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HUMANİTAR VƏ İCTİMAİ ELMLƏR

HUMANITIES AND SOCIAL SCIENCES

Mobilization of Household Savings as a Factor of Financial Stability of the EU Countries in the Context of Macroeconomic Instability

Dmytro Riabtsev[1*], Volodymyr Shevchuk[2], Olena Slavkova[3], Dmytro Pulcha[4], and Svitlana Luchkovska[5]

Abstract. *The households' financial stability is a key component of macroeconomic stability across the European Union countries. This issue gains particular importance in periods of economic instability, global financial shocks, and pandemics. The study utilized cluster analysis to identify similarities and differences in financial trends in the Czech Republic, Italy and Spain, supported by data visualization techniques. The findings show that household savings exhibit wave-like dynamics in response to both market fluctuations as well as macroeconomic shocks. Distinct behavioral patterns across countries are revealed due to comparative analysis, in accordance with differences in economic structure, the state of the stock market and macroeconomic conditions. In the Czech Republic, the savings steadily remained high (18–19%), whereas Italy yielded rather moderate levels (10–11%). In Spain, savings were more sensitive to crisis changes (14% in 2020). The fall in the PX, FTSE MIB and IBEX 35 stock indices in 2018 and 2020 stimulated savings. On the other hand, sustained growth in 2021-2025 restored confidence and promoted moderate investment. GDP, unemployment, and interest rates shaped adaptive financial behavior. This study integrates macroeconomic, market and behavioral factors, which enables a more comprehensive understanding of household financial behavior and improves the basis for forecasting and policy development aimed at stimulating savings and managing financial risks.*

Keywords: *stock market, macroeconomic instability, econometric analysis, market shocks, GDP*

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Makroiqtisadi qeyri-sabitlik kontekstində Aİ ölkələrinin maliyyə sabitliyinin amili kimi ev təsərrüfatlarının əmanətlərinin səfərbər edilməsi

Dmytro Riabtsev[1*], Volodymyr Shevchuk[2], Olena Slavkova[3], Dmytro Pulcha[4], Svitlana Luchkovska[5]

Xülasə. *Ev təsərrüfatlarının maliyyə sabitliyi Avropa Birliyi ölkələrində makroiqtisadi sabitliyin əsas komponentidir. Bu məsələ iqtisadi qeyri-sabitlik, qlobal maliyyə şokları və pandemiya dövrlərində xüsusilə əhəmiyyət kəsb edir. Tədqiqatda Çexiya, İtaliya və İspaniyada maliyyə trendlərindəki oxşarlıqları və fərqləri müəyyən etmək üçün klaster təhlilindən istifadə edilmişdir ki, bu da məlumatların vizuallaşdırılması üsulları ilə dəstəklənir. Nəticələr göstərir ki, ev təsərrüfatlarının əmanətləri həm bazar dalğalanmalarına, həm də makroiqtisadi şoklara cavab olaraq dalğavari dinamika nümayiş etdirir. İqtisadi strukturdakı, fond bazarının vəziyyətindəki və makroiqtisadi şəraitdəki fərqlərə uyğun olaraq müqayisəli təhlillər nəticəsində ölkələr arasında fərqli davranış nümunələri aşkar edilmişdir. Çexiyada əmanətlər davamlı olaraq yüksək olaraq qalmışdır (18-19%), İtaliya isə kifayət qədər orta səviyyələr göstərmişdir (10-11%). İspaniyada əmanətlər böhran dəyişikliklərinə daha həssas olmuşdur (2020-ci ildə 14%). 2018 və 2020-ci illərdə PX, FTSE MIB və IBEX 35 fond indekslərinin düşməsi əmanətləri stimullaşdırmışdır. Digər tərəfdən, 2021-2025-ci illərdə davamlı artım inamı bərpa etmiş və orta investisiyaları təşviq etmişdir. ÜDM, işsizlik və faiz dərəcələri adaptiv maliyyə davranışını formalaşdırdı. Bu tədqiqat makroiqtisadi, bazar və davranış amillərini birləşdirir ki, bu da ev təsərrüfatlarının maliyyə davranışını daha əhatəli şəkildə anlamağa imkan verir və əmanətləri stimullaşdırmaq və maliyyə risklərini idarə etmək məqsədi daşıyan proqnozlaşdırma və siyasətin hazırlanması üçün əsasları təkmilləşdirir.*

Açar sözlər: *fond bazarı, makroiqtisadi qeyri-sabitlik, ekonometrik təhlil, bazar şokları, ÜDM*

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Introduction

Currently, the world is increasingly complex and the financial stability of a national economy extends far beyond a simple set of macrofinancial indicators. Instead, it is deeply rooted in the capacity of its internal sectors to rapidly accumulate and efficiently redistribute resources in response to external shocks. In fact, the financial integration in the EU member states has reached a high level, so this capacity is critically important, as the close interconnection of economies intensifies and accelerates the transfer of crisis phenomena from one country to another. Such a volatile environment leads the household savings to be a fundamental internal source of stability. According to Stanciu (2025), they not only form a vital resource base for future investment but at the same time act as a powerful buffer that helps mitigate the effects of macroeconomic fluctuations.

A substantial body of academic research is consistent confirms that household savings' accumulation has a significant positive impact on investment activity, contributing to higher liquidity in financial markets and strengthening general macrofinancial stability. For instance, Slavkova and Shevaldina (2025) particularly emphasize the dual role of such savings: they serve not only as a reliable financing source for economic development but also as a countercyclical mechanism that can stabilize the economy in periods of crisis. Similarly, László (2025) and Moon et al. (2023) demonstrated empirically that household behavior tends to move towards increased saving in the face of severe crisis shocks, such as the global COVID-19 pandemic or high inflation. Accordingly, this significantly alters consumption patterns and reshapes financial flows.

At the same time, an important place in economic policy as a key component is held by the mobilization of household savings. For example, Knicker et al. (2025) maintains that the effective and well-managed attraction of these funds directly leads to a noticeable expansion of a country's domestic financial resources. Further, Phil-Ugochukwu (2024) and Roe et al. (2015) underscore the critical importance of building strong public trust in financial institutions, considering it an essential prerequisite to successfully transform the private savings into long-term, sustainable investments that support economic growth.

However, despite numerous scholarly works devoted to this issue, several important aspects remain insufficiently explored. In particular, Sahudin et al. (2024) rightly accentuates the critical importance of domestic financial resources as a method to significantly reduce economy's dependence on external financing. At the same time, comprehensive and general approaches that would allow for a full-fledged assessment of these complex processes are scarce and call for further elaboration.

In addition to the above mentioned gaps, the majority of existing research appears to be distinctly fragmentary in itself. First, there is a tendency toward analyzing household savings in isolation, oftentimes beyond the framework of their interaction with other key macrofinancial variables. Second, there is a conspicuous lack of generalized cross-country econometric approaches that would make it possible to assess these savings' impact on financial stability in EU diverse economies. Third, the mechanism through which savings are transformed into productive investments, in particular under conditions of present-day global instability, remains insufficiently explored and requires comprehensive investigation.

Hence, it follows that a key scientific gap lies in the absence of integrated cross-country econometric studies capable of combining household savings, macrofinancial shocks and financial stability indicators within a unified analytical framework. From this perspective, the central research problem is defined as the necessity not only to determine the role of household savings in strengthening financial stability, but also to fully assess their interaction with various macrofinancial factors under conditions of ever-changing and unpredictable instability.

The scientific novelty of this study lies in its novel approach to comprehensive analysis of the relationship between stock market fluctuations and household savings levels in the Czech Republic, Italy and Spain over the period 2016–2025. For the first time, normalized stock indices, market "shocks" and savings levels are integrated into a single analytical model. In terms of comparing the cross-country dynamics, the cluster analysis enables a more precise evaluation of savings mobilization in ensuring financial stability under conditions of macroeconomic instability.

Research hypotheses are as follows:

Hypothesis 1: Short-term declines in stock markets stimulate the households to increase savings as a risk-protection mechanism.

Hypothesis 2: The financial behavior of households in the Czech Republic, Italy and Spain responds differently to market shocks due to differences in economic structure and stock market volatility.
Hypothesis 3: Sustained growth in stock indices contributes to restoring household confidence and stimulates investment activity, along with a moderate increase in savings.

Purpose of the study is to assess the role of household savings in ensuring the financial stability of European Union countries during periods of macroeconomic instability, with a focus on the Czech Republic, Italy and Spain.

Research objectives:

To scrutinize the dynamics of household savings levels in the Czech Republic, Italy and Spain over the period 2016–2025, to analyze their relationship with key macroeconomic indicators (GDP, unemployment, interest rates).

To examine the impact of fluctuations in stock indices (PX, FTSE MIB, IBEX 35) on household financial behavior, particularly in terms of accumulating liquid reserves.

To calculate annual "market shocks" (Shock%) in order to assess short-term household reactions to both market declines and increases.

To apply cluster analysis and principal component analysis (PCA) to identify similarities and differences in stock market dynamics and household behavior in the three countries.

Current scientific research on household savings demonstrates a clear interdisciplinary character. As a matter of fact, it is expedient to systematize existing studies according to several key approaches, namely: classical (neoclassical), behavioral, institutional and macrofinancial. Such a classification enables a clearer identification of both the strengths and the limitations of each approach.

The classical approach considers savings as the result of rational intertemporal choice. According to Maftuhin and Kusumawardani (2022), households aim to maximize utility over their life cycle. However, this approach has a significant limitation, namely the assumption of full rationality and perfect information, which does not always reflect real-life conditions. Further, Snower and Wilson (2025) maintain that savings perform a much broader set of functions, ranging from the formation of financial security to the support of macroeconomic stability.

The behavioral approach, outlined in the works works of Esposito and Mastromatteo (2024), notably complements classical theory by emphasizing bounded rationality, psychological factors and social norms. The scholarly work by Zaiats (2024) holds that even with identical income levels, savings behavior can differ significantly, which is something that classical models struggle to explain. However, this approach also is not devoid of its limitations, particularly its weak integration with macroeconomic models, which complicates the assessment of how savings influence general financial stability.

The institutional approach is concentrated on the role of financial markets, the banking system and public policy. In particular, Anser et al. (2024) and Jumena et al. (2022) claim that the level of financial infrastructure development and trust in institutions to a great extent impact the volume and structure of savings. At the same time, many studies within this approach are mainly descriptive or restricted to individual countries, which limits their the ability to draw broader conclusions.

Within the macrofinancial approach, researchers examine the relationship between savings, economic cycles and crisis phenomena. For instance, Challoumis (2025) argues that during periods of instability, households tend to hold savings in liquid forms, while research by Feng et al. (2022)

notes an increase in savings rates during crises. However, the majority of studies in this area are prevailingly empirical and provide limited scrutiny of the underlying mechanisms linking savings and financial stability.

Particular attention should also be given to studies addressing the motivational factors behind savings. For instance, Barrafrem et al. (2024) underlines the importance of income levels, expenditure structure and trust in financial institutions. At the same time, Kicova et al. (2025) and Chiabai et al. (2018) highlight the role of low financial literacy and institutional instability as key barriers to savings accumulation. However, in line with the behavioral approach, these studies are largely confined to the microeconomic level and do not sufficiently include macrofinancial dimensions.

A critical literature review reveals several key contradictions: between the assumption of rational household behavior and its actual heterogeneity; next, between micro-level explanations of savings behavior and their limited integration into macrofinancial models; between the observation of crisis-driven changes and the limited explanation of their impact on financial stability. Furthermore, there is a clear lack of systematic cross-country comparisons. From this perspective, household savings should be viewed as an integral element of the macrofinancial system, making an impact via mechanisms such as investment, liquidity and confidence in financial institutions.

Summing up, despite the substantial body of research, the systemic relationship between household savings and financial stability remains insufficiently explored, in particular under conditions of macroeconomic instability and cross-country heterogeneity, which highlights the need for further research in this direction.

Materials and Methods

Research procedure

The study draws on analyzing the relationship between stock market fluctuations and the level of household savings in three European countries: the Czech Republic, Italy and Spain. The selection of these countries is preconditioned the differing characteristics of their stock markets and economic structures. The Czech Republic is characterized by a relatively small and stable stock market, which makes it possible to trace the impact of moderate fluctuations on savings behavior. In contrast, Italy has a more developed and capitalized market with a medium level of volatility, which enables a comparison of household behavior within a more complex economic structure. Spain features a higher stock market volatility and a stronger exposure to global financial shocks, thereby making it a particularly relevant example for exploring the psychological effects of market downturns on savings behavior. The study design integrates a temporal analysis of stock indices and macroeconomic indicators with regression modeling, as well as countries clustering based on their market dynamics.

Stages of research

The study was conducted in several consecutive stages. First, statistical data on GDP, unemployment, and household savings for the period 2016–2025 was collected, together with annual data on the stock indices PX (Czech Republic), FTSE MIB (Italy) and IBEX 35 (Spain). The selection of this period was due to the fact that it covers both the pre-crisis phase and a period of significant economic shocks, including the COVID-19 pandemic and subsequent inflationary instability. This makes it possible to examine how household saving behavior changes under the influence of different macroeconomic conditions. Next, the following stage involved calculating annual "market shocks", which show percentage changes in stock indices and can be used as independent variables across the models of household savings.

The calculation was performed using the formula as follows:

$$\text{Shock}_t = \frac{Index_t - Index_{t-1}}{Index_{t-1}} * 100,$$

where Indext is the value of the stock index in year t, Indext−1 is the value of the index in the previous year.
At the next stage, to estimate the delayed response of households to market changes, a lag regression model was built. The model looks as follows:

$$St=\alpha+\beta 1 GDPt+\beta 2 Unempt+\beta 3 Shock_{t-1}+\epsilon t,$$

where St is the level of savings in the year ttt, GDPt is the annual GDP growth, Unempt is the unemployment rate, Shock $_{t-1}$ is the annual market shock of the previous year, εt is the incidental error. This approach allows assessing the psychological effect of "market wealth" on the household behavior.

At the final stage, countries were clustered according to the stock indices dynamics. With that in mind, the indices were normalized, after which the principal component analysis (PCA) and cluster analysis were applied, which made it possible to identify countries with similar market trends and savings levels.

