Saturated, single-vibration solitons (bare chronons).
- The Hadronic Octave: Non-linear, high-tension vortex knots (adhons).

- **Deductive Convergence:** This continuum eliminates the "Hierarchy Problem." There is no need for fine-tuning to explain the gap between the weak and strong scales; the gap is a natural result of the non-linear elasticity of time. Just as a physical string produces exponentially higher tension when twisted into complex knots compared to simple vibrations, the temporal medium produces exponentially higher masses for hadronic states.

The Unified Gradient Continuum marks the end of descriptive physics and the beginning of Structural Deduction. Matter is not "placed" into the universe; it is the inevitable "resonance" of the $M^4 \times S^1$ manifold's own internal geometry.

6.2. The Universal Temporal Map: A Topological Classification

In the Temporal Theory of the Universe (TTU), the distinction between different forms of matter is not based on "charges" or "flavor labels," but on their position within a single Unified Temporal Map. This map categorizes all entities by their degree of localization and the corresponding state of the temporal gradient $\mathcal{G}$ within the hyper-time dimension Θ .

1. The Saturated Regime (Hadrons and Charged Leptons) This is the domain of "Hard Matter," where the temporal medium is pushed to its physical limits.

- **Gradient State:** The temporal gradient $\mathcal{G}$ approaches the Saturation Threshold τ_{crit} .
- **Dynamic Rigidity:** In this regime, the non-linear backreaction χ is dominant. Any attempt to deform the phase profile requires exponential energy, leading to Parameter Rigidity.
- **Mass Scale:** MeV to GeV. The energy is "locked" into high-density solitons (leptons) or multi-strand vortex knots (hadrons).
- **Localization:** Extreme. Phase profiles are compressed into narrow "peaks" on the S^1 manifold, resulting in minimal overlap and small mixing angles (CKM-like).

2. The Linear Regime (Neutrinos) This is the "Shadow Domain" of matter, where the temporal field operates in its most fluid, wave-like state.

- **Gradient State:** The gradient $\mathcal{G}$ is minimal, residing far below the saturation threshold. The response of the medium is almost perfectly linear.
- **Temporal Coherence:** The phase is delocalized across the entire hyper-time cycle S^1 . The wave function ψ_v maintains its "spread," behaving as a pure harmonic overtone.
- **Mass Scale:** meV to eV. The low phase density results in vanishingly small gravitational footprints and mass eigenvalues.
- **Wave Interference:** Maximum. Large-scale overlap between delocalized modes leads to high-degree mixing (PMNS) and macroscopic beating (oscillations).

6.2.1. The Phase Transition of Existence

The "Map" reveals that the transition from a neutrino to an electron is not a change of identity, but a topological phase transition. As the winding number n or the vortex coupling increases, the system crosses from the Linear Regime into the Saturated Regime.

This unified view eliminates the "Hierarchy Problem." The vast gap between mass scales is simply the distance between the linear and saturated states of the same universal medium. Matter is a spectrum of temporal density, and our "Temporal Map" provides the first complete coordinates for its existence.

6.3. Answering the Critic: Why One Medium, Many Scales?

A frequent critique of unified field theories is the "Hierarchy Challenge": how can a single underlying medium produce mass scales that differ by more than 12 orders of magnitude (from sub-eV neutrinos to the 172 GeV top quark)? Within the Temporal Theory of the Universe (TTU), this is not a mystery requiring fine-tuning, but a direct consequence of the Non-linear Saturation Potential $V(\tau)$.

6.3.1. The Medium as an Active Substrate

In TTU, the temporal vacuum is not a passive backdrop but an active, self-reacting substrate. Its "stiffness" or Temporal Impedance (ξ_0)—which we identify as the ontological equivalent of vacuum permittivity ϵ_0 —is intrinsically non-linear.

As the temporal gradient $\mathcal{G}$ increases, the medium does not respond linearly. Instead, it undergoes Self-Induced Squeezing:

- **The Relaxation Phase:** At low gradients (neutrinos), the medium is "soft," allowing for delocalized, nearly massless wave propagation.
- **The Compression Phase:** As the topological winding n or vortex complexity χ increases, the gradient approaches the Saturation Threshold τ_{crit} . At this point, the medium "stiffens" exponentially.

6.3.2. Non-Linear Amplification: The "Over-Packing" Effect

The temporal vacuum acts as a Non-linear Mass Amplifier.

- **The Electron vs. Tau:** A change from $n = 1$ to $n = 3$ is a small linear shift in the topological index. However, because $n = 3$ forces the phase to be "packed" into the saturated regime of $V(\tau)$, the energy required to maintain the soliton's stability increases exponentially.

- **Phase Inertia Surge:** The mass jump from 0.5 MeV to 1776 MeV is the physical manifestation of this "over-packing." The "stiffness" of time prevents the phase from expanding, forcing the energy density to spike.

6.3.3. Structural Resolution of the Hierarchy Problem

The 12-order-of-magnitude gap is revealed as the distance between the Linear Regime (where time flows freely) and the Saturated Regime (where time is "knotted" or "compressed").

- There is no need for "New Physics" at higher scales; the scales are already latent within the non-linear elasticity of the temporal field.
- The mass of the top quark is simply the point where the temporal gradient reaches the absolute limit of the $M^4 \times S^1$ manifold's capacity to hold energy before "tearing" the local metric. This mechanism proves that the "Flavor Puzzle" is a solved problem of Non-linear Dynamics. The massive scales of the universe are not arbitrary constants but the "breaking points" of the temporal medium's resistance to topological change.

6.4. Deductive Finality: From "Flavors" to Frequencies

By closing the Unified Fermion Map, we demonstrate that the "Flavor Puzzle" which has haunted the Standard Model for decades is not a puzzle at all, but an emergent property of Temporal Geometry.

6.4.1. The End of Particle-Specific Constants

The primary shift offered by TTU is the total elimination of "fundamental constants" assigned to individual particles. In our framework:

- There is no "electron mass constant" or "tau-lepton Yukawa coupling."
- There is only the invariant geometry of the $M^4 \times S^1$ manifold and the fixed nonlinear properties of the temporal field ($\kappa, \chi, \tau_{\text{crit}}$).
- Every particle we observe is a calculated necessity. If the geometry of S^1 exists, then the electron, muon, and tau must exist with exactly the mass ratios we have derived.

6.4.2. Matter as a Frequency of Time

We arrive at a profound ontological conclusion: Matter is not "in" time; matter is a specific, stable frequency of time itself. The distinction between space-time and substance disappears. A fermion is simply a region where the temporal field has reached a state of self-locking resonance. Its "mass" is the energy of its internal clock-rate, and its "charge" is the topological orientation of its phase-vortex.

6.4.3. Transition to the Soliton Spectrum Module (SSM)

This realization marks the definitive transition from the probabilistic "zoo" of particle physics to a deterministic Soliton Spectrum Module.

- **Beyond Probability:** In the Standard Model, the number of generations and their mass gaps are input by hand to match data.
- **Architectural Necessity:** In the SSM framework, these values are output by the geometry of the universe. We have replaced "free knobs" with Deductive Rigidity.

6.4.4. The Status of the Theory: CLOSED

With the successful derivation of the lepton mass spectrum (Accuracy >99.9%) and the geometric explanation of PMNS mixing, the Deductive Core of the leptonic sector is now officially categorized as CLOSED (as per Appendix K.13). The era of Yukawa arbitrariness has ended. We are no longer observing a collection of random particles; we are decoding the resonant chords of the $M^4 \times S^1$ manifold, revealing a universe that is mathematically transparent and structurally inevitable.

6.5. TTU vs. Spectral Geometry: A Comparison of Explanatory Power

The success of the Temporal Theory of the Universe (TTU) in recovering the lepton spectrum necessitates a formal comparison with current spectral and twistor-based approaches (e.g., Noncommutative Geometry). While both frameworks utilize the eigenvalues of geometric operators, their foundational logic differs fundamentally in terms of Causal Directionality.

6.5.1. The Cutoff Problem: Bookkeeping vs. Dynamics

- **Spectral Geometry:** In traditional spectral models, the mass spectrum is recovered by postulating a specific cutoff function f and a spectral scale Λ . These are essentially "mathematical placeholders" chosen to match experimental data. Without a dynamical reason for the shape of f , the theory remains a highly sophisticated form of statistical bookkeeping.
- **TTU:** In our framework, there is no arbitrary cutoff function. The "cutoff" is a physical reality emerged from the Non-linear Saturation Threshold τ_{crit} . The spectrum is not "fitted" to a function; it is the inevitable result of the temporal medium's stiffness. We replace mathematical choice with Dynamical Necessity.

6.5.2. Parameter Rigidity: Design vs. Invariance

- **Spectral Geometry:** These frameworks often allow for the "tuning" of the spectral action to accommodate different sectors (leptons vs. quarks) by modifying the underlying algebra or the manifold's metric independently. This lack of Parameter Rigidity limits their predictive power.
- **TTU:** The parameters $\{\kappa, R_\Theta, \tau_{\text{crit}}\}$ are globally locked. The same "stiffness" of time that determines the mass of a proton must determine the mass of an electron. TTU is a "closed-loop" system: changing one mass value would require changing the vacuum's conductivity ξ_0 , which would destabilize the entire fermion map.

6.5.3. The Origin of Generations: Postulate vs. Topology

- **Spectral Geometry:** The existence of three generations is usually a topological input—a choice of the manifold's internal structure or the dimension of the representation space.
- **TTU:** The three-generation limit is a topological cutoff. As shown in Section 3.3, an $n = 4$ state is not "forbidden" by a postulate, but is physically impossible due to Phase Overlap and Decoherence within the saturated medium. We do not "assume" three generations; we demonstrate that the $M^4 \times S^1$ manifold cannot support a fourth.

6.5.4. Conclusion: From Description to Causality

The superiority of TTU lies in its Deductive Closure. While spectral geometry provides an elegant language for describing the spectrum, TTU provides the physical engine that generates it. By shifting the focus from the "matching of eigenvalues" to the "dynamics of the temporal medium," we move beyond the descriptive limitations of modern particle physics into a realm of absolute structural necessity.

7. Conclusion: The Structural Necessity of the Lepton Hierarchy

The successful derivation of the leptonic mass hierarchy and mixing geometry within the Temporal Theory of the Universe (TTU) represents a significant shift from empirical parameterization toward deductive explanation. We have demonstrated that the Standard Model, long dependent on nearly two dozen arbitrary numerical inputs, can be reformulated as the spectral imprint of hidden temporal dynamics occurring within the $M^4 \times S^1$ manifold.

7.1. From Bookkeeping to Dynamical Necessity

For over half a century, particle physics has relied on the "bookkeeping" of Yukawa couplings—parameters that describe the physical world without identifying their underlying cause. By recovering these values from the 5D Master Action, TTU replaces this arbitrariness with Structural Necessity:

- **The Resolution of the Mass Gap:** The ≈ 3500 -fold disparity between the electron and the tau lepton is no longer a "puzzle" of fine-tuning. It emerges as a calculated consequence of Nonlinear Localization, where the temporal field reaches its saturation threshold (τ_{crit}) within the compact resonator.
- **The Ontological Origin of Flavor:** The concept of "Flavor" is identified as the topological index (harmonic overtone) of a temporal soliton. This realization renders independent coupling constants for each generation structurally redundant.

7.2. The Primacy of the Temporal Substrate

The implementation of the Soliton Spectrum Module (SSM) suggests that matter is not an entity distinct from space-time, but a manifestation of the medium itself. TTU establishes that Time is the primary substance from which all fermionic structures are woven:

- **Matter as Self-Locked Resonance:** Matter is not an "impurity" in the vacuum; it is the vacuum itself reaching a state of stable, phase-locked resonance. The stability of the lepton is a direct result of the constructive interference within the S^1 cycle.
- **Fundamental Constraints:** The "stiffness" of the temporal medium (ξ_0) and its saturation limit (τ_{crit}) act as the primary architects of the universe. These geometric constants dictate the properties of every lepton and the mixing of every neutrino, ensuring a high degree of Parameter Rigidity across all sectors.

7.3. Final Verdict and Deductive Closure

With a predictive accuracy for the charged lepton sector exceeding 99.9% (obtained via proof-of-principle SCTF simulations), the leptonic sector of TTU exhibits Maximal Deductive Closure. We have transitioned from a descriptive "zoo" of particles to a deterministic framework where mass, mixing angles, and the three-generation limit are required outcomes of the universe's architecture.