Data sources

Data on the stock indices PX (Czech Republic), FTSE MIB (Italy) and IBEX 35 (Spain) were obtained from official exchange websites and the annual reports of the respective national stock exchanges, which allowed to ensure a high level of reliability and relevance. A representative overview of the Czech stock market is provided by the PX index, including the major companies influencing the national economy. The performance of the largest Italian corporations is reflected by FTSE MIB, making it possible to assess the impact of market fluctuations within a more capitalized economy. In turn, the IBEX 35 is represented by the condition of the Spanish stock market, taking into account global financial risks.

Statistical data on household savings, GDP, unemployment rates and other macroeconomic indicators were collected from national statistical agencies, including the Český statistický úřad (Czech Republic), Istituto Nazionale di Statistica (Italy), Instituto Nacional de Estadística (Spain), as well as from international and financial institutions such as the European Central Bank, the Czech National Bank, the Bank of Italy, the Bank of Spain, Trading Economics and the International Monetary Fund. Also, data from the Eurostat database were used because it standardizes statistics across EU countries and enables cross-country comparisons based on consistent methodologies, which is particularly important for cross-country type of analysis.

Research methods

The applied research methods combine a quantitative analysis of market fluctuations and household behavior. Annual changes in stock indices (“market shocks”) are calculated to assess their impact on the level of savings. Cluster analysis and principal component analysis (PCA) are utilized to reveal similarities in stock market dynamics and household savings across the Czech Republic, Italy and Spain as well as to clearly illustrate the relationship between economic shocks and household behavior.

Visualization of market resilience

For a better presentation of stock markets’ impact on household behavior, a visualization of market resilience was conducted by plotting normalized stock indices (PX, FTSE MIB and IBEX 35) along with the Shock indicator and the level of household savings. The use of normalization makes it possible to compare different markets despite differences in scale and volatility. Admittedly, such a visualization clearly demonstrates the relationship between market dynamics and household

behavior. It can highlight the psychological response to stock market fluctuations and confirm the importance of accounting for lagged effects in savings forecasting models.

Results and Discussion

Over the period 2016–2025, the level of household savings in EU countries changed under the influence of various economic and social factors. In 2020, it increased due to a forced reduction in consumption associated with quarantine measures, as well as precautionary savings behavior under conditions of heightened uncertainty. During 2021–2023, the value declined, which can be explained by the realization of accumulated demand and the inflation impact, which negatively affected households' real incomes. In 2024–2025, the situation tended to stabilize at a higher level, reflecting the consolidation of more cautious household behavior, with continued prioritization of saving (Fig. 1).

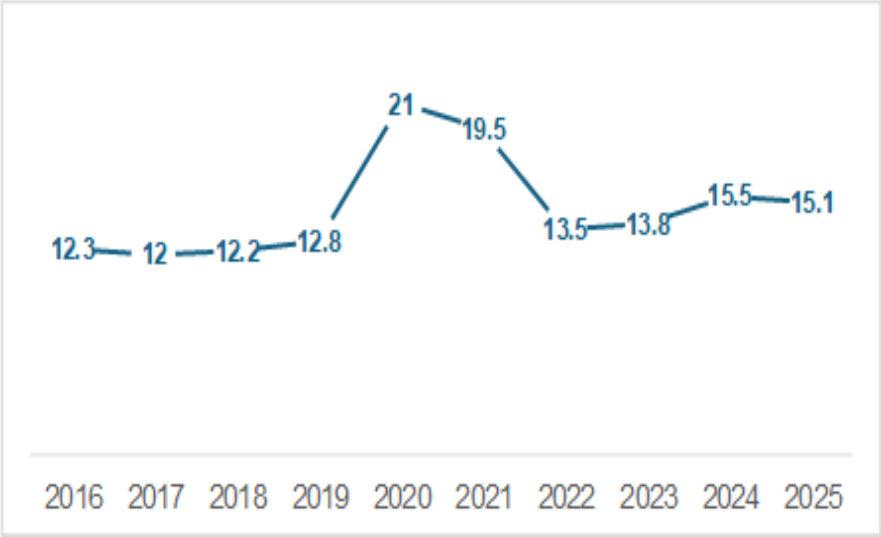

Figure 1
Household savings rate in the EU as a whole

Source. Eurostat (2026a).

Over the period 2016–2025, the level of household savings was composed by various economic factors. The Czech Republic is characterized by consistently high savings rates (18–19%), which can be explained by a relatively large share of stable incomes and overall trust in the financial system, both of which encourage saving even after economic shocks. The savings rate in Italy is lower (10–11%), possibly due to a higher proportion of consumption expenditures and structural economic challenges that limit households' capacity to save. Spain exhibits the highest volatility: the sharp increase in 2020 was driven by forced savings and heightened uncertainty, while the subsequent decline can be attributed to the release of pent-up demand and the recovery of consumer spending (Fig. 2).

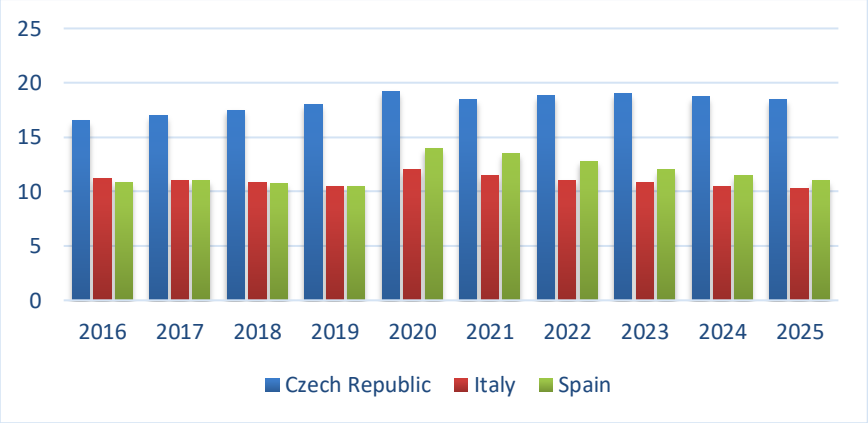

Figure 2
Household savings rate (% of income)

Sources. Eurostat (2026b), ECB (2026), CNB (2026), TradingEconomics (2026), Statista (2026).

The level of household savings in the Czech Republic, Italy and Spain over the period 2016–2025 shows a close relationship with GDP dynamics. During the pre-crisis period (2016–2019), the economies in these countries experienced moderate growth, namely in the Czech Republic, GDP increased from $195 billion to $225 billion, in Italy from $1,810 to $1,930 billion, in Spain from $1,210 to $1,330 billion. A stable level of household savings was recorded, amounting to 16–17% in the Czech Republic, 10–11% in Italy and 12–13% in Spain. When the COVID-19 pandemic began in 2020, all three countries experienced a noticeable decrease in GDP due to quarantine restrictions. However, the decrease scale differed: in the Czech Republic GDP fell to $210 billion, in Italy to $1,750 billion and in Spain to $1,150 billion. This was accompanied by an increase in household savings, in particular to 18–19% in the Czech Republic, 11–12% in Italy and 14% in Spain. This growth was mainly driven by forced reductions in consumption and precautionary saving under conditions of elevated uncertainty. The deeper GDP decrease in Italy and Spain is explained by their higher reliance on the service sector, while the more diversified structure of the Czech economy helped to reduce losses. During the period 2021–2025, the economies gradually recovered, with GDP reaching $270 billion in the Czech Republic, $2,050 billion in Italy and $1,500 billion in Spain. In some households savings stabilized, in others they declined. This can be attributed to realizing the deferred demand and a gradual return to normal consumption patterns. At the same time, in financial behavior crisis-induced caution remained, in particular in the Czech Republic and Spain (Fig. 3).

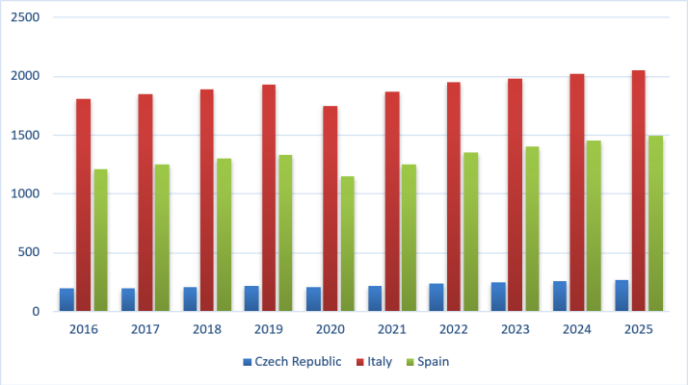

Figure 3
Nominal GDP (US$ billion)

Sources: TradingEconomics (2026), IMF (2026), Statista (2026). Český statistický úřad (Czech Republic) (2026), Istituto Nazionale di Statistica (Italy) (2026), Instituto Nacional de Estadística (Spain) (2026)

The significant impact of employment conditions on household incomes and financial decision-making is confirmed by labor market analysis. During 2016–2019, the unemployment rate declined in all the three countries under study: in the Czech Republic from 3.0% to 2.5%, in Italy from 11.5% to 10.2% and in Spain from 19.5% to 14%. This trend coincided with GDP growth and comparatively stable levels of household savings.

In 2020, during the crisis period, a sharp deterioration in labor market conditions was observed. Spain recorded unemployment at 15.9% and Italy at around 10.5%. However, the Czech Republic remained at a low level of 2.5%, indicating greater resilience of its labor market and overall economy. The increase in unemployment in Spain and, to a lesser extent, in Italy stimulated the households to raise savings as a financial safety buffer, whereas in the Czech Republic stable incomes helped maintain a traditionally high savings level.

During 2021–2025, a gradual decline in unemployment occurred due to the recovery of economic activity in Spain from 14% to 9.9%, in Italy to 7–7.1%, and in the Czech Republic to 2.2–2.7%. Still, the savings behavior remained different across these countries: in economies with lower unemployment, particularly the Czech Republic, savings remained consistently high, while Spain and Italy exhibited greater volatility. This finding highlights that labor market conditions produce a long-term influence of household financial behavior (Figure 4). Overall, the dynamics of unemployment is indicative of the fact that macroeconomic stability and the sustainability of household savings are largely determined by employment levels and income stability. In this process, the countries characterized by more efficient labor markets show lower sensitivity of saving behavior to crisis shocks.

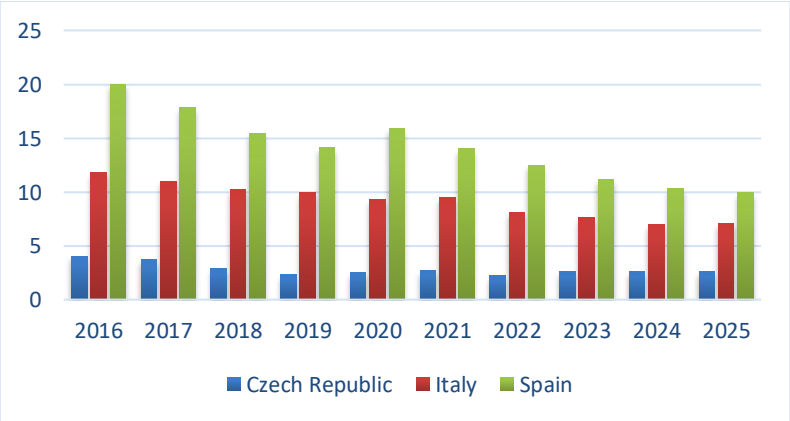

Figure 4

Unemployment (%) - annual values of the general level

Sources. Eurostat (2026c), ECB (2026), CNB (2026), TradingEconomics (2026), Statista (2026).

A significant impact of interest rates on household saving and consumer behavior is shown through analyzing the monetary policies of the Czech Republic, Italy and Spain over the period 2016–2025. The interest rates remained at historically low levels between 2016 and 2020. For example, in the Czech Republic they gradually increased from 0.05% to 2%, while in Italy and Spain remained close to zero. This monetary approach supported consumption growth while reducing the saving attractiveness. Since 2021, central banks in said countries have been adjusting their policies in response to rising inflation pressures. In the Czech Republic, the policy rate increased to 3.75% by 2024–2025, while in Italy and Spain rates incresed sharply up to around 4% in 2022–2023. The above mentioned measures were aimed at curbing the inflation and ensuring macroeconomic stability. As a consequence, interest in bank deposits and other savings instruments increased indeed.

However, the data determine that cause-and-effect relationships remain complex. In spite of the higher interest rates and GDP recovery, the savings rate in the Czech Republic increased only insufficiently (to 18–19%), but in Italy and Spain it partially recovered (to about 10–11% and 12–13%, respectively). This may suggest the influence of additional factors, such as inflation expectations, household indebtedness and general economic uncertainty. Therefore, monetary policy is a key instrument for influencing household financial behavior, yet its effectiveness depends heavily on economic structure, income levels and financial literacy. Interest rates create incentives for either saving or consumption, but across studied countries their effects vary significantly in view of additional macroeconomic and microeconomic conditions (Fig. 5).

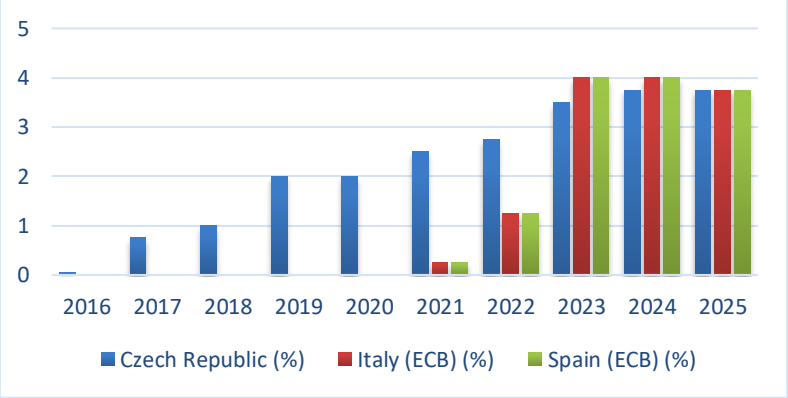

Figure 5
Interest rates (central banks/monetary policy)
Sources. IMF (2026), Bank of Italy (2026), CNB (2026).

Stock markets, together with macroeconomic indicators such as GDP, unemployment rates and interest rates, make an essential impact on the financial behavior of households in the Czech Republic, Italy and Spain. Household confidence increases due to the growth in the PX, FTSE MIB and IBEX 35 indices in both investment and saving decisions. Although market downturns and periods of high volatility stimulate a shift toward more conservative saving strategies. The interaction between market fluctuations and macroeconomic factors is shaping a complex mechanism that determines the household financial behavior and is noticeable in overall economic stability (Table 1).

Table 1
Dynamics of stock indices PX (Czech Republic), FTSE MIB (Italy) and IBEX 35 (Spain) in 2016–2025

Year	Czech Republic PX	Italy FTSE MIB	Spain IBEX 35
2016	1 000	19 234	9 352
2017	1 200	21 853	10 044
2018	1 100	18 324	8 540
2019	1 300	23 506	9 549
2020	1 200	22 233	8 074
2021	1 450	27 347	8 714
2022	1 500	23 707	8 229
2023	1 700	30 352	10 102
2024	1 900	34 186	11 595
2025	2 686	44 945	17 308

Notes. PX is the Prague Stock Exchange Index, the main stock index of the Czech Republic.
The FTSE MIB is Italy's main stock index (the 40 largest companies on Borsa Italiana).
IBEX 35 is the major stock index of Spain (the 35 most liquid companies on the Bolsa de Madrid).
Source. Consolidated by the authors.

As can be seen in Table 2, the household financial behavior is closely associated with alterations in stock indices and market shocks. Short-term declines in 2018 and 2020 produced an increase in savings due to elevated uncertainty and the risk of capital losses. On the other hand, during 2021–2025 stability in market growth contributed to a gradual increase in savings alongside a rise in investment activity. In terms of the sharp changes in the Shock indicator in 2025 for the PX and IBEX indices, those reflected a rapid increase in market capitalization, which had a positive effect on household wealth and financial participation in investment markets. Overall, household behavior demonstrates a high degree of adaptability, combining the accumulation of liquid reserves with engagement in financial markets, thus indicating a pursuit of long-term financial stability.

Table 2
Normalized stock indices PX, FTSE MIB and IBEX 35, annual Shock (%) and household savings rate (2016-2025)

Year	PX_norm	PX_Shock (%)	FTSE_MIB_norm	FTSE_Shock (%)	IBEX_norm	IBEX_Shock (%)	Savings_norm
2016	100	–	100	–	100	–	100
2017	120	20	114	14	107	7	102
2018	110	-8.3	95	-17.3	91	-14.4	104
2019	130	18.2	122	28.9	102	12.1	105
2020	120	-7.7	115	-5.3	86	-15.7	110
2021	145	20.8	142	23.5	93	8.1	108
2022	150	3.4	123	-13.0	88	-5.4	106
2023	170	13.3	158	28.9	102	15.9	107
2024	190	11.8	178	12.5	124	21.6	108
2025	269	41.6	234	30.8	185	50.7	110

Source. Consolidated by the authors.

The graph presented in Figure 6 shows a close relationship between the dynamics of stock markets and the level of household savings. The PX index in the Czech Republic exhibits higher volatility as compared to the other indicators, which can be explained by greater market fluctuations during the 2017–2020 period. Instead, the Italian and Spanish markets, represented by the FTSE MIB and IBEX 35 indices, form a relatively tight cluster together with the savings level and the impact of yearly economic shocks. These markets are characterized by a consistent pattern: declines in stock indices are associated with increases in household savings, when long-term market growth results in stabilization or a gradual rise in savings. On the whole, the figure substantiates both the economic conditions and the psychological linkage between stock market behavior and household financial situation in the Czech Republic, Italy and Spain over the period of 2016–2025.

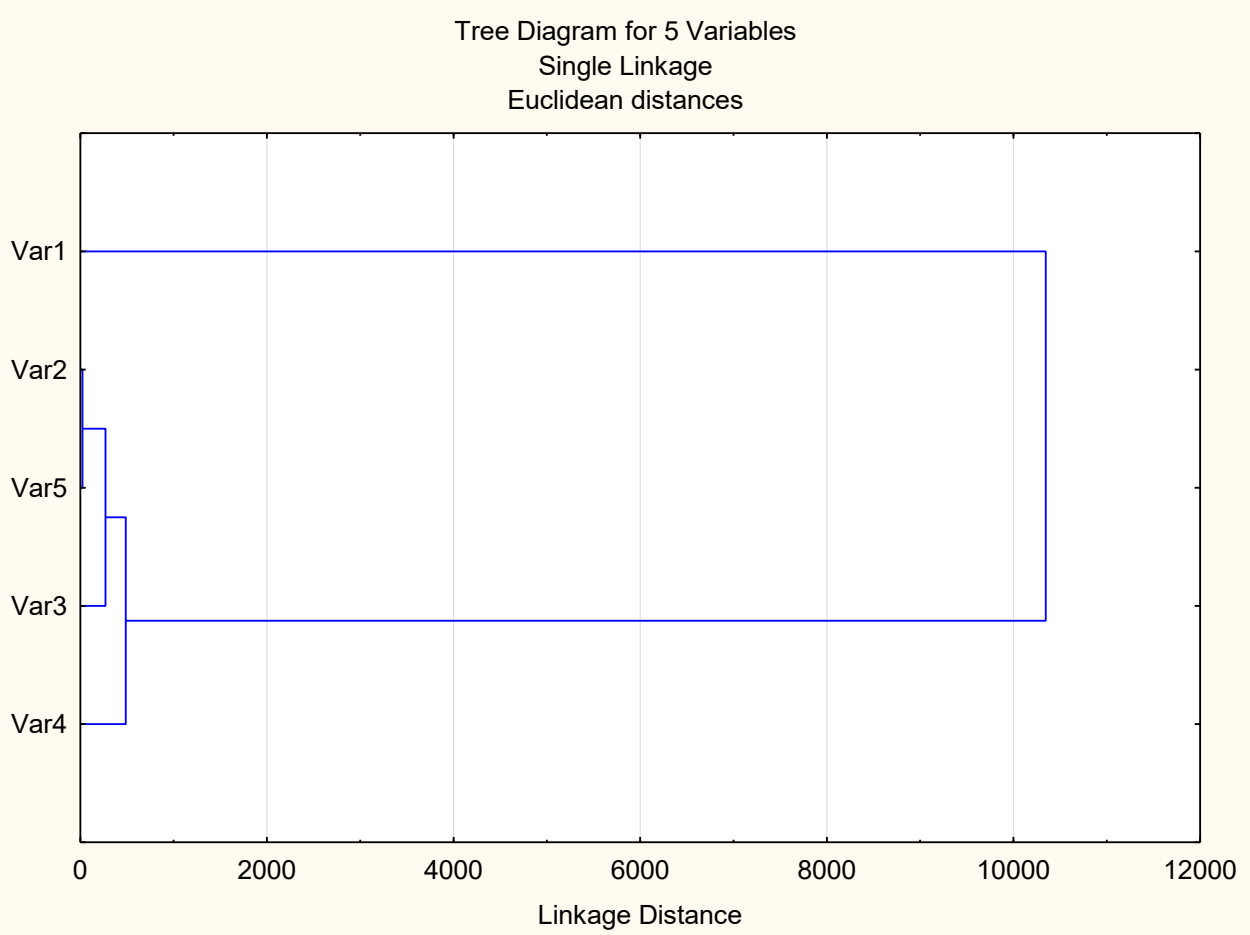

Figure 6
Distribution of countries by stock market clusters

Note.
Var1 → PX_norm is the normalized Czech stock index PX
Var2 → FTSE_MIB_norm is the normalized Italian FTSE MIB index
Var3 → IBEX_norm is the normalized Spanish IBEX 35 index
Var4 → Savings_norm is the level of household savings
Var5 → Shock (%) — Annual Stock Index Shocks or Average Shock
Source: consolidated by the authors

Thus, the chart clearly shows that the PX index stands out among the three indices due to stronger fluctuations, but the FTSE MIB, IBEX 35 and household savings levels demonstrate more synchronized responses. This makes it possible to conclude that the mobilization of household savings functions as an adaptive mechanism that reduces the effects of macroeconomic instability and contributes to financial stability in EU countries.

Results and Discussion

A complex interaction of macroeconomic, financial and behavioral factors is demonstrated by the study of household savings dynamics in EU countries over the period 2016–2025. Although general patterns, such as the sharp increase in savings during the crisis year 2020, are in line with classical economic predictions and substantiate the findings of Skoblar (2024) and Zhao et al. (2022), the results appear to indicate a considerably stronger role of psychological factors and market shocks. Namely, even during periods of low interest rates, households exhibited active accumulation of

savings, which is to some extent inconsistent with traditional models that assume a direct relationship between the cost of credit and the propensity to save.

A comparative analysis of the Czech Republic, Italy and Spain can offer a critical reassessment of generalized assumptions regarding homogeneous household behavior within a single economic area. The Czech Republic, which is characterized by stable and high savings levels (from 100% in 2016 to 110% in 2025), supports the conservative behavior pattern described by Matějková and Tichá (2025). Italy and Spain demonstrate greater volatility, as the decline observed during the crisis year of 2020 (Italy to 95–100%, Spain to 110%) uncovers higher sensitivity to macroeconomic and social risks. It is consistent with the findings of Colabella et al. (2023) and Barrella et al. (2025). These differences demonstrate that even within the EU, household behavior is predominantly shaped by national economic and social factors.

Monetary policy is characterized by complex and non-linear impact. During 2016–2020, low interest rates supported consumption; yet, during crisis periods (notably 2020), households increased savings regardless of interest rate levels, which indicates the predominance of behavioral factors over classical economic determinants. After 2021, interest rate increases (to 3.75% in the Czech Republic and around 4% in Italy and Spain) made saving appear more attractive and moderately restrained consumption, which is consistent with Schrank's (2024) the findings. It should be noted that this also highlights the complexity of interactions between economic incentives and households' psychological responses.

Undoubtedly, the macroeconomic environment is one of the principal determinants of savings formation. The analysis shows that GDP growth has a positive effect on savings levels. This aligns with Besley et al. (2026) conclusions of perceiving economic growth as a strong driver of income accumulation. Notably, the paradoxical increase in savings in 2020, when economic fall was followed by higher financial reserves, partly confirms the theoretical arguments of Sydorchuk et al. (2024) and Pyatnychuk et al. (2024), who attribute such behavior to households' desire to build liquidity buffers during periods of uncertainty. However, the results of the current study further suggest that psychological factors and market shocks also play a crucial role, enabling a more accurate explanation of cross-country differences in savings.

The dynamics of the stock indices PX, FTSE MIB and IBEX 35 highlight the importance of structural differences across financial markets. The Czech Republic responds comparatively quickly to fluctuations in the PX index. At the same time, during periods of rising indices Italy and Spain demonstrate more synchronized savings behavior, which supports the "wealth effect" concept proposed by Grillet-Aubert (2020). Still, the high volatility of the FTSE MIB and IBEX 35 in 2018 and 2020 stimulated households to increase savings, while the stable growth of the PX index during 2021–2025 contributed to the formation of longer-term financial reserves. The above observations are indicative of the idea that any assessment of household financial behavior that does not include stock market fluctuations remains incomplete.

Summing up, the research results generally confirm the offered hypotheses. In particular, household savings levels respond to stock market volatility: during sharp declines in indices, savings tend to increase; however, during periods of market growth they exhibit stability or show gradual and moderate increases (Hypothesis 1). As observed in the Czech Republic, high and stable savings rate supports greater financial stability and reduces the unpredictability of household behavior during crisis periods. In Italy and Spain, household financial behavior appears highly synchronized with market fluctuations, indicating similar response patterns in countries with comparable economic structures (Hypothesis 2). As observed in 2021–2025, during periods of sustained stock market growth, household confidence is restored, thus fostering moderate growth in savings and a greater willingness to allocate part of disposable income to investments. Overall, this substantiates that

positive and stable market dynamics not only support household financial stability but also actively stimulate investment activity (Hypothesis 3).

Limitations

Despite the obtained results, the study is not without its limitations. The overriding limitation is that the analysis encompasses only three countries (the Czech Republic, Italy, Spain), which restricts the generalizability of the findings to other European or global markets. Furthermore, the models include a limited set of macroeconomic variables, such as GDP and unemployment. Yet, other potentially important determinants of savings behavior are excluded such as income levels, tax policy and cultural patterns of financial behavior. The above limitations should be taken into account when interpreting the results and designing future research.

Conclusions

The study of household savings dynamics in the Czech Republic, Italy and Spain during 2016–2025 uncovered essential differences in trends depending on economic structure, stock market conditions and unemployment rates. The savings remained the most stable in the Czech Republic, having increased from 100% in 2016 to 110% in 2025, which may indicate the traditionally high propensity of households to accumulate financial reserves. In Italy, a gradual recovery of confidence was observed following earlier crises: the savings rate fluctuated between 95% and 100%, reaching 108% by the end of the studied period.

In Spain, savings exhibited the highest volatility, reaching 110% during the crisis year of 2020, which may be indicative of strong sensitivity to changes in the economic environment. The importance of market wealth effects on household financial behavior is substantiated by the analysis of stock indices. For instance, in the Czech Republic, the PX index increased from 1,000 points in 2016 to 2,686 points in 2025, though fluctuations were observed in 2018 and 2020. In Italy, the FTSE MIB rose from 19,234 to 44,945 points with periodic declines. Yet, in Spain the IBEX 35 ranged from 9,352 to 17,308 points, also indicating declines in the same periods. The above mentioned stock market dynamics contributed to increased savings during the times of economic shocks and stimulated investment activity over the periods of stable growth. Also, it is evident that nominal GDP influences savings dynamics. In the Czech Republic, GDP increased from USD 195 billion to USD 270 billion, in Italy from USD 1,810 billion to USD 2,050 billion and in Spain from USD 1,210 billion to USD 1,500 billion, while the fall in 2020 was associated with increased savings across all countries.

Notably, the unemployment rate served as an important indicator of economic resilience. In the Czech Republic, it remained low, ranging from 2.2% to 2.7%, while in Italy and Spain it declined significantly over the period—respectively, from 11.2% to 7.1% and from 20% to 9.9%, despite highest levels during crisis periods (e.g., in Spain reaching 15.9% in 2020). In parallel, the increase in interest rates during 2023–2025 to 3.75–4% led to a more pronounced tendency toward savings and a moderate reduction in consumption, reflecting household adaptation to changing financial conditions. On the whole, the results demonstrate that household financial behavior is largely determined by the interaction of macroeconomic indicators, stock market dynamics and monetary policy. The highest savings stability is noted in countries characterized by low unemployment rate and clear signals of economic stability and growth.

The practical value of the study lies in its possibility to be applied for forecasting household responses to financial shocks, developing policies to encourage savings and enhancing the stability of national financial systems. Further research should expand the countries sample, incorporate additional economic variables and examine short-term effects of market shocks using higher-frequency (monthly or quarterly) data.