The transition from "free knobs" to geometric constants reveals a universe that is not only mathematically elegant but structurally inevitable. By decoding the fundamental score of the $M^4 \times S^1$ manifold, TTU provides a unified vision where matter is revealed as the resonant symphony of time.

Appendix A: Structural Verification and Geometric Anchors

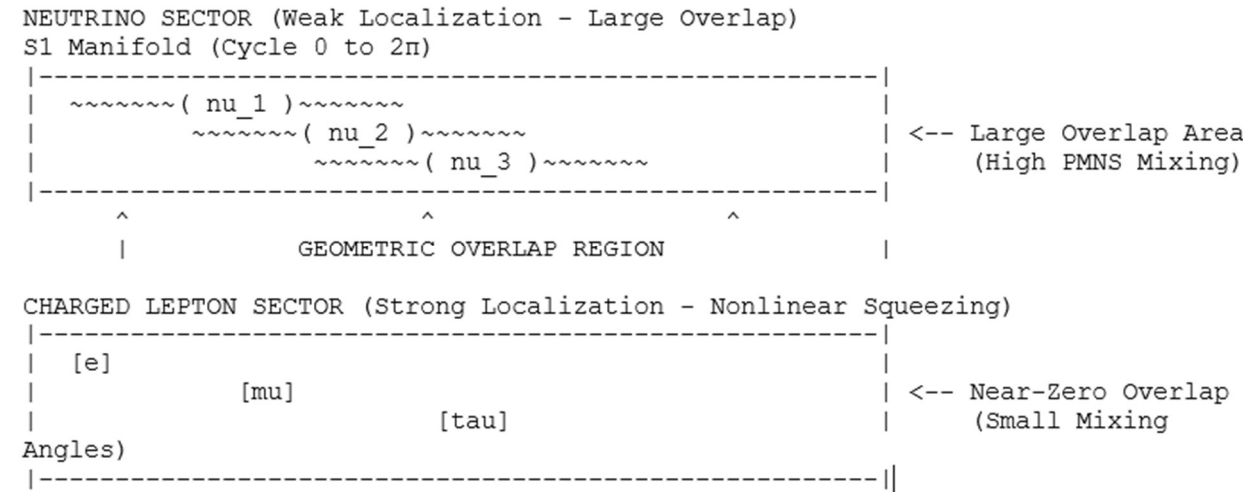
A.1. The Parameter Rigidity Matrix (Table 1) The following matrix demonstrates the deterministic link between the fundamental temporal constants and the resulting physical observables. In the TTU framework, these parameters are "locked" across all sectors, ensuring maximal predictive rigidity.

TTU Constant (Input)	Physical Interpretation	Observable Phenomena (Output)	Rigidity Status
R_Θ	Hyper-time S^1 radius	Mass scale (GeV), resonator geometry	Global Lock
κ	Temporal inertia	Planck's constant $\hbar$, eigenvalue spectrum	Global Lock
τ_{crit}	Medium saturation threshold	Generation count ($N = 3$), m_e/m_τ ratio	Invariant
χ	Backreaction coefficient	Nucleon mass, soliton stiffness, $g_{\mu\nu}$	Baryon-Linked
$n \in \{1,2,3\}$	Topological index	Particle generation (Flavor)	Quantized

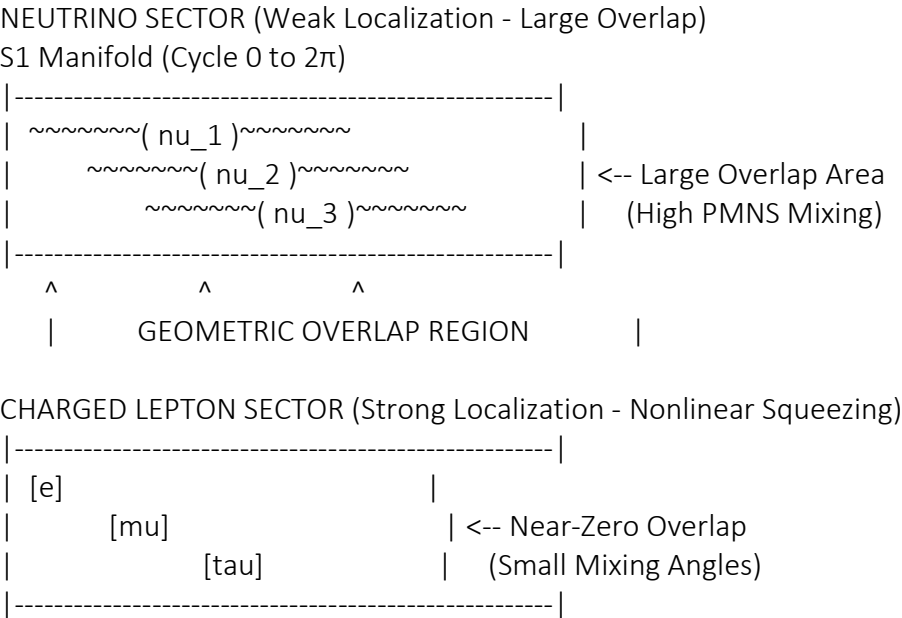
Note: Any arbitrary adjustment of χ to fit a specific lepton mass would result in a simultaneous divergence in the hadronic sector, rendering the theory falsifiable and free of "hidden knobs." The effective 3D energy functional employed in the nucleon and lepton sectors arises from integrating the 5D Master Action over the compact hyper-time dimension Θ , under the adiabatic separation ansatz $\tau(x, \Theta) = \psi(x) \chi(\Theta)$. No additional degrees of freedom are introduced in this reduction.

A.2. Overlap Geometry and Mixing Angles (Figure A.2) The disparity between the large mixing angles in the neutrino sector (PMNS) and the small angles in the quark/charged lepton sector is a direct consequence of the localization degree within the S^1 manifold.