References

Anser, M. K., Khan, M. A., Khan, M. A., Huizhen, W., & Haider, A. (2024). The effectiveness of emerging markets' legal structure in explaining financial development. *PLoS ONE*, *19*(4), e0299831. https://doi.org/10.1371/journal.pone.0299831

Bank of Italy. (2026). *Monetary policy and interest rates*. *https://www.bancaditalia.it/compiti/polmon-garanzie/index.html?com.dotmarketing.htmlpage.language=1.* Accessed on June 15, 2026.

Barrafrem, K., Tinghög, G., & Västfjäll, D. (2024). Behavioral and contextual determinants of different stages of saving behavior. *Frontiers in Behavioral Economics*, *3*, 1381080. https://doi.org/10.3389/frbhe.2024.1381080

Barrella, R., Mora Rosado, S., & Romero, J. C. (2025). The 2022 energy and inflationary crises: Data, experiences and opinions of Spanish energy vulnerable households. *Energy Research & Social Science*, *121*, 103961. https://doi.org/10.1016/j.erss.2025.103961

Besley, T., Dann, C., & Dray, S. (2026). Growth experiences and trust in government. *The Quarterly Journal of Economics*, *141*(2), 1761-1822. https://doi.org/10.1093/qje/qjaf056

Český statistický úřad (Czech Republic). (2026). Home page. *https://www.czso.cz/.* Accessed on June 15, 2026.

Challoumis, C. (2025). Economocracy: Global economic governance. *Economies*, *13*(8), 230. https://doi.org/10.3390/economies13080230

Chiabai, A., Spadaro, J. V., & Neumann, M. B. (2018). Valuing deaths or years of life lost? Economic benefits of avoided mortality from early heat warning systems. *Mitigation and Adaptation Strategies for Global Change*, *23*(7), 1159-1176. https://doi.org/10.1007/s11027-017-9778-4

CNB. (2026). *Interest rates (2W Repo Rate)*. *https://www.cnb.cz/en/faq/How-has-the-CNB-two-week-repo-rate-changed-over-time/.* Accessed on June 15, 2026.

Colabella, A., Guglielminetti, E., & Rondinelli, C. (2023). *The distribution and use of Italian households' savings after the pandemic* (Research Gate Discussion Paper No. 797). https://doi.org/10.13140/RG.2.2.29958.75849

ECB. (2026). Household saving statistics. *https://www.ecb.europa.eu/stats/macroeconomic_and_sectoral/sector_accounts/html/index.en.html.* Accessed on June 15, 2026.

Esposito, L., & Mastromatteo, G. (2024). Behavioral economics and the nature of neoclassical paradigm. *Mind & Society*, *23*(1–2), 45-78. https://doi.org/10.1007/s11299-024-00303-y

Eurostat. (2026a). Household saving rate (indicator explanation). https://ec.europa.eu/eurostat/databrowser/view/nasq_10_ki/default/table. Accessed on June 15, 2026.

Eurostat. (2026b). Household saving rate (Sector accounts). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Household_saving_rate. Accessed on June 15, 2026.

Eurostat. (2026c). Household saving rate up to 15.7% in the euro area. https://ec.europa.eu/eurostat/web/products-euro-indicators/w/2-04102024-ap? Accessed on June 15, 2026.

Feng, Q., Wu, G. L., Yuan, M., & Zhou, S. (2022). Save lives or save livelihoods? A cross-country analysis of COVID-19 pandemic and economic growth. *Journal of Economic Behavior & Organization*, *197*, 221-256. https://doi.org/10.1016/j.jebo.2022.02.027

Grillet-Aubert, L. (2020). *Opportunities and risks in the financial index markets* (SSRN Scholarly Paper No. 4954561). *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4954561

IMF. (2026). World Economic Outlook Database. *https://www.imf.org/en/Publications/WEO/weo-database.* Accessed on June 15.

Instituto Nacional de Estadística (Spain). (2026). Home page. https://www.ine.es/. Accessed on June 15, 2026.

Istituto Nazionale di Statistica (Italy). (2026). Home page. *https://www.istat.it/en/.* Accessed on June 15, 2026.

Jumena, B. B., Siaila, S., & Widokarti, J. R. (2022). Saving behaviour: Factors that affect saving decisions (systematic literature review approach). *Jurnal Economic Resource*, *5*(2), 217-235. https://doi.org/10.56750/jer.v5i2.365

Kicova, E., Michulek, J., Ponisciakova, O., & Fabus, J. (2025). When financial awareness meets reality: Financial literacy and Gen Z's entrepreneurship interest. *International Journal of Financial Studies*, *13*(3), 171. https://doi.org/10.3390/ijfs13030171

Knicker, M. S., Naumann-Woleske, K., Bouchaud, J. P., & Zamponi, F. (2024). Post-COVID inflation and the monetary policy dilemma: An agent-based scenario analysis. *Journal of Economic Interaction and Coordination*, *20*(1), 141-195. https://doi.org/10.1007/s11403-024-00413-3

László, T. (2025). Structural divergences in the european economy: A cluster approach to macroeconomic performance (2013–2023). *Sustainable Futures*, *10*, 100996. https://doi.org/10.1016/j.sftr.2025.100996

Maftuhin, M., & Kusumawardani, D. (2022). Household saving behavior on formal financial institutions in urban and rural areas. *Ekuilibrium Jurnal Ilmiah Bidang Ilmu Ekonomi*, *17*(1), 40-53. https://doi.org/10.24269/ekuilibrium.v17i1.2022.pp40-53

Matějková, J., & Tichá, A. (2025). Housing market trends and affordability in Central Europe: Insights from the Czech Republic, Slovakia, Austria, and Poland. *Buildings*, *15*(10), 1729. https://doi.org/10.3390/buildings15101729

Moon, K., Heo, W., Lee, J. M., & Grable, J. E. (2023). Financial stress and COVID-19: A comprehensive analysis of the factors associated with the pandemic. *Risks*, *11*(12), 218. https://doi.org/10.3390/risks11120218

Phil-Ugochukwu, A. I. (2024). Informal financial savings practices to facilitate formal financial inclusion. *World Journal of Advanced Research and Reviews*, *24*(3), 1970-1979. https://doi.org/10.30574/wjarr.2024.24.3.3779

Pyatnychuk, I., Akimova, L., Pavlovskyi, O., Vengerskyi, O., Akimov, O., & Pershko, L. (2024). The economic and legal dimension of the migration of intellectual and human capital as a threat to national security: The role and possibilities of public administration. *Edelweiss Applied Science and Technology*, *8*(6), 1481-1491. https://doi.org/10.55214/25768484.v8i6.2264

Roe, D., Booker, F., Day, M., Zhou, W., Allebone-Webb, S., Hill, N. A. O., Kumpel, N., & others. (2015). Are alternative livelihood projects effective at reducing local threats to specified elements of biodiversity and/or improving or maintaining the conservation status of those elements? *Environmental Evidence*, *4*, 22. https://doi.org/10.1186/s13750-015-0048-1

Sahudin, Z., Ridzuan, A. R., Razak, M. I. M., & Bahrudin, N. Z. (2024). Determinants of household savings. *Advances in Social Sciences Research Journal*, *11*(2.2), 347-362. https://doi.org/10.14738/assrj.112.2.16422.

Schrank, J. (2024). The impact of a crisis on monetary policy's influence on financial markets: Evidence from the COVID-19 pandemic. *Cogent Economics & Finance*, *12*(1), 2322874. https://doi.org/10.1080/23322039.2024.2322874

Skoblar, A. (2024). The puzzle of household savings in the European Union: Tracing influences across time and space. *Public Sector Economics*, *48*(3), 247-282.

Slavkova, A. A., & Shevaldina, V. H. (2025). Household savings and their impact on the Ukrainian economy. *The Problems of Economy*, *1*(63), 342-349. https://doi.org/10.32983/2222-0712-2025-1-342-349

Snower, D. J., & Wilson, D. S. (2025). Rethinking the theoretical foundation of economics II: Core themes of the multilevel paradigm. *Economics*, *19*(1). https://doi.org/10.1515/econ-2025-0133

Stanciu, L. (2025). Financial stability – a prerequisite for sustainable development of non-financial economic entities. *International Conference Knowledge-Based Organization*, *31*(2), 88-95. https://doi.org/10.2478/kbo-2025-0053

Statista. (2026). Household saving rate in Europe. *https://www.statista.com/topics/6820/saving-rate-in-europe/.* Accessed on June 15, 2026.

Sydorchuk, O., Kharechko, D., Khomenko, H., Akimova, L., Kosarevych, N., & Akimov, O. (2024). Competencies for sustainable financial and economic management: Their impact on human capital development and national security. *Edelweiss Applied Science and Technology*, *8*(6), 1445-1454. https://doi.org/10.55214/25768484.v8i6.2261

TradingEconomics. (2026). Household saving rate (EU countries). *https://tradingeconomics.com/country-list/personal-savings.* Accessed on June 15, 2026.

Zaiats, V. (2024). Financial behavior of households in the context of their resilient development. *Demography and Social Economy*, *55*(1), 41-58. https://doi.org/10.15407/dse2024.01.041

Zhao, L., Rasoulinezhad, E., Sarker, T., & Taghizadeh-Hesary, F. (2022). Effects of COVID-19 on global financial markets: Evidence from qualitative research for developed and developing economies. *European Journal of Development Research*, *35*(1), 148-166. https://doi.org/10.1057/s41287-021-00494-x

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The Problem of Constructing a Political Paradigm in Muslim Thought

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Abstract. *Our research will focus on the problem of conceiving and constructing a political paradigm, which is the most important dilemma of Muslim thought. We will evaluate the traditional political conceptions of Muslims that have emerged throughout the historical process, beginning with the death of the Prophet Muhammad (peace be upon him). Solving problems first requires identifying and examining their root causes. If we fail to accurately diagnose the problems, we will not only fail to solve them but will also become part of the problem. Naturally, politics constitutes only a part of individual and social life, not the whole. To conceive of politics as encompassing all of life is contrary to the nature of political thought. Such a way of thinking would harm all values outside the political sphere. In this context, when discussing religion and politics, it is important to note that although they appear separate, these concepts, which are in fact interconnected in a vibrant and intricate network, point to two crucial dimensions of individual and societal reality. Both religion and politics are human phenomena that, in their own dimensions and planes, exert a decisive influence on the social, political, and economic structures that shape the individual and society. Both phenomena fulfill their respective missions in the writing of history. On the contrary, they pave the way for an increase in problems related to these issues in individual and social life, leading to insolubility and chaos.*

Keywords: *human, religion, politics, caliphate institution, prophet*

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Müsəlman dünyasında siyasi paradiqmanın problemi

Erdoğan Köycü[1*], Mustafa Özden[1]

Xülasə. *Tədqiqatımız müsəlman düşüncəsinin ən vacib dilemması olan siyasi paradiqmanın təsəvvür edilməsi və qurulması probleminə yönələcək. Məhəmməd Peyğəmbərin (ona Allahınsalavatı və salamı olsun) vəfatından başlayaraq tarixi proses boyunca müsəlmanların ortaya çıxan ənənəvi siyasi konsepsiyalarını qiymətləndirəcəyik. Problemləri həll etmək üçün əvvəlcə onların kök səbəblərini müəyyən etmək və araşdırmaq lazımdır. Problemləri dəqiq diaqnoz edə bilməsək, nəinki onları həll edə bilməyəcəyik, həm də problemin özünün bir hissəsinə çevriləcəyik. Təbii ki, siyasət fərdi və sosial həyatın yalnız bir hissəsini təşkil edir, bütövlükdə deyil. Siyasəti həyatın bütün sahələrini əhatə edən bir şey kimi təsəvvür etmək siyasi düşüncənin təbiətinə ziddir. Belə bir düşüncə tərzi siyasi sahədən kənar bütün dəyərlərə zərər verərdi. Bu kontekstdə, din və siyasət məsələsinə toxunarkən qeyd etmək vacibdir ki, zahirən ayrı görünsələr də, əslində canlı və mürəkkəb bir şəbəkədə bir-biri ilə əlaqəli olan bu anlayışlar fərdi və ictimai reallığın iki vacib ölçüsünə işarə edir. Hər iki fenomen tarixin yazılmasında öz missiyalarını yerinə yetirir.*

Bu fenomenlərdən birini və ya hər ikisini inkaredən və ya görməzdən gələn ideoloji və siyasi yanaşmalar onları aradan qaldırmır. Əksinə, fərdi və sosial həyatda bu məsələlərlə bağlı problemlərin artmasına yol açır və həll olunmazlığa və xaosa səbəb olur.

Açar sözlər: *insan, din, siyasət, xilafət quruluşu, peyğəmbər*

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Introduction

One of the most fundamental problems of social and political science is the relationship between religion and the individual, society, and politics. Since the Middle Ages, the relationship between politics and religion has been a central topic on humanity's intellectual and political agenda. When considering religion and politics, it is crucial to understand that, although they appear distinct in reality, they are fundamentally interconnected and share a vibrant, intricate network of relationships that serve the essential needs of human nature. In this sense, the concepts of religion and politics point to two vital dimensions of individual and societal reality. Naturally, concepts like religion and politics are inherent human phenomena that, in their own dimensions, affect individuals and society and have a decisive influence on intellectual, social, political, and economic structures. Humanity cannot neglect or ignore these inherent phenomena, for both fulfill their respective missions in the writing of history. In this context, the Prophet Muhammad also engaged in political activities and made decisions as part of his human responsibility. Based on this understanding, we would like first to evaluate the Prophet Muhammad's political decisions, the political model of the founding generation (the Companions and the Tabi'in), and the theoretical and practical views of Muslim scholars on this subject. The Prophet Muhammad's period in Medina was a movement that, while religious, also had political dimensions. The socio-political conditions in Medina compelled the Prophet to engage in political activity. The political activities the Prophet undertook in Medina were entirely a human, earthly, and jurisprudential endeavor dictated by the prevailing circumstances. Therefore, the vision of social leadership that the Prophet Muhammad undertook in Medina was not a part of, or a continuation of, his prophetic mission, but rather a necessity and a consequence of his humanity. We see that the Prophet Muhammad, in establishing the city-state of Medina based on a social contract, structured it according to the general principles defined by the Quranic teachings, such as establishing justice, consultation, and entrusting affairs to competent individuals, while also incorporating his own traditional tribal, political, and human experience, intellectual imagination, and the common good. As is well known, the Quran does not propose any model for state and governance. In other words, the Quran does not offer a systematic, defined, and modeled political understanding. In this regard, the Quran merely sets forth universal principles for political legitimacy. It leaves the structuring, organization, and execution of politics to humanity, that is, to the social will and the collective wisdom of society.