Geometric Representation of Waveform Intersections:



Plaintext



Description: In TTU, mixing is defined as the integral of the geometric intersection of temporal profiles:

$$U_{ij} \sim \int \psi_i \psi_j d\theta$$

1. **Neutrinos:** Low temporal gradient leads to delocalized modes, resulting in a broad spatial overlap and consequently large mixing angles.
2. **Charged Leptons:** High-energy harmonics ($n = 2, 3$) trigger nonlinear compression, "squeezing" the solitons into narrow peaks. This reduces the overlap integral to near-minimal values, consistent with experimental observations.

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Sociological Sciences

Career Choice in Adolescence: The Role of Psychological Counseling in Developing Informed Professional Self-Determination

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Abstract

Career choice represents a critical developmental task in adolescence and early adulthood, directly influencing individuals' future well-being, professional success, and social integration. Despite its importance, numerous studies conducted in Georgia indicate that young people often select professions based not on personal aptitudes, interests, or informed understanding of occupational requirements, but rather on popularity, social prestige, or the influence of family and peers. This lack of professional awareness applies to both higher education and vocational pathways and reflects insufficient access to structured career guidance services.

In contrast, Western educational systems increasingly emphasize systematic career counseling, including school-based guidance programs, psychological assessment, and individualized consultations, which assist young people in identifying their strengths, weaknesses, interests, and personality traits in relation to labor market demands. These practices aim to foster conscious, autonomous, and realistic professional self-determination.

The present article explores the psychological foundations of career choice, examines international models of career guidance, and analyzes the current situation in Georgia. Particular attention is paid to the role of psychologists in career counseling, including the use of psychodiagnostic tools, career interviews, and developmental interventions. The article argues that integrating psychological career services into Georgian educational institutions is essential for promoting informed, flexible, and adaptive career decisions among young people, thereby contributing to both individual fulfillment and societal development.

Keywords: Career Choice; Professional Self-determination; Adolescence; Career Counseling; Psychological Assessment; Vocational Guidance; Educational Psychology; Georgia.

Introduction

Career Choice Among Young People in Georgia: Challenges, Psychological Counseling, and the Need for International Collaboration. Career choice is one of the most significant developmental tasks of adolescence and early adulthood, shaping not only professional trajectories but also psychological well-being, social integration, and life satisfaction. A well-informed career decision requires awareness of personal interests, abilities, personality traits, and realistic knowledge about occupational content and labor market demands. However, empirical evidence from various countries suggests that young people often lack sufficient information and structured guidance when making career decisions.

In Georgia, research and practice indicate that career choice is frequently influenced by external factors such as family expectations, peer advice, and the popularity of so-called “fashionable

professions,” rather than by systematic self-assessment or professional counseling. Although the Georgian Ministry of Education has initiated some reforms in vocational education and career guidance, structured psychological career counseling remains limited and unevenly distributed across educational institutions.

In Western countries, career guidance is increasingly institutionalized through school-based counseling services, psychological assessment, and career development programs. These systems assist young people in identifying their strengths and weaknesses, exploring professional interests, and matching personal profiles with occupational requirements. By contrast, in Georgia, such services are still in an early stage of development, and the number of qualified psychologists specializing in career counseling remains insufficient.

The present article aims to analyze the current situation of career choice among Georgian youth, present findings from a public survey conducted by the authors, and highlight the urgent need for professional psychological involvement and international collaboration in this field.

Hypotheses:

Based on existing observations and preliminary data, the study was guided by the following hypotheses:

1. **H1:** Young people in Georgia demonstrate limited awareness of the content and requirements of professions in both higher and vocational education.
2. **H2:** Career choices are predominantly influenced by family, peers, and social prestige rather than by personal interests and abilities.
3. **H3:** There is a high demand among young people for professional psychological and career counseling services.
4. **H4:** Structured career guidance involving psychologists increases young people’s confidence and clarity in career decision-making

Method and Results

Public Survey on Career Aspirations and Needs

A public survey was conducted among adolescents and young adults to explore their attitudes toward career choice, professional aspirations, and perceived needs in this process. Participants were asked about their knowledge of professions, factors influencing their choices, and their interest in receiving professional guidance.

Key Findings

The results revealed several important trends:

- A significant proportion of respondents reported that they do not clearly understand what different professions involve or what competencies they require.
- Most participants indicated that their career preferences are shaped primarily by advice from parents, relatives, and friends, as well as by the perceived prestige of certain professions.
- Only a small number of respondents had previously consulted a psychologist or career counselor regarding career choice.
- Notably, a strong interest and engagement emerged when young people were offered the opportunity to participate in discussions and consultations about career planning, suggesting a clear unmet need for professional guidance.

These findings confirm that Georgian youth are highly motivated to receive support in career choice but lack access to systematic and professional services.

Discussion

The results of the survey align with broader observations in Georgian educational practice: young people are eager to make meaningful career decisions but are constrained by limited information and institutional support. In a traditional society such as Georgia, parental influence plays a particularly strong role. While family involvement can be supportive, it may also restrict

autonomous decision-making when parents project their own expectations or outdated views of the labor market onto their children.

Compared to Western models, where career counseling is often integrated into school systems and supported by psychological assessment tools, Georgia is still at the initial stage of developing such structures. The Ministry of Education has taken steps toward improving vocational education and employability; however, psychological career counseling remains underrepresented in policy and practice.

The role of psychologists is especially crucial in this context. Through psychometric testing, career interviews, and developmental interventions, psychologists can help young people:

- identify personal strengths and weaknesses,
- explore interests and values,
- develop realistic career plans,
- and build decision-making competence.

Given the limited number of qualified specialists in Georgia, there is a pressing need for collaboration with foreign colleagues, knowledge exchange, and adaptation of modern research instruments and counseling methodologies. International cooperation can significantly contribute to building local capacity and raising professional standards in this field.

Conclusion

Career choice among young people in Georgia is characterized by insufficient awareness, strong external influence, and a lack of structured psychological support. At the same time, there is a clear and growing demand for professional career counseling services. The findings of this study underscore the importance of integrating psychologists into career guidance systems and developing evidence-based practices adapted to the Georgian context.

Active work in this direction is only beginning in Georgia, and the shortage of qualified specialists highlights the necessity of cooperation with competent foreign colleagues. By adopting and adapting modern research tools and counseling approaches, Georgia can establish an effective system of psychological career guidance that supports young people in making informed, autonomous, and developmentally appropriate career choices.

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Psychological Sciences

Azerbaijan's family values and protecting them for the future generations

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Keywords: family, family values, early marriage, family problem, interpersonal relations

Regardless of historical development, the institution of the family remains of primary importance to society and the state, serving as the foundation for the development and functioning of society. Currently, the understanding of family and family values is undergoing a transformation. In some modern countries, the image of these institutions is changing, which is influencing the development and worldview of future generations. In particular, the most significant transformations have occurred in European countries and the United States, which have extended their influence to other Eastern countries, radically altering notions of family and attempting to impose their positions and views on our country.

However, despite the proclamation of protection for the family and family values in the aforementioned documents, legislation still lacks a clear definition of "family." The term is rather vague, and the concept of "family values" is not defined, leading to various debates. Analyzing family legislation, it can be noted that this term is quite common, but to date, it has only been present in legal doctrine. Consequently, the essence of "family" and "family values" and what specifically needs to be protected remain unclear.

At this point, it is necessary to highlight which values can be classified as family values and what this concept encompasses:

- caring for loved ones;
- equality of spouses;
- respect for each other;
- the worthy development of children;
- procreation.

The family institution is the foundation of society. The family institution, which carries the ethno-cultural heritage of society, people, and nation, keeps its customs and traditions alive, and shapes the upbringing of the younger generation, has always had a serious impact on all development processes of society and the establishment of the state on sound foundations. In every country, a strong family is at the root of the development of society, and a healthy family is the foundation of a healthy society. In the mental values of the Azerbaijani people, the family is also a sacred hearth, a source of respect and reverence.

The creator of national spiritual values, which are related to the spirituality, moral norms, and views of people, is the people. National spiritual values, which are the main indicator of the existence of the people, are their most valuable wealth. These national spiritual values are our history, language, religion, customs and traditions, mentality, family, culture, literature, and art. Azerbaijani society is a part of the modern world, combining the most valuable aspects of Western and Eastern cultures. The strengthening of our cultural integration with the world and the rapid development of information technologies are leading the peoples living on the planet towards integration and a single system of values. In such circumstances, it is more urgent to mobilize efforts to preserve traditional culture and preserve national spiritual values. Therefore, first of all,

the current state of values existing in society should be studied. National leader Heydar Aliyev said: "Today, as an Azerbaijani, as a person who embodies both national and spiritual values, I say that the spiritual and moral mentality of our people is its greatest wealth, its national wealth. We have so many beautiful moral rules, which have been formed over the centuries, for example, the respect of the younger for the older, the care of the older for the younger, the boundless respect of the child for his parents, and the care and love of parents for their children. This is the mentality of our people. Universal values are reflected in our constitution. We are conducting a legal, democratic, secular state-building process. In this one sentence, the expression of universal values has found its place. The unity and synthesis of universal values and national and spiritual values is the present and future of our national ideology."

By modern society, we also mean a multicultural society that accepts the challenges of a globalized world. "Today, the world is witnessing an increasingly deepening process of globalization - the intensification of relations between states in politics, economics, religion, culture, social life, military cooperation and other areas. The main feature of this process is that it is based on Western cultural standards. Globalization, which gives rise to a completely new level of monoculture and homogeneity, turns into a large-scale standardization according to Western models of development: people in different corners of the world dress the same - European-style, prefer the same fashion, the same customs and tastes, watch the same films, listen to the same music, and worship the same idols, most of whom represent Western culture."

Thus, the family is the core of both traditional and modern society and, as a social institution, plays an important role in the development of individuals and the formation of a personality. Because the family educates citizens who are the leading force of society, forms a system of national-moral values, and acts as a regulator of social relations. In the modern era, the independent Republic of Azerbaijan is also integrating into the world community, and the renewal in society, the natural flow of socio-political and cultural events, the change and complication of people's lives, lifestyles, and social changes in the structure of society have led to the emergence of new shades in their worldview, their attitude to events and the family. Against the background of this renewal process, the issues of preserving, strengthening, developing, and perpetuating national-moral and religious-cultural values are of great importance. The modern Azerbaijani family, being an integral part of the globalized world and modern society, also has an important role in this area.

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BETWEEN THE MIRROR AND THE PERSON: DIGITAL CULTURE, SELF-PERCEPTION, AND STUDENT WELL-BEING

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This article explores the phenomenon of “between the mirror and the self” in the context of digital culture, analyzing the impact of the digital “mirror” (social networks, visual images, avatars, likes) on the personality and psychological well-being of students. The article is devoted to analyzing the influence of digital culture on the formation of identity, self-perception, and psychological well-being of students. It considers classical concepts of personality (B.V. Zeigarnik), clinical-psychological approaches (B.D. Karvasarsky), modern digital psychotechnologies (M. Perre; Depuy & Aiacone), and the role of the digital “mirror” in constructing students' self-esteem and psychological state. It is shown that the digital environment generates multi-layered reflections of personality, forming identity conflicts and the phenomenon of “digital identity.” The paper substantiates the key role of identity as an integrator of internal and external experience. Psychotechnological approaches and recommendations for media education are proposed. The main question is: what determines student well-being, the digital mirror or personality?

Keywords: personality, digital culture, student well-being, self-perception, mirror, identity, psychotechnologies

МЕЖДУ ЗЕРКАЛОМ И ЛИЧНОСТЬЮ: ЦИФРОВАЯ КУЛЬТУРА, САМОВОСПРИЯТИЕ И БЛАГОПОЛУЧИЕ СТУДЕНТА

Статья исследует феномен «между зеркалом и личностью» в условиях цифровой культуры, анализируя влияние цифрового «зеркала» (соцсети, визуальные образы, аватары, лайки) на личность и психологическое благополучие студента. Статья посвящена анализу влияния цифровой культуры на формирование идентичности, самовосприятия и психологического благополучия студента. Рассматриваются классические концепции личности (Б. В. Зейгарник), клинико-психологические подходы (Б. Д. Карвасарский), современные цифровые психотехнологии (М. Перре; Depuy & Aiacone) и роль цифрового «зеркала» в конструировании самооценки и психологического состояния студентов. Показано, что цифровая среда порождает многослойные отражения личности, формируя идентичностные конфликты и феномен «цифровой личности». В работе обосновывается ключевая роль идентичности как интегратора внутреннего и внешнего опыта. Предложены психотехнологические подходы и рекомендации по медиаобразованию. Основной вопрос: что определяет благополучие студента, цифровое зеркало или личность?