The death of the Prophet Muhammad marked the beginning of a new and significant era in Islam, for Muslims had lost not only their Prophet but also their head of state. Neither the Quran nor the Sunnah of the Prophet contained any decree or political regulation regarding the identity of the person who would lead the state or how they should be chosen. The Companions faced the need to rebuild the state after the Prophet Muhammad's death. The Ansar gathered in the shade of the Banu Sa'ida to choose one of their own to lead the Muslim state. This disagreement over governance, which arose even while the Prophet's body was still there, left its mark not only on that era but for centuries to

come. In the courtyard of Beni Sa'ida, it is observed that the discussions were based on the Arab understanding of politics, as required by the existing administrative, political, and social conditions; neither the Ansar nor the Muhajir groups put forward a religious justification; instead, they presented arguments with purely political and social content. (İbn Hişam, 1978, Vol. 4, pp. 225–228) We wish to evaluate these arguments, taking into account the social and political conditions, in accordance with Qur'anic principles. When we examine the content and arguments put forward in the caliphate debate between the Ansar and the Muhajirun in the courtyard of Beni Sa'ida, we see that the discussion was not conducted within the framework of the general principles outlined in the Quran. The meeting of the Ansar, gathered in the shade of Beni Sa'ida to elect a caliph, was joined by a group of Muhajirun, and the discussion unfolded as follows: Should the caliph be from the Ansar or the Muhajirun? (İbn Hişam, 1978, Vol. 4, p. 225). Thus, the matter was framed within tribal logic. As the discussion continued, Abu Bakr, who was attending the meeting on behalf of the Muhajirun, asked, "What is the purpose of this meeting?" (Taberî, 1907, Vol. 3, p. 198). The spokesman for the Ansar stood up and responded to Abu Bakr as follows: “We are the helpers of God's religion and the soldiers of Islam. O community of Muhajirun! You are a small group compared to us.” “You are slow-moving and few in number. However, look, such a group wants to seize a task that belongs to us," he concluded his speech. Although Umar attempted to respond, Abu Bakr prevented him. Then Abu Bakr asked Sa'd ibn Ubadah, "O Sa'd! What is your opinion?" Sa'd ibn Ubadah replied, "I am one of them!" (Andalusi, p. 2/175). Then Hubab ibn Munzir said, “Let one leader be from us and one from you!” (İbn Sa’d, 1957, p. 182). “The service of the Muhajirun to religion pales in comparison to the service of the Ansar.” Umar replied, “Indeed, the service of the Ansar to religion pales in comparison to the service of the Muhajirun.” Hubab ibn Munzir rejected Umar’s statement. (İbn Abdirabbih, 1948, p. 2/175). Umar asked, “O people of Ansar, do you not know that the Messenger of Allah appointed Abu Bakr to lead the people in prayer?” The Ansar replied, “Yes, we know.” Umar said, “Which of you would be willing to go ahead of Abu Bakr after this?” They replied, “We seek refuge in Allah from going ahead of Abu Bakr.” (İbn Hanbel, 1981, Vol. 1, p. 21). After these discussions, Abu Bakr addressed the Ansar as follows: “O people! We, the Muhajirun, are the first of all people to accept Islam, the most honorable in lineage and ancestry, the most superior in homeland, the most beautiful in appearance, and the closest to the Prophet among the Arabs. We became Muslims before you. Allah mentioned our names in the Quran before yours. You are our brothers in faith, our partners in the spoils of war, and our helpers against our enemies. We are the commanders, and you are the ministers. (İbn Abdirabbih, 1948, p. 2/111). We will not cease consulting you; we will not do anything without consulting you. (Dineverî, 1909, Vol. 1, pp. 14–15).”

O community of Ansar! You are the people of the good and righteousness you speak of, but all the Arabs do not recognize the right of this leadership for anyone other than the tribe of Quraysh. They are the middle ones among the Arabs in terms of lineage and status (İbn Hişam, 1978, Vol. 4, p. 227). The Arabs embraced Islam only for the sake of this particular tribe, Quraysh (İbn Abdirabbih, 1948, p. 2/175); (Belâzurî, 1959, Vol. 1, p. 582). It is even stated that, in this gathering, Abu Bakr cited the hadith from the Prophet, "The Imams are from Quraysh," as evidence (Maverdî, 1966, p. 6). Thereupon, the Ansar proposed, "Let there be one commander from us and one from you" (Buhârî, 1981, Vol. 4, p. 194). Abu Bakr rejected this proposal, saying, “We are the commanders, and you are the ministers.” Hubab ibn Munzir said, “No! By Allah, we do not accept what you say. Let there be one commander from us and one from you.” Again, Abu Bakr replied to Hubab ibn Munzir, “No, we are the commanders, and you are the ministers,” and added, “You can pledge allegiance to either Umar ibn al-Khattab or Ubayda ibn al-Jarrah” (İbn Sa’d, 1957, Vol. 2, p. 269). Upon hearing this proposal and seeing the voices rise and the argument escalate, Umar, fearing that the dispute would reach a dangerous level, extended his hand to Abu Bakr to pledge allegiance, and the Muhajirun and Ansar who were present followed Umar (İbn Hişam, 1978, Vol. 4, p. 227).

Sa'd ibn Ubadah, initially the Ansar's candidate for caliph, was the leader of the Khazraj. The Aws, another Ansar tribe, were former opponents of the Khazraj and therefore preferred Abu Bakr over

Sa'd, leaving Sa'd in the minority (Hatipoğlu, 1978, p. 39). The limited pledge of allegiance made in the courtyard of Beni Sa'ida was followed the next day by a general pledge of allegiance in the Mosque of Medina, and Abu Bakr was elected the first Caliph of the Muslims with the overwhelming majority of the Muslims in Medina (Suyûtî, 1951, pp. 67–72); (Hatipoğlu, 1978, p. 39). In the following days, when criticized for the hasty selection of Abu Bakr as caliph, Umar responded: "By Allah, in the situation we were in that day, there was nothing better than pledging allegiance to Abu Bakr. If we had left without pledging allegiance to Abu Bakr, the Ansar would have pledged allegiance to one of their own, which we feared. For in that case, we would either have reluctantly pledged allegiance to the Ansar or we would have remained in opposition, which would have resulted in anarchy." (İbn Hişam, 1978, Vol. 4, p. 226); (İbn Hanbel, 1981, Vol. 1, p. 56).

It is clear from the above words of Caliph Umar that the first caliph election was not conducted properly. Even Caliph Umar, the main political actor in the first caliph election, later expressed his dissatisfaction, stating that the election was rushed and conducted without consultation (İbn Hişam, 1978, Vol. 4, p. 226). However, despite our consideration of this, we find it surprising that he did not conduct a self-critique of the evidence presented in the Beni Sa'ida case, which we consider surprising for a genius like Caliph Umar. We also find it difficult to explain why the Companions, who were educated under the Prophet Muhammad, would engage in a low-level political polemic by making accusatory statements and engaging in actions against each other, despite the command to "Entrust the trust to those who are worthy of it" (Nisa, 4/58); (Akbulut, 2001, pp. 42–67). However, according to the worldview of the Holy Quran, being from the Prophet's people, or even his son, daughter, brother, or uncle, does not grant any privilege. Because the Quran explains that believers are brothers (Hujurat, 49/10), that superiority lies only in piety, and that the reason for the division of people into nations and tribes is related to divine wisdom aimed at enabling people to love and recognize one another (Hujurat, 49/13); Compare (Al-i Imran, 3/139). Given this, how can tribal and racial differences be presented as a means of privilege and superiority? Furthermore, the Quran bases Islamic brotherhood not on blood ties or tribal values, but on the principle of believing in shared values (Buhârî, 1981, Vol. 4, p. 194). These Qur'anic values indicate that, according to the Qur'an, being related to the Prophet Muhammad grants no privilege or superiority. The theory of the superiority of the Quraysh, voiced by Abu Bakr on election day, originated in the Beni Sa'ida tribe as a result of the exploitation of being from the Prophet's tribe, later developed into a hadith, and entered Islamic culture (Akbulut, 2001, 42–67). The Quraysh, who championed their lineage from the Prophet's tribe, even pushed the Ansar, who had welcomed them, out of the political bureaucracy, ensuring that the Muslim aristocracy consisted of members of the Quraysh. Thus, the tribal mentality of the pre-Islamic era, while no longer in its old, primitive, and crude forms, continued to influence Islam in a more refined, sophisticated, and transformed way. At the same time, there are no specific rulings in the Quran and Sunnah that favor any particular tribe or clan. The unnecessary humility, self-denial, and tolerance of Muslims in the Islamic era allowed for the emergence of un-Islamic thought. This was initially reflected in the restriction of the leadership position to the Prophet's tribe. Subsequently, it even extended to the sanctification of a tribe, including this tribe (Hatipoğlu, 1978, p. 87).

Although the Ansar were the first to seriously oppose the theory of Quraysh superiority under the shade of Beni Sa'ida, their reaction was not rooted in Islamic concerns but rather in anxieties stemming from tribal instincts (İbn Hişam, 1978, Vol. 4, p. 226). Although the Ansar were the first to seriously oppose the theory of Quraysh superiority under the shade of Beni Sa'ida, their reaction was not rooted in Islamic concerns but rather in anxieties stemming from tribal instincts (İbn Hanbel, 1981, Vol. 1, p. 56); (Buhârî, 1981, Vol. 8, p. 28). Despite the inadequacy and lack of substance in the justifications put forward by the Quraysh to gain leadership, which were far from Islamic concerns and convincing, it is possible to say that, compared to other pledges of allegiance and political practices throughout Islamic history, this was closer to the Quranic understanding and the Prophet Muhammad's style of politics (Celî, 1986, p. 7). Ultimately, it would have been more appropriate for

the Companions of the Prophet, after his death, to choose a leader for the Muslim state through social consensus, after obtaining the opinions and consent of all segments of the Muslim community on political matters concerning the Muslim society. If only the Companions of the Prophet had been able to transcend tribal and clan values and establish a solid foundation for the political structure, and if only they had been able to construct the political paradigm they envisioned in accordance with the Islamic value system, this would have benefited both Muslims and humanity. Naturally, the political system they established might not have collapsed upon itself so quickly. Following this brief assessment, we now wish to focus on the concept of the Caliphate established by the Companions after the Prophet.

Some books have been published that are indirectly related to our research. These works and articles mainly address topics such as the political reason in Islam, vicegerency of man, Islam and the formation of state power, religion-state relations, Islam and political reform, Islamic political sociology and Islamic political theory and rationalism, Islam and Democracy after the Arab Spring, Religion and State in the Middle East, What is Political Islam?, Sharia policies in the modern world, etc. In this respect, our research is original in every aspect and will serve as a source for future studies.

Jabirî, *Political Reason in Islam* (1997); March, *The caliphate of Man: Popular Sovereignty in modern Islamic thought* (2019); Nasr, The Islamic Leviathan: Islam and the Making of State Power (2001); Roy, Globalized Islam: The Search for A New Ummah (2004); Yavuz, *Nostalgia for the Caliphate: Islamism and İdentity* (2020). Asad, Secular Translations: Nation-State, Modern Self, and Calculative Reason (2018); Ayoob, The Many Faces Of Political Islam: Religion and Politics İn The Muslim World. (2008); Brown, *Islamic Law and Political Authority*, (2020); Esposito et al., Islam and Democracy After The Arab Spring (2016); Fuller*, Islam And Political Reform İn The Middle East* (2021); Brown, *Religion and state in the Middle East*. (2021); Cesari, What Is Political Islam? (2018); Hefner, Sharia Politics: Islamic Law And Society İn The Modern World (2011); Mandaville (2020). *Islam And Politics; Bacık, Islamic Political Theory And Rationalism*. (2024); Şentürk, *Islamic Political Sociology* (2025).

Some articles indirectly related to our research have also been published. The topics addressed in these publications mainly include Islam and secularism, totalitarian movements and political religions, politics and religious society, Islam and democracy in the Middle East, democracy in Islamic political thought, political Islam, Islamic political thought and its application, religion and politics in contemporary societies, political thought in Islam: Development and evolution, Political Islam, Islam and government, Islamic political thought: A contemporary analysis, Reconstructing political Islam: A discursive tradition approach, Reimagining Islamic political structures in contemporary Muslim societies, Islamophobia and political discourse. In this respect, our research is original in every aspect and will serve as a source for future studies.

Tibi, “Islamism and secularism. Totalitarian Movements and Political Religions” (2019); Sariolghalam, “Political Development in the Muslim World” (2020); Ke, “Political Polarization in Religious Societies”; Hashemi, “Sectarianization and Political Islam” (2020); Volpi, “Political Islam: A Critical Review” (2020); Kawtharani, “Political Thought in contemporary Shi’a Islam” (2020); Schwedler, “Islamists in politics: Inclusion and Contestation” (2021); Cavatorta, F. “Islamism and Democracy in the Middle East. Democratization”, (2021); El-Affendi, “Democracy in Islamic Political Thought” (2021); Khan, Political Islam A literature Review” (2022); Turam, “Religion and Politics in Contemporary Societies” (2022); Ilhamni & Rahman, “Islamic Political Thought and Its Implementation” (2022); Faris, “Political Thought in Islam: Development and Evolution” (2023); Ibrahim, “Islam and Governance: A Global Review” (2023); Salihu, “Islamic Political Thought: A Contemporary Analysis” (2024); Jong, “Reconfiguring political Islam: A Discursive Tradition Approach” (2025); Ahmed, & Ali, “Reimagining Islamic Political Structures in Contemporary Muslim Cocieties”, (2025); Mustafa & Noor, Islamophobia and Political Discourse. (2025).

Materials and Methods

This research is a qualitative study that aims to analyze the problem of constructing a political paradigm in Muslim thought. The research primarily uses historical-analytical approaches along with comparative and interpretive methods.

The starting point of this research is the examination of the political structures that emerged after the death of the Prophet Muhammad and the intellectual foundations on which they were based. In this context, events from early Islamic history (especially the Beni Sa'ida meeting and the caliphate process) are first examined within their historical context. Their effects on Muslim political thought are then analyzed. In this respect, the research employs a historical analysis method.