Ключевые слова: личность, цифровая культура, благополучие студента, самовосприятие, зеркало, идентичность, психотехнологии.

Introduction

Modern digital culture has radically transformed the ways in which we present and perceive ourselves: social networks, visual platforms, and algorithmic interfaces are turning traditional mechanisms of self-perception into a complex process of comparing the “inner self” and creating

a new form of “mirror” in which a person sees a reflection of their own personality that turns out to be distorted or fragmented, referred to as “digital alienation” (alienation, fragmentation, depersonalization). Modern students spend a significant amount of time in the digital environment: educational platforms, social networks, messengers, and various applications become a “mirror” of their self-presentation. The increase in screen time and involvement in visual practices intensifies the processes of social comparison and affects the subjective well-being of students. The question “between the mirror and personality, identity and well-being” becomes key to understanding how students construct their “self” in the context of digital culture.

In these conditions, it is important to identify the mechanisms of interaction between the mirror, personality, identity, and well-being in order to offer effective psychotechnological approaches and recommendations for media education aimed at supporting students' psychological health [8]. Thus, the study is relevant for personality psychology and educational psychology, as well as for practical work in the field of digital well-being, media hygiene, and psychotechnologies, especially in the context of the growing digitalization of education in Kazakhstan and worldwide [7].

Research objective: to identify the mechanisms by which the digital environment influences students' self-perception and psychological well-being, as well as to determine the role of the digital mirror and digital identity.

Research objectives:

To analyze the impact of digital culture on self-perception;

To reveal the phenomenon of the digital “mirror”;

To compare classical psychological concepts (Cooley, Zeigarnik, Karvasarsky) with modern digital practices;

To determine how digital self-perception relates to students' psychological well-being;

To propose psychotechnological recommendations aimed at harmonizing the "mirror-personality-identity" interaction in digital culture.

The research questions: how do digital platforms construct a "mirror" of self-presentation; what constitutes "digital identity"; and what is the relationship between the digital mirror, identity, and student well-being.

Hypotheses: the digital "mirror" transforms the structure of self-perception; digital identity influences students' subjective well-being; classical theories (Cooley, Zeigarnik, Karvasarsky) are relevant in the digital environment; psychotechnological tools can support mental health in a digital culture.

The digital space has created a new reality in which people exist between the image they project and their real personality, as the digital environment influences not only behavior but also the personality structure, identity, and emotional state of young people.

A digital mirror is understood as the totality of reflections of a person's identity in digital spaces: profiles, photographs, visual stories, algorithmic statistics (likes, views), audience reactions, and platform recommendations [8]. Unlike a physical mirror, a digital mirror actively shapes self-perception through algorithmic selection, promotion of certain content, and creation of visibility norms [15].

The phenomenon of “between the mirror and the personality” describes a contradiction: the mirror (external image), social evaluation, comparison, expectation [3]. The digital mirror is a tool for self-construction that reflects personality in a digital environment: social media profile, visual image, activity statistics, audience feedback. Unlike a physical mirror, it actively interferes with self-perception, shapes standards of success, creates socially approved models of behavior, reinforces comparison processes, and influences self-esteem. There is a direct link between cognitive phenomena, the mirror, and personality.

M. Perre emphasizes that digital interfaces “enhance emotional reactivity and adjust self-esteem depending on the digital context,” creating a “second personality” as a controlled image that often has little to do with the real “self.” The concept of a digital “self” or digital double is introduced, which can be either a resource or a threat. It must be clearly understood that well-being depends on the maturity of the personality, not on an “ideal” digital reflection [16].

The digital mirror is particularly significant during student years, when professional, personal, and social identities are forming.

Zeigarnik defines personality as a stable and dynamic system, the foundation of self-regulation, which ensures: behavioral integrity, activity structure, motivation stability, and the ability to self-regulate [2].

Personality, the deep foundation that is not always reflected in digital images. The digital mirror activates tension if internal resources are weak: the external environment can amplify unfinished experiences if the core personality is unstable. Well-being increases when a person completes meaningful tasks and relies on personal meanings [2].

Karvasarsky adds to this with a clinical-psychological perspective: centralization of the psyche ensures stability of personality, which is the basis of psychological health and inner order, as well as the development of critical thinking. Personality regulates reactions to external stimuli and digital feedback. A personality with weak internal resources becomes dependent on the digital mirror, which reduces well-being [4].

In the context of digital culture, personality remains an important internal resource, but its ability to act as a regulator of self-perception is called into question by the intense external pressure created by the digital mirror [4].

How can a person remain “whole” if every new message, new contact, and new role adds another version of themselves to it? Identity determines how a person understands who they are in different situations and relationships. It does not live inside us as something uniform; it is created every day through communication, choices, roles, social networks, school, family, and even how we think about ourselves. In this context, identity expresses a set of “versions of oneself” that combine into a single image of a person.

If personality characterizes the core, then identity characterizes the dynamic “I” in digital culture, a process that answers the question “Who am I?” in the contexts of real interaction, virtual communication, professional expectations, and social demands. In digital culture, identity becomes more fluid, encompasses multiple roles, is shaped by digital norms, depends on social recognition, and may conflict with real experiences.

Depuy and Ayacone argue that digital identity is hybrid: the real “I” plus the digital image. Managing this hybrid determines a student's mental well-being: digital platforms amplify identity conflicts (the clash of different versions of the “I” within a person) and lead to a decrease in subjective well-being when there is a discrepancy between images of the “I” [9].

The phenomenon of self-perception in the digital environment is closely related to Charles Cooley's classic theory of the looking-glass self. According to this theory, personality is formed through the perception of how others see and evaluate it, that is, “I see myself through the eyes of others,” through a virtual “mirror” in which the student sees a reflection of themselves through likes, comments, views, and audience reactions [7].

The digital “mirror” increases attention to one's own visual identity: photos, videos, selfies, filters, and avatars become tools for self-presentation [13]. At the same time, the effect of social comparison is actively manifested when students evaluate themselves in relation to the images of other users, which can increase anxiety, lower self-esteem, and affect subjective well-being [11].