The research utilized classical Islamic history, hadiths, works on Kalam and political thought, and modern academic studies as data sources. The data obtained within this framework were examined using a textual analysis method, without adhering to any ideological preconceptions. Quranic verses and hadiths were interpreted in their contexts, and their potential to serve as a direct normative model for the production of political theory was discussed.

The research also includes a comparative analysis of different approaches, primarily within the Sunni and Shia traditions of political thought. This reveals how religious and political authority are positioned within Islamic political thought and how these authorities have diverged over time.

In conclusion, this research is grounded in historical data and employs a critical, interpretive methodological framework, supported by textual analysis and comparative readings. Through this approach, the possibilities and limitations of the paradigm-building process in Muslim political thought have been evaluated holistically.

1. Concepts Related to the Theory of Caliphate

Generally, three concepts have been used in classical Kalam literature for those who assume the task of governance in the Muslim world. These are the concepts of “Caliph,” "Commander of the Faithful," and “Imam” (Teftâzânî, 1998, Vol. 5, p. 232 et seq.).

Each of these concepts corresponds to a function, operation, or characteristic of governance in traditional Muslim societies. Depending on the stages the institution of the Caliphate underwent. On the emergence of alternative power structures, the term "malik" (sultan) also began to denote the true governing authority (Teftâzânî, 1998, Vol. 5, p. 239). Now, let us explain these concepts related to governance.

1.1. The Concept of Caliph

The root of the word is خَ-لَ-فَ **“ha-le-fe”**. Its infinitive is caliphate. Half is the opposite of kuddam (İsfahânî, 1997, p. 293). In the dictionary, caliphate is defined as "succeeding someone, acting as a representative for someone else, an apprentice, or a second master" (İbn Manzûr, 1990, Vol. 5, p. 540). Taking the place of someone else; It occurs either due to the absence of the successor, or his death, or incapacity, or to honor the successor (İsfahânî, 1997, p. 29). The plural of Caliph is خَلَائِفٌ **“halâif”** or خُلَفَاءٌ **“hulefâ”** (İbn Manzûr, 1990, Vol. 1, p. 883), and it refers to the one who succeeds another in their position (Yazır, 1979, Vol. 1, p. 300). The technical meaning of Caliphate is the succession of the Prophet Muhammad (peace be upon him) to the position of Caliph. It is the general leadership in religious and worldly affairs on behalf of the Prophet (Teftâzânî, 1998, Vol. 5, p. 232); (Hasan, 1964, Vol. 1, p. 428). The word "caliph" is used in the sense of someone who succeeds another, with the plural forms "khalaif" and "khulafa" (al-Baqara, 2:30; al-Araf, 7:69, 74). Furthermore, the word "caliph" appears in Surah Sa'd, differing from its dictionary meaning. Allah says, "O David! We have indeed made you a caliph on earth. So judge justly between people and do

not follow your desires, lest they lead you astray from Allah..." (Sa'd, 38:26). This verse requests that Prophet David (peace be upon him) judge not according to his own whims, but in accordance with the principles revealed to him by Allah Almighty (Yazır, 1979, Vol. 6, p. 4093). In other words, Prophet David was tasked with establishing justice (Seyyid Bey, 1969, p. 9).

1.2. The Concept of Emir

In the pre-Islamic period, Arabs prepared divisions and units for warfare. They gave the title of emir to the commander they appointed to lead the military unit. Emir, in Arabic, is a verb form meaning 'someone who is appointed, assigned, or placed under command.' Its plural is umara (Firuzabadi, 1987, p. 430).

Some Arabs, unable to abandon the customs of the pre-Islamic era, referred to the Prophet Muhammad as "Emir of Mecca" and "Emir of Hijaz." The Companions addressed Sa'd ibn Abi Waqqas (d. 55/675), the commander-in-chief of the Kâdîsiyya army, as "Emir of the Believers" (İbn Haldun, 1990, Vol. 1, p. 578). It is stated that the term "Emir al-Mu'minin" was first used for Umar (d. 23/644) (Suyûtî, 1931, p. 138); The word "emir" (commander/authority) appears in the Quran in one place. In this verse, Allah demands that believers obey Allah, the Prophet, and those in authority among them (Ulu'l-Emr) (Nisa, 4/59); (For the interpretation of Ulu'l-Emr, see Akbulut, 2001, pp. 75–77). The Prophet Muhammad would give the title of "emir" to the commanders he appointed to lead military units for certain military operations in which he did not participate (İbn Hişam, 1978, Vol. 4, p. 226). Abdullah ibn Jahsh, who migrated to Abyssinia, participated in the Battle of Uhud, was martyred, and had his nose cut off (İbn Abdilberr, 1995, p. 14). The Prophet Muhammad appointed him commander of a military expedition sent to Nahle in the seventeenth month of the Hijra (Çakan, 1988, 89), and he was called emir because of his position as commander of such a military unit (İbn Hişam, 1978, Vol. 2, p. 179). He is also recorded in history as the first emir appointed by the Messenger of Allah for a military expedition (al-Jazari, 1995, Vol. 3, p. 89). This concept was not an ambitious title, but it was an influential one, encompassing enough authority to maintain discipline within a military unit and in society. When the Prophet passed away, the Companions, discussing governance in Beni Sa'ida, first conceived and uttered this title. The Ansar suggested to the Muhajirun: "Let there be a leader from among us and a leader from among you" (İbn Hanbel, 1981, p. 1/56). The reason the title "Emir al-Mu'minin" (Commander of the Faithful) was used during the time of Caliph Umar was that it was not overly grandiose or exaggerated. It was also suitable for the social and political understanding of the Arabs who came from tribal life. Therefore, the title "Emir al-Mu'minin" was adopted and embraced (Uludağ, 1998, p. 52). From then on, "Emir al-Mu'minin" was accepted as the title of the caliph, and this title was reserved for caliphs. Even during the Umayyad period, no one other than the caliph could use this title (İbn Haldun, 1990, 1/579). In later periods, the title of emir was given to viziers, governors, commanders, and especially to beys who established autonomous rule in a small region or to those who headed small dynasties (Uludağ, 1998, p. 52).

1.3. The Concept of Imam

The word إِمَامٌ **(Imam)** is sometimes used in place of the word caliph in classical sources. In both Shia and Sunni sources, governance is referred to as imamate, and the ruler as imam (Kâdî, 1988, p. 750). The root of the word Imam is أَمَّ **"emme"**, and its plural is أَئِمَّةٌ **"eimme"**. In the dictionary, it means leader, ruler, person who leads a community of people, and guides them, etc. It means (İsfahânî, 1997, p. 294); (Develioğlu, 1984, p. 516). Imamate, on the other hand, is a general leadership in religious and worldly affairs. After the Prophet Muhammad Maverdî (d. 450/1058), the imamate is also defined as the caliphate to prophethood, stating that the caliph undertakes the duties of protecting religion and managing worldly politics (Maverdî, 1966, p. 5). İbn Haldun (d. 808/1406), on the other hand, defines caliphate, or imamate as it is used in its place, as follows: "It means acting as deputy to the possessor of Sharia in protecting religion and managing worldly politics in accordance with religion" (İbn

Haldun, 1990, Vol. 1, pp. 481–482). The word "Imam" appears in the Quran, in accordance with its dictionary meaning. When Allah said to Prophet Abraham (peace be upon him), "I will make you a leader for mankind," he said, "And make leaders from my descendants, O Lord!" (Baqara, 2:124). Those who pray, "Make us leaders of the righteous" (Furqan, 25:74) are praised in the Quran. The Quran states that Allah granted Isaac and Jacob the authority to lead by His command (Al-Anbiya, 21:72); (Sajdah, 32:24). The Quran also refers to the disbelieving leaders who lead the unbelievers as: "The leaders of the unbelievers (Eimme-i Küfür)" (Tawbah, 9/12). Furthermore, the word "imam" is used in the Quran for the books that God sent to His prophets (Hud, 11/17); (Yasin, 36/12); (Ahkaf, 46/12).

1.4. The Concept of Malik/Mulk

In the dictionary, the word مَلِكٌ melik, derived from the root مُلْكٌ mülk (mulk, melk), meaning to possess and own, to have under one's control and to dispose of alone (İsfahânî, 1997, 774–775), has its plural مُلُوكٌ mulûk. It is found in many Semitic languages. It is seen to have been used as a king's title in some inscriptions before Islam. As a term, melik is a title for rulers, kings, and high-ranking state officials from a royal family, responsible for the administration of a city or region (Topaloğlu, 2004, Vol. 29, pp. 50–51). Following the death of the Prophet Muhammad, during the political restructuring of society, Muslims adopted the title "Malik" (king). Whether during the reigns of the first four caliphs or the Umayyad period, those at the head of state, including the Abbasid rulers, mostly used the titles of caliph, "Amir al-Mu'minin" (Commander of the Faithful), and rarely "Imam." However, the majority of Muslims viewed the Umayyads not as an Islamic government but as a kingdom, due to their reliance on hereditary succession to determine the head of state and their perceived moral depravity (Teftâzânî, 1998, Vol. 5, p. 239). (İrfan Aycan has published a book demonstrating that the caliphate was transformed into a monarchy during the reign of Muawiya.) (Aycan, 2020, pp. 1–254).

It is stated that the Umayyads, even before seizing the caliphate, emulated the kings, dressing and living like them. When Muawiya was the governor of Damascus, and Umar came to Damascus, he disapproved of Muawiya's attire and rebuked him, saying, "O Muawiya! Are you taking the Kisras as your role models?" (İbn Haldun, 1990, Vol. 1, p. 513); cf. (Suyûtî, 1951, p. 195). The concept of "king" (melik/mülk) is also used in the Quran, in accordance with its dictionary meaning. When the concept of "king" is attributed to Allah in the Quran, it expresses Allah's sovereignty, power, and the fact that He holds the ownership and right of disposal over everything in His own hands (Fatiha, 1/3); (Baqara, 2/107); (Al-Imran, 3/189); (Ma'idah, 5/17, 18, 40); (An'am, 6/73); (A'raf, 7/158); (Tawbah, 9/116); (Isra, 17/11); (Hajj, 22/56); (Mu'minun, 23/88); (Nur, 24/42); (Furqan, 25/2). (For other verses regarding God's sovereignty, see Abdulbâkî, 1994, pp. 673–674). When attributed to humans, it includes political sovereignty (İsfahânî, 1997, pp. 774–775); (See Maide, 5/20); (Neml, 27/34); (En'âm, 6/75); (Araf, 7/185). In this sense, the Quran states that the family of Prophet Abraham was given dominion (Nisa, 4/54). It was also given to Prophet Joseph, who descended from him (Yusuf, 12/101), Prophet David (Bakara, 2/251; Sa'd, 38/20), and Prophet... The Quran states that political sovereignty was granted to Solomon (Baqara, 2:102), describing this sovereignty as a blessing. Furthermore, the Quran explains that Satan tempted Adam by speaking of an endless kingdom (Taha, 20/120). Furthermore, the Quran mentions that even tyrants like Nimrod and Pharaoh, who opposed God's prophets and prevented them from fulfilling their duties, were granted dominion (rulership) (Baqara, 2:258); (Zuhruf, 43:51). As can be seen, the Quran speaks of both God's sovereignty and the dominion of the prophets and their enemies. When power and dominion are in the hands of prophets and righteous people, it is a blessing from God (Sa'd, 38:35); when they are in the hands of dictators, tyrants, and oppressors, it becomes an instrument of oppression (Baqara, 2:258; Qasas, 28:4). What is condemned or praised in the Quran is not dominion or sovereignty itself, but rather how the person who possesses it uses it, whether justly or unjustly. Kur'ân melik-kral, hükümdar, peygamberlerin mevcudiyetinden bahsettiği halde (Yûsuf, 12/101); (Bakara, 2/102, 251); (Sa'd, 38/20, 35). The Prophet Muhammad (peace be upon him) never referred to himself as a king or ruler. Nor did he ever

introduce himself as a king or ruler. He always told his companions that he was the servant and messenger of God. He advised them not to elevate him as Christians elevate Jesus (peace be upon him), son of Mary, saying, "Surely I am the servant of God, the servant of God and His messenger." (Buhârî, 1992, Vol. 4, p. 142). As can be understood from the above explanations, the terms "caliph," "imam," "emir," "king," and "king" used in the Quran are not fundamentally religious or Islamic. These terms are more human and political, and their connection to religion is indirect (Uludağ, 1998, p. 51). At the Beni Sa'ida meeting, Abu Bakr was elected caliph, becoming the first person to lead the Muslim state after the death of the Prophet (İbn Hişam, 1978, Vol. 4, p. 225); (İbn Hanbel, 1981, 1/56). Although the caliphate regime was established after the Prophet, Muslims generally regarded the caliphate as a religious office (Akbulut, 2001, p. 77). Abu Bakr was also considered the caliph by the Prophet. They regarded him as a successor to the Prophet (İbn Hanbel, 1981, Vol. 5, p. 404). Some of the Companions even addressed Abu Bakr as "Khalifatullah" (Khalil of Allah), believing him to be Allah's representative. Upon hearing this, Abu Bakr warned, "I am not Allah's Caliph; I am only the Caliph of Allah's Messenger." (İbn Hanbel, 1981, 1/10–11). (İbn Haldun, 1990, 1/482); (İbn Sa'd, 3/183). The understanding that the Caliph was the representative of the Prophet Muhammad, rather than of society, posed many problems. Such a political thought model was also incompatible with the Quran's understanding of politics. For God Almighty did not grant even His prophets the privilege of being a representative (Shu'ara, 26/36); (Qaf, 50/45); (Ghashiyah, 88/21), 22); (Taghabun, 64/12); (Yasin, 36/17); (Ankabut, 29/18); (Nur, 24/54). Because one of the most fundamental characteristics of Islam is the rejection of religious authority. The Quran describes the Prophet Muhammad not as a controller, enforcer, or ruler, but only as a messenger, a warner, a reminder, and someone tasked with explaining the religion. In this regard, God Almighty says to His prophet:

"We have not sent down the Qur'an to cause you distress, but as an admonition to those who fear Allah." (Taha, 20/2, 3).

"Give advice, you are only a giver of advice, not a tyrant over them." (Ghashiyah, 88/21-22).

"If they turn away, then your duty is only to convey the message." (Al-Imran, 3:20). "Your duty is only to convey the message." (Maidah, 5:19, 99).

"If they turn away, we have not sent you as a guardian over them." (Nisa, 4:80); (Enam, 6:104, 107); (Hud, 11:86).

"We have sent you only as a warner and a bringer of good tidings." (Baqara, 2:213; Ma'idah, 5:67, 99; Ahzab, 33:45). "There is no compulsion in religion..." (Baqara, 2:256). "You shall not compel people to believe." (Yunus, 10:99). As seen in the aforementioned verses, the Quran never approves of acting as a representative for either God or the Prophet. This type of representation is neither politically nor legally correct. Legal representation is only permissible in temporary situations. Since the Prophet Muhammad has passed away, there is no legal way to act as his representative. Because representation is only possible for those who are alive, it is also necessary not to equate the Prophet Muhammad with the Muslim state (Akbulut, 2002, p. 76); cf. (Akdoğan, 2000, p. 29). Furthermore, the principle that "there is no monasticism in Islam" is not straightforward; it has many dimensions. Firstly, this means that it is impossible for a special and privileged class, or any group or leader claiming to transform society, to integrate themselves with the will of God, to interpret the literal meanings of religious texts as God's will, and to impose them on people as God's decree. The absence of a sacred class eliminates any political action driven by the desire for rule by a privileged class and their authority to legislate in the name of God (Macit, 2000, p. 118). Since Islam does not accept a priestly class, that is, a class that would share God's power and authority in His name, the sharing of power in the name of religion is out of the question (Ethem, 1997, p. 23).

The absence of religious authority indicates that state authority is not religious in character, and therefore religion does not determine political authority. Thus, governance is a human endeavor. The principles upon which governance is based, that is, the normative structure of governance, also depend on humanity. In short, governance is a human undertaking. For God created man as His vicegerent, entrusting him with the task of developing the earth, ensuring a safe and orderly social life without neglecting anyone's rights, and granting him authority and responsibility, it follows that the source of political choice and power must be human. Otherwise, man's role as vicegerent would lose its meaning (Bardakoğlu, 1989, p. 367).

2. The Qur'an's Approach to the Concept of Representation

Although the Qur'an does not explicitly mention representation for God or the Prophet, Muslims generally accept that after the Prophet's death, the person who succeeds him is considered the Caliph of the Prophet (Khalifatu Rasulillah). As a result of this understanding, the concept that the head of the Islamic state is the Caliph of the Prophet placed the question of "Who will be the Caliph of the Prophet?" at the center of Muslims' political agenda. If Muslims could develop a political philosophy based on the fact that the Caliph is the representative of the Ummah, not the Prophet (Hamidullah, 1995, p. 51), many problems would not arise. Political disagreements could be resolved more easily. However, it is unclear in Muslim political thought whether the caliph assumed a spiritual or religious leadership role or merely a political one. Indeed, the Prophet Muhammad, during his lifetime, held both leadership roles: religious leadership stemming from his prophetic mission and social and political leadership. The fact that the Prophet Muhammad combined religious and political leadership simultaneously and intrinsically in his personality presented a serious problem. The perspectives that began with the discussions on the Caliphate and gradually developed into schools of thought brought with them a fundamental problem regarding the perception and understanding of the Prophet. Two opposing yet unacknowledged modes of perception sought to define the Prophet's political and religious roles. One approach modeled the Prophet's experience without separating the political and religious dimensions; the other distinguished between the Prophet's actions related to prophethood and those related to politics and ijtihad (Evkuran, 2005, p. 164). The first was later explicitly systematized in the Shi'ite understanding of imamate. Shia Islam believed that the religious and divine leadership mission encompassed within the prophetic mission also applied to the imams. They interpreted the continuation of religious leadership through political leadership as a requirement of God's justice and grace (Kummî, 1978, p. 19). Ahl al-Sunnah, however, separated political and religious leadership. According to the Ahl al-Sunnah approach, with the death of the Prophet Muhammad, the prophethood ended both institutionally and functionally. Therefore, a person who became caliph after the Prophet assumed the mission of political leadership, not religious leadership. Indeed, in the Sunni theory of caliphate, the effort to place political power on a plane distinct from religious power is clearly evident. However, the Sunni approach should not be confused with a secular approach. Because what Sunni political scientists were trying to do was not to completely separate religion from politics, but to soften the thesis of the identity of religion and politics. The statement that politics is not a matter of procedure but of ijtihad (legal reasoning) serves this purpose. Indeed, Sunni scholars think that politics is an indispensable tool for achieving the aims of religion (Bağdâdî, n.d., p. 349); (Bakıllânî, 1987, p. 477). The fact that God's command regarding governance dictates that societal affairs be regulated by the collective will (Shura, 42:38), that tasks be entrusted to competent individuals, and that judgment be rendered justly (Nisa, 4:58) demonstrates that political sovereignty belongs to humanity. However, those with the power to choose are expected to appoint competent individuals; those with the power to rule are expected to uphold justice; and those who will make decisions based on their experience are advised to consult the people. To interpret verses that emphasize God's ontological sovereignty in the context of political sovereignty is nothing short of recklessness. These verses have no connection whatsoever with political dominance. One of the three verses where the word "judgment" appears is verse 57 of Surah Al-An'am. This verse states that worship and adoration are by God's decree, and that even the Prophet Muhammad has no say in

matters of urgent request. In verse 40 of Surah Yusuf, it is stated that for worship to be legitimate, God must provide proof of it, and that only God can make a ruling on this matter. Verse 67 of the same surah is as follows: “Their father (Jacob) said, ‘My sons, enter through separate gates, not through one gate. However, I can be of no benefit to you in the sight of God. The judgment belongs only to God; in Him I have trusted, and let those who trust, trust in Him.’”

In this verse, Jacob advises his sons on how to enter the city safely. However, he also emphasizes the necessity of relying on God. As can be seen, these verses are not related to the governance of society, that is, politics, and the state, and they assert that God is the absolute possessor of power (Akbulut, A. 3–4, 1995, pp. 3–4/150–151). To conclude that political sovereignty belongs to Allah simply by considering verses such as, “The sovereignty of the heavens and the earth belongs to Allah alone,” (Al-Shura, 42:49), “Do you not know that the ownership and sovereignty of the heavens and the earth belong only to Allah?” (Baqarah, 2:107), “The sovereignty of the heavens and the earth belongs to Allah…” (Imran, 3:189), “The dominion of the heavens and the earth belongs only to Allah…” (Tawbah, 9:116), etc., as Allah being the Lord of both the heavens and the earth, means overlooking the theocentric rhetoric of these verses. If these verses are read only as theological texts, they lose all their implications. The expressions in these verses are rebukes and threats against stubborn polytheists. They are not sophisticated doctrinal texts. Here, the emphasis is on God's divinity and sovereignty (Güler, 2000, pp. 125, 139, 147). The verses cited as references in Islamic political discourse emphasize the importance of upholding the fundamental principles of power, ensuring justice, and maintaining a balanced, measured approach, free of all forms of malice and prejudice. This includes preventing oppression, rectifying injustice, denying troublemakers opportunities, safeguarding the common good, and upholding truth and righteousness. For example, when we look at the verses before and after the verse, "Those who do not judge by what Allah has revealed are disbelievers" (Ma'idah, 5/44) (Aydın, 1999, p. 162). Most importantly, in other verses, we see that what Allah has revealed clearly refers to the principles of "justice and fairness" (Fığlalı, 1997, p. 25). Therefore, the verse "Whoever does not judge by the judgment of Allah" should be understood as "whoever does not uphold truth, justice, and fairness." Indeed, a study on this subject indicates that the crucial point in the verse is that "judging" is attributed to humans. Judging is not merely acting or applying established rulings, but rather arriving at new rulings and conclusions by starting from the premises of the Holy Quran. In this sense, judging also means establishing the sovereignty of knowledge and the supremacy of law (Îcî, n.d., p. 395). Indeed, Sunni scholars have interpreted the phrase وَمَنْ لَمْ يَحْكُمْ “wa man lam yahkum” as وَمَنْ لَمْ يُصَدِّقْ “wa man lam yusaddık”. That is, according to them, what makes a person an unbeliever, a tyrant, or a transgressor is not failing to apply God's judgments, but rather failing to believe in them. Sunni theologians have valued the state not as a part of faith, but as a matter of public benefit and social organization (Cüveynî, 1950, p. 410). Sunni Islam viewed the state as a contract and considered governance as a secondary matter, a part of transactions. The fundamental principles of transactions are public benefit and human welfare.

The Ahl al-Sunnah, in stating that a state is necessary by hearing (sem'an), based their argument on the following evidence: Appointing a ruler means warding off harm from people, and warding off harm from the self is obligatory (Razi, n.d., p. 240). Furthermore, some Mu'tazilite thinkers have argued that the necessity of a state is not based on hearing (sem'an), but on reason (aql). That is, according to them, reason, not religion, deems the existence of a state necessary. Famous theologians such as Abu al-Hasan al-Basri (d. 110/728), al-Jahiz (d. 255/865), al-Ka'bi (d. 319/931), and al-Hayyat (d. 300/913) adopted this latter view.

Sunni and Mu'tazilite scholars who ruled that the appointment of a ruler is (Îcî, n.d., p. 395) also stated that this obligation is on society, not on God, contrary to the Shia view (Teftâzânî, 1998, Vol. 5, pp. 235–236). To reject this authority as divine and to base it on human nature is unacceptable. The method of appointing a ruler is a free choice that will emerge through ijtihad (independent reasoning). This is because there is no explicit text from the Prophet Muhammad regarding the

appointment of a ruler. The prerequisite for being a ruler is knowledge, justice, and political acumen (Bağdâdî, n.d., p. 349). The Sunni school of Kalam has at least given us this: The issue of legal power is not a matter of faith, but an intellectual one, and therefore a subject open to rational discussion and change. The state is a reality, a social and human necessity. However, it is not a religious necessity. Indeed, the Companions viewed the caliphate not as a matter of faith, but as a political matter. When Abu Bakr asked the Companions to exempt him from the caliphate, Ali responded to Abu Bakr: "The Prophet has been pleased with you for the sake of our religion; should we not be pleased with you for the sake of our worldly affairs (caliphate)?" (Îcî, n.d., p. 407). When Ali said "our religion," he meant the Prophet's appointment of Abu Bakr as imam for prayer (Pezdevî, 1988, p. 261).

The absence of any text prohibiting Muslims from any form of government, and the fact that the first four caliphs were appointed to the caliphate through different methods and procedures, is the clearest evidence that this matter was left to reason and ijtihad (independent reasoning). (For the methods by which the caliphs came to power, see Teftâzânî, 1998, 5/233); (Ebû Zehrâ, 1983, p. 101–103). Although Muslims did not initially consider the issue of imamate as a matter of faith, it has since been incorporated into the realm of belief. The historical event that led to the inclusion of the imamate issue in Kalam (Islamic theology) books is the Shia sect's view of the election of the head of state as a fundamental issue of faith. Sunni theologians also included this issue in their Kalam books to refute the Shia theory of imamate. (For the methods of caliphs' ascension to the caliphate, see Teftâzânî, 1998, 5/233 ff.). The inclusion of the concept of imamate in theological texts paved the way for the equivalence of religion and politics within traditional Muslim culture. Consequently, Muslims have become prisoners of their own actions, laws, or institutions in matters of politics (Fazlurrahman, 1997, p. 103). The political solution found by the Companions after the death of the Prophet Muhammad eventually led to deadlock, chaos, and instability. In fact, Muslims even shed each other's blood over this issue of imamate.

Jabirî explains the constitutional loopholes that caused the caliphate regime established by the Companions to fall into instability, stagnation, failure to institutionalize, and its transformation into a monarchy as follows:

1. The absence of a single legal method for appointing the Caliph,
2. The lack of a limit on the Caliph's term of office,
3. The lack of limitations on the Caliph's authority and powers. (Jabirî, 2001, pp. 85–87); cf. (Hamidullah, 1995, pp. 167–168). Although there were constitutional loopholes as pointed out by Jabirî, when Abu Bakr became caliph, he said, "I have been appointed to lead you, but I am no better than you in any way. If I do good deeds, support me; if I do bad deeds, correct me!" (İbn Hişam, 1978, Vol. 4, p. 228). Umar also said similar things in his sermons (Suyûtî, 1951, pp. 139–146); (Ashmawy, 1993, p. 89). Both Abu Bakr and Umar individually drew upon religious texts to the very end. However, they never dogmatically based their political decisions on God or the Quran. Abu Bakr decided to compile the Quran (make it a book) for the sake of expediency, even without any verse or hadith supporting it. Similarly, when he decided to wage war against those who apostatized during the "ridda" events, he felt no need to base his decision on any verse or hadith (Suyûtî, 1951, pp. 72–77). When Caliph Umar decided against distributing the land of Sawad to the veterans who participated in the war and abolished the share given to those whose hearts were inclined towards Islam, he was aware that this contradicted the verses on the subject (İbn Kesir, 1983, Vol. 2, p. 365). However, Caliph Umar understood the circumstances, context, and purpose for which these verses were revealed. He did not understand them in the same way as the conservative Companions (Güler, 2002, 69). Caliph Ali also avoided citing Quranic evidence to convince the Kharijites (Ebû Zehrâ, 1983, p. 80), thus not using the Holy Quran to advance his political ambitions. Despite some shortcomings, the era of the first four caliphs symbolizes adherence to the law in classical Muslim culture. Consequently, Islam does not offer a system or theory of governance as an institutional

structure. With the development of the Islamic call, initially, and after the death of the Prophet, a system of governance based on the example of the "commander of war" was established. This was a situation necessitated by the needs of the time and the circumstances (Jabirî, 2001, p. 88); cf. (Hamidullah, 1995, pp. 167–168). Initially sufficient, this political structure later gave way to conflict when a peaceful, legal solution could not be found, thereby transforming the caliphate into a monarchy. The political rebellions that began during the caliphate of Uthman continued for centuries after his assassination. In a society that had previously agreed, harmoniously cohesive, and even fraternally, conflicts and confrontations arose, swords were drawn, and a new era of division and fragmentation, filled with hatred and ambition, began. This process of separation and fragmentation accelerated further with Ali's ascension to the caliphate, and political rivalries escalated into civil wars. Taking advantage of this political division and separation, Muawiya, seeking to realize his political ambitions, used the idea of Uthman's injustice, innocence, and the wasting of his blood as a shield and seized the caliphate through various political games, deceptions, and staged events (For more information, see Akbulut, 2001, 164 et seq.). After Muawiya seized the caliphate, the Islamic state, which expanded rapidly through conquests, entered a new phase. During this period, state administration became increasingly secularized, and the caliph's absolute authority began to strengthen. Apart from these characteristics, it is observed that, with a few exceptions, those who came to the caliphate did not place much value on Islamic precepts (Suyûtî, 1951, pp. 194-254); (Mumcu, 1963, p. 12). Therefore, debates and disagreements regarding the political paradigm continue to occupy the agenda of the Muslim world.

Analysis

In this research, the problem of political paradigm in Muslim thought has been systematically addressed in three main areas: (1) normative-theoretical framework, (2) historical-practical applications, and (3) comparative evaluation in the context of sectarian approaches.

1. Normative-Theoretical Framework

First, the normative foundations of the political sphere were examined within the framework of the Quran and the practices of the Prophet Muhammad. The findings show that the Quran does not propose a specific political model or institutional structure; instead, it sets forth general principles such as justice, consultation, competence, and public interest. These principles focus not on the form of the political structure, but on its functioning and moral quality. Therefore, the determination of the political order is left to human responsibility, rather than being a field directly determined by revelation.

In this context, an analysis of the Prophet Muhammad's practices during the Medina period reveals that the political order was neither independent of revelation nor a fixed model directly determined by it. On the contrary, these practices have a pragmatic and interpretive character, adapting to the existing socio-political conditions.

2. Historical-Practical Process Analysis

In the second stage, the political structures that emerged in the post-Prophet Muhammad period were examined from a historical perspective. In particular, the Beni Saide meeting and the process of determining the first caliph demonstrate that political decisions were shaped by social and tribal dynamics rather than by religious references.

The emergence of the caliphate, initially seen as a pragmatic solution, eventually faced institutionalization problems and evolved into different forms of governance. Indeed, the transformation of the caliphate into a monarchy led to significant ruptures in the legitimacy of

political authority. This situation reveals that the political paradigm is not historically fixed but rather variable, often shaped by power relations.

3. Comparative Analysis of Sectarian Approaches

In the third stage, the Sunni and Shia paradigms, two fundamental approaches prominent in Islamic political thought, were evaluated comparatively. Shia thought, by viewing political leadership as a divine appointment and religious necessity, grounded the doctrine of imamate on a theological basis. In contrast, the Sunni approach evaluated political authority more within the framework of social consensus, ijtihad (independent reasoning), and public interest.

The fundamental difference between these two approaches lies in the source of political authority: divine legitimacy is paramount in the Shia tradition. In contrast, human legitimacy is more decisive in the Sunni tradition. This clearly demonstrates that there is no single, homogeneous paradigm in Islamic political thought.

4. Conceptual Transformation and the Problem of Legitimacy

In the final stage of the research, the transformation of the concepts of caliphate, imamate, emirate, and kingdom throughout history was examined. These concepts initially carried more functional and human meanings; over time, they acquired a religious content. This transformation led to serious problems, including the sacralization of political authority and its immunity from criticism.

In this context, the absolutization of political structures through religious references does not fully align with either historical reality or the principles outlined in the Quran. On the contrary, this situation hinders the establishment of a healthy relationship between religion and politics.

Conclusion

In this study, the problem of constructing a political paradigm in Muslim thought was analyzed in light of historical processes, conceptual frameworks, and theoretical approaches. The findings clearly show that Islam does not propose a fixed, institutional political model; instead, it offers normative principles such as justice, consultation, competence, and public interest. This indicates that the political structure is shaped not by a divine form but by human experience and social will.

A historical comparison reveals significant differences between the era of the Prophet Muhammad and the subsequent caliphate practices. The Prophet's practices in Medina reflected a flexible, pragmatic political order that emerged in response to specific circumstances, within the framework of the general principles established by revelation. In contrast, in the post-Prophet era, particularly during the formation of the caliphate, political choices were often shaped by tribal, sociological, and power dynamics. This confirms that the political structure was a historical construct, not a religious necessity.

The comparison between Sunni and Shia political thought traditions further deepens this problem. While the Shia approach grounds political authority in a religious and divine foundation, viewing imamate as a theological necessity, the Sunni tradition considers governance more as a human and social issue open to ijtihad (independent reasoning). The difference between these two approaches demonstrates that the relationship between religion and politics in Islamic political thought cannot be explained through a single, uniform model. However, the fact that many of the caliphates, sultanates, and other forms of government that emerged throughout history were often justified by religious legitimacy has resulted in the sacralization of the political sphere. This situation has led to the instrumentalization of religion by political authority and the weakening of critical thinking. In contrast, from a Quranic perspective, the essential principle is not the absolutization of political authority, but rather its limitation by the principles of justice, fairness, and accountability.

Compared to the modern era, Muslim societies still face similar problems in generating political paradigms. The idealization of traditional models and the inability to critically synthesize them with modern political systems lead to an intellectual impasse. Therefore, the fundamental issue for contemporary Muslim thought is not to absolutize the historical legacy, but to develop a new political paradigm that is pluralistic, critical, and human-centered, based on the universal principles of the Quran. In conclusion, it can be said that in Islam, the political order is not a fixed, divinely determined model, but rather a dynamic realm left to human responsibility. Within this framework, the criteria for a legitimate political structure are: establishing justice, protecting individual freedoms, reflecting the collective will, and being open to critical scrutiny. No political model that fails to fulfill these principles, even if based on religious references, can be said to align with the value system envisioned by Islam fully.

References

Abdulbakî, M. F. (1994). *Mu'cemu'l-müfehres li elfâzi'l-kur'âni'l-kerîm*. Çağrı Publications.

Ahmed, S. S., Khan, R., & Ali, M. (2025). Reimagining Islamic political structures in contemporary Muslim societies. *Al-Istinbath Journal, 10*(1), 45–62.

Akbulut, A. (1995). The issue of sovereignty from the perspective of the holy Quran. *Journal of Islamic Studies, 8*(3–4).

Akbulut, A. (2001). *The struggle for power in the Sahaba period*. Pozitif Publications.

Akdoğan, Y. (2000). *Turkey and change: Secularism and the change in Turkey in the 2000s*.

Asad, T. (2018). *Secular translations: Nation-state, modern self, and calculative reason*. Columbia University Press.

Ashmawy, M. S. (1993). *Islamism against Islam*. Trans. Sibel Özbudun, Istanbul.

Aycan, İ. (2020). *Mu'âviye b*. Ebî Sufyân on the Road to the Sultanate. OTTO Publications.

Aydın, M. S. (1999). *A critical look inside*. ed. Mehmet Gündem, İstanbul.

Ayoob, M. (2008). *The many faces of political Islam: Religion and politics in the Muslim world*. University of Michigan Press.

Bacık, G. (2024). *Islamic political theory and rationalism*. Palgrave Macmillan.

Bağdâdî, A. (n.d.). *El-fark beyne'l-firâk*.

Bakıllânî, E. M. (1987). *Temhidu al-evâai'l ve telhisu al-delâil*. ed. İmâduddîn Ahmed Haydar, Beirut.

Bardakoğlu, A. (1989). *Theocratic perspective on Islam and democracy: Legislative Islam and democracy*.

Belâzurî, A. (1959). *Ansâbu'l-eşrâf*.

Brown, J. A. C. (2020). *Islamic law and political authority*. Oxford University Press.

Brown, N. J. (2021). *Religion and state in the Middle East*. Carnegie Endowment Reports.

Buhârî, M. (1981). *Al-câmi as-sahîh*. Çağrı Publications.

Buhârî, M. (1992). *Al-câmi as-sahîh*. (2nd ed.). Publications.

Çakan, İ. L. (1988). Abdullah b. Cahş. Turkish Religious Affairs Foundation Encyclopedia of Islam. 1/89. Turkish Religious Affairs Foundation Publications.

Cavatorta, F. (2021). Islamism and democracy in the Middle East. *Democratization, 28*(4), 678–695. https://doi.org/10.1080/13510347.2020.1865319

Celî, A. M. (1986). *Dirasatu an a'l-firak fi tarihi al-muslimin el-khawarij wa'sh-Shia*.

Cesari, J. (2018). *What is political Islam? lynne rienner publishers*.

Cürcânî, S. Ş. (1893). *Şerhu'l-mevâkıf*.

Cüveynî, A. (1950). *Kitab al-irşâd*.

Develioğlu, F. (1984). *Osmanlıca türkçe ansiklopedik lügat*.

Dineverî, M. (1909). *Al-imâme ve as-siyâse*.

Ebû Zehrâ, M. (1983). *History of political and doctrinal sects in Islam*. Trans. Hasan Karakaya & Kerim Aytekin, Hisar Publishing House.

El-Affendi, A. (2021). Democracy in Islamic political thought. *Journal of Democracy, 32*(3), 90–104.
Eşarî, A. (1954). *Makalatu al-islâmiyyin ve ihtilâfu al-musallin, kahire*.
Eşarî, A. (1994). *El ibâne an usûl al-diyane*.
Esposito, J. L., Sonn, T., & Voll, J. O. (2016). *Islam and democracy after the Arab spring*. Oxford University Press.
Eş'arî, A. (2019). *Makalatu al-islamiyyin*. Trans. Ömer Aydın & Mehmet Dalkılıç, Publications of the Ministry of Culture and Tourism.
Evkuran, M. (2005). *Understanding the Sunni paradigm*. Ankara Okulu Publications.
Faris, S. (2023). Political thought in Islam: Development and evolution. *Maqolat Journal, 5*(2), 120–138.
Fazlurrahman. (1997). *The messenger of God and his message*. Trans. Adil Çiftçi, Ankara.
Fığlalı, E. R. (Mart-Nisan, 1997), Whose Sovereignty Is It?, Türkiye Diary, 23.
Firuzabadi, Mecduddin Muhammed b. Ya'kub. (1987). *Al-kâmûsu al-muhit, muessesetu ar-risâle*.
Fuller, G. E. (2021). *Islam and political reform in the Middle East*. Routledge.
Gazzali, E. H. (n.d.). *Al iktisad fi al-i'tikâd*.
Gölçük, Ş. (1994). *Islamic beliefs*.
Güler, İ. (2000). The problem of God's morality.
Güler, İ. (2002). *Essays on political theology*. Kitâbiyât.
Hamidullah, M. (1995). *Islamic constitutional law*. Edited by Vecdi Akyüz, Istanbul.
Hashemi, N. (2020). Sectarianization and political Islam. In J. Esposito (Ed.), The Oxford Handbook of Islam and Politics (pp. 210–230). Oxford University Press.
Hatipoğlu, M. S. (1978). The first political nationalism in Islam. *Ankara University Faculty of Theology Journal, 23*(3–4), 1–93.
Hefner, R. W. (Ed.). (2011). *Shari'a politics: Islamic law and society in the modern world*. Indiana University Press.
Hizmetli, S. (1983). Jahiz's understanding of imamate. *Ankara University Faculty of Theology Journal, 26*(1–4) 681-716.
Ibrahim, A. (2023). Islam and governance: A global review. *Third World Quarterly, 44*(6), 987–1005. https://doi.org/10.1080/01436597.2022.2101234
Îcî, A. (n.d.). *El-mevâkıf fi ilmi al-kalam*.
Ilhamni, I., & Rahman, A. (2022). Islamic political thought and its implementation. *Islamadina Journal, 23*(1), 55–70.
İbn Abdilberr, Ebu Ömer Yûsuf b. Abdillah b. Muhammed. (1995). *Al-istîab fî ma'rifet al-ashâb*. Daru al-Kutub al-İlmiyye.
İbn Abdirabbih, A. (1948). *Kitabu'l ikdi al-ferid*. Commentary and Correction: Ahmet Emin, Kahire.
İbn Haldun, A. (1990). *Mukaddime*. Trans. Z. Kadiri Ugan, İstanbul.
İbn Hanbel, A. (1981). *Al-musnad*. Çağrı Yayınları.
İbn Hişam, A. (1978). *Al-sîre al-nabaviye*.
İbn Kesir, İ. (1983). *Tefsîru al-kur'ân al-azim*.
İbn Manzûr, C. (1990). *Lisan al-Arab*. Daru as-Sadır.
İbn Sa'd, M. (1957). *Al-tabakatu al-kubrâ*.
İbnu Esir al-Cezerî, Ebu al-Hasen Ali b. Muhammed. (1995). *Usdu al-ğâbe fî ma'rifeti as-sahabe*. Dâru'l-Fikr.
İmâm Ebû Yûsuf. (1982). *Kitabu al-harâc*. Trans. Muhammed Ataullah Efendi, Simplifying: İsmail Kara, Ankara.
İsfahânî, R. (1997). *Müfredatü alfâz al-kur'ân, verification: Saffan adnan davudi, ed-dâru'ş-şâmiyye*.
Jabirî, M. A. (1997). *Political reason in Islam*. Trans. Vecdi Akyüz, İstanbul.
Jabirî, M. A. (2001). *Restructuring in contemporary Arab Islamic thought*. Trans. Ali İhsan Pala & M. Şirin Çıkar, Ankara.

Jong, A. (2025). Reconfiguring political Islam: A discursive tradition approach. *American Journal of Islam and Society, 42*(1), 1–25.
Kawtharani, F. W. (2020). *Political thought in contemporary shi'a Islam*. Springer.
Ke, L. (2025). Political polarization in religious societies. [preprint]. arXiv. https://arxiv.org/abs/2502.56789
Khan, M. (2022). Political Islam: A literature review. *Journal of Muslim Minority Affairs, 42*(2), 300–315.
Kummî, M. (1978). *Risâletu'l-itikâdâti'l-imâmiyye* (Shia Imami Beliefs). çev. Ethem Ruhi Fığlalı. Ankara University Faculty of Theology Publications.
Kâdî, A. (1988). *Şerhu usûli'l-hamse* (A. Osman, Tahkik). Kahire.
Macit, N. (2000). *The theological interpretation of the relationship between religion and politics*.
Mandaville, P. (2020). *Islam and politics* (3rd ed.). Routledge.
March, A. F. (2019). *The caliphate of man: Popular sovereignty in modern Islamic thought*. Harvard University Press.
Maverdî, M. (1966). *Ahkamu as-sultaniyye*.
Mumcu, A. (1963). *Political assassination in the Ottoman empire*.
Mustafa, İ., others. (1989). *Mucemu al-vasıt*. Çağrı Publications.
Mustafa, R. U., Ahmad, T., & Noor, S. (2025). Islamophobia and political discourse. [Preprint]. arXiv. https://arxiv.org/abs/2503.45678
Muzaffer, M. R. (1978). *Akaidu al-imamiye* (Shia Beliefs