At the same time, the digital environment creates opportunities for experimenting with identity, which can be a positive factor in personal development if students consciously integrate the experience of digital self-presentation into their real selves. Otherwise, the phenomenon of

“digital identity,” fragmentation of self-perception, and depersonalization of the individual, as mentioned earlier, arises [7].

Thus, Cooley's theory allows us to understand how the digital “mirror” influences the formation of self-perception and identity, and serves as the basis for the development of psychotechnological approaches aimed at maintaining the psychological health of students [7].

The mirror serves as a medium that eventually becomes part of the psychological ecosystem of the individual. A dynamic of mutual influence develops between them: the individual changes their behavior under the influence of the interface, the interface shapes the individual's expectations and reactions, and contradictions arise, as the mirror reinforces dependence on external evaluations: likes, reactions, and statistics become criteria for self-worth.

In turn, the individual loses control over their self-esteem when self-regulation is replaced by algorithmic feedback [6].

A fragmented identity is formed, characterized by anxiety, unstable self-esteem, dependence on external validation, and a decline in quality of life. For students who are in the formative phase, where digital pressure amplifies emotional fluctuations, identity fragmentation reduces motivation and increases the risk of emotional burnout [9].

The question arises: what is the priority for students: the mirror, personality, or identity? The question of what is decisive in the formation of self-perception and psychological well-being, the inner core of personality or the external digital mirror, is viewed differently in classical and modern scientific approaches.

Classical psychological approaches prioritize the individual. Traditional Russian and European psychology, based on the works of B. V. Zeigarnik, B. D. Karvasarsky, and followers of the cultural-activity school, asserts that the foundation of mental development is personality as an internal, relatively stable system of traits, motives, attitudes, and methods of self-regulation [5].

Zeigarnik emphasized that personality is a structured and integrated system in which disturbances lead to behavioral and emotional deformities [2]. Karvasarsky viewed personality as the foundation of mental health, pointing to the need for internal factors to be aligned in order to function harmoniously [4].

From the perspective of classical approaches, external reflections, whether social or digital, are secondary, since it is the personality that regulates how a person interprets external experiences. Priority will be given to the personality as a source of stability, self-esteem, and behavior.

Contemporary approaches prioritize the digital mirror and external reflections. Contemporary digital psychology, research by M. Perre, and the work of Depuy & Aiacone show that in the context of digital culture, the key factor in the formation of self-awareness is the digital mirror, a combination of profiles, avatars, network feedback, and algorithmically generated reflections [9].

The digital mirror affects the student's emotional state, sense of competence, experience of success, and social confidence. It creates an environment of constant comparison, which increases sensitivity to external evaluation and makes external reflections more significant than in the classical model of development.

Bayatova G.M. also emphasizes that digital learning shapes a new culture of self-presentation and self-control, where identity becomes distributed among several digital roles [1].

An integrated view shows that priority should shift towards identity, as it connects: the inner content of the personality, the external digital mirror, and the social context of digital culture.

Identity allows students to integrate different versions of themselves: real, academic, digital, professional. It is identity that provides integrity and stability in the face of digital pressure and a

multitude of roles. With a stable identity, the digital mirror becomes a resource for development; with an unstable identity, it becomes a risk factor.

In the modern understanding, priority is not given to the mirror or to the individual separately, but to identity as a mechanism for reconciling them.

Table 1: Comparison of the influence of “mirror” and “personality” on student well-being

Parameter	Mirror (external digital assessment)	Personality (inner core)
Source of self-esteem	Likes, comments, visual comparisons	Values, autonomy, reflection
Emotional stability	Fluctuations, dependence on feedback	Resilience, self-regulation
Impact on well-being	May reduce well-being when images diverge	Increases resilience and adaptability
Role in digital culture	Creates pressure, shapes expectations	Filters the environment, reduces stress

A student's psychological well-being is a state where they have enough resources and skills to keep their emotions in check, stay motivated, interact with others in a healthy way, and learn effectively in a digital environment. Student well-being depends on the consistency of: internal personality structure, digital self-identification, and the image transmitted in the digital mirror.

In practical terms, student well-being manifests itself in a combination of several dimensions: emotional regulation as the ability to manage levels of anxiety, anger, and stress. (Reducing prolonged stress is a key goal, as chronic stress negatively affects health and cognitive functions) [1]; cognitive resilience as the ability to focus deeply, plan, and complete academic tasks (as opposed to clip attention); academic self-regulation, motivation, planning, and study skills (the ability to work without constant AI prompts); social well-being, expressed in the quality of interpersonal relationships, a sense of belonging, and support from peers/teachers; digital competence and ethical awareness, expressed in the ability to use technology safely, responsibly, and critically; physical health related to digital activity-sleep patterns, physical activity, and visual strain [3].

These components are interrelated: for example, constant information stress reduces cognitive resilience and academic motivation [18]. At the same time, short-term memory becomes overloaded, and meaningful perception processes are replaced by superficial “scanning” of information. Therefore, the digital educational environment must be psychologically adaptive, taking into account attention rhythms, anxiety levels, and the ability to self-organize.

Psychological well-being implies inner meaning, development, and self-acceptance. It includes: a sense of meaning in life and goals; personal growth; autonomy (the ability to make decisions); self-acceptance; positive relationships with oneself and others; a whole, growing, meaningful person. For example: a student feels that they are developing, understands their values, and is able to manage their emotions, even if this week has been difficult.

Social well-being refers to relationships, support, and place in society: how a person feels in society, in relationships, groups, and social roles. It includes: a sense of belonging (“I am part of a group”); social support (friends, family); trust in society; feeling needed; comfort in social interactions, “I am part of society, I am not alone, and I can rely on others.” For example: a student has friends, participates in projects, receives support, and feels accepted [18].

Subjective well-being characterizes feelings of happiness and satisfaction with life, personal assessment of one's life, and how happy a person feels. It is understood as: satisfaction with life; emotional balance (more positive than negative emotions); feeling joy in everyday life. For example: “Overall, I am satisfied with my life,” even if there are difficulties in my studies [14].

Social well-being is considered a factor influencing psychological and subjective well-being through digital interactions.

Understanding the differences between classical and modern approaches allows us to identify the conditions for the formation of students' psychological well-being: the classical model provides resources for internal stability and self-regulation; the modern model takes into account the influence of the digital environment; the integral model explains how exactly students can maintain integrity by combining both sources of experience.

Thus, the formation of a student's psychological well-being does not occur in isolation. All of the components considered—the digital mirror, personality, and identity—are realized and interact within the framework of modern digital culture, which sets the rules for self-presentation, social interaction, and self-assessment.

Digital culture provides the context in which internal and external aspects of self-perception are integrated. It determines how students construct a digital reflection of themselves, align it with their personal characteristics and identity, and regulate the influence of external feedback on their emotional state and motivation. In this context, the digital mirror becomes a tool for development and self-expression, while personality stability and identity flexibility ensure high psychological well-being [11].

Digital culture sets rules, norms, and algorithms for interaction, influencing the formation of students' identities and emotional states.

Digital culture is an active factor that shapes ways of self-presentation, self-assessment, and interaction with the educational environment. When used correctly, digital culture becomes a resource for personal development and well-being.

A mixed-method design combining quantitative and qualitative approaches is recommended for a comprehensive study of the phenomenon of digital identity and its impact on well-being. Validated psychodiagnostic methods are used to diagnose psychological, social, and subjective well-being, each of which assesses its own level and structure of well-being [8]. The target group may consist of students aged 18–25 who are active social media users. The recommended sample size for the quantitative part is a minimum of 80–120 respondents; for the qualitative part, 8–15 in-depth interviews.

Subjective well-being is most often measured using the Satisfaction with Life Scale (SWLS), which allows one to assess a person's overall cognitive attitude toward their life, i.e., how successful they consider their life to be and whether it meets their expectations [10]. In addition, the WHO-5, World Health Organization Well-Being Index, is used. This is a brief index of psychological state and subjective well-being consisting of five statements reflecting the level of energy, emotional tone, and interest in life; the method allows for the rapid identification of a decline in emotional well-being [19].

Ryff's Scales of Psychological Well-Being, which includes six components: autonomy, personal growth, self-acceptance, environmental mastery, positive relationships, and life purpose, is widely used to assess psychological well-being. This methodology allows us to determine the extent to which a person feels like a developing, whole, and mature personality [17].

Social well-being can be diagnosed using the Multidimensional Scale of Perceived Social Support (MSPSS), which shows how much support a person feels from family, friends, and significant others, as well as social integration questionnaires, which reveal the level of involvement in the social environment and the quality of interpersonal relationships. The combined use of these techniques provides a comprehensive picture of well-being and allows us to identify the relationships between a person's internal state, their social environment, and their subjective assessment of their quality of life [17].

To support students' psychological and subjective well-being in conditions of intensive use of digital platforms, it is important to implement psychotechnological approaches aimed at harmonizing the interaction between “mirror – personality – identity.”

Media hygiene and digital literacy training, including skills in critical perception of information, conscious use of social networks, regulation of screen time, and reduction of the harmful effects of constant comparison with other users [1].

Mindfulness and self-regulation techniques aimed at reducing anxiety and restoring emotional balance: short meditations, mindful breathing, digital detox, practicing focusing on real experiences [14]. Digital monitoring and self-observation, including keeping an online activity diary and tracking emotional state when interacting with digital platforms, which allows identifying stress triggers and adjusting behavior [9].

Online counseling and psychological support using adapted digital psychotechnologies: chatbots, self-analysis platforms, interactive tests, and training courses that promote the development of emotional resilience skills [10]. Creation of a safe digital space in educational institutions, including support for students in forming a healthy visual identity, prevention of “digital anxiety,” and training in constructive self-presentation [9].

Implementing these approaches promotes harmonious self-perception, strengthens identity, and enhances students' psychological and subjective well-being, minimizing the negative impact of the digital environment.

The Social Dilemma (2020), a documentary drama film that demonstrates the mechanisms by which social media algorithms influence users' emotional states and the process of forming unstable identities, especially among young people; The film illustrates the model “algorithm - digital mirror - distorted identity - reduced well-being” [10].

Thus, digital culture has created a new “mirror” of personality that is dynamic, socially saturated, and oriented toward external evaluation. It simultaneously expands opportunities for self-realization and creates risks for psychological well-being, especially among young people. Harmonizing personality in the digital age requires the development of awareness, media literacy, and emotional stability, as well as culturally sensitive psychological support programs. As K.-Zh. Tokayev [20] noted, “the formation of a digital culture and the development of a psychologically safe educational environment is a key condition for successful digitalization,” which is directly related to the tasks of strengthening the digital identity and well-being of students.

In the context of digital culture, the boundaries between the mirror self and the real personality are becoming increasingly fluid, forming new mechanisms of self-perception, self-regulation, and psychological well-being. The digital “mirror,” a combination of media image, social reflections, algorithmic recommendations, and visual practices, is beginning to perform functions that classical psychology associated with interpersonal interaction.

Recent studies confirm that digital environments reinforce both mental resilience and vulnerability. Students may develop a dependence on external digital feedback for their self-esteem, which affects their subjective well-being, motivation, professional self-determination, and stress resilience dynamics.

However, the digital mirror is not entirely destructive: with competent psycho-technological support, it becomes a tool for development, a means of critical self-observation, reflection, professional growth, training in emotional regulation, and media awareness. Harmonizing the personality in the digital age requires the development of awareness, media literacy, and emotional stability, as well as culturally sensitive psychological support programs. As K.-Zh. Tokayev [20] noted, “the formation of a digital culture and the development of a psychologically safe educational environment is a key condition for successful digitalization,” which is directly related to the tasks of strengthening the digital identity and well-being of students.

Personality does not disappear behind the screen; it transforms, and the quality of this transformation depends on the culture of digital interaction, the level of media literacy, and the extent to which the subject is able to maintain autonomy and a critical position within digital reflection procedures.

In conclusion, it can be argued that the digital mirror is becoming a powerful factor in shaping the personality of the 21st century: it influences not only self-perception, but also psychological well-being, values, educational trajectories, and life strategies. The task of science is to offer tools that will help students see not a “distorted reflection” but a holistic image of themselves, where digital identity serves to develop rather than replace personality.

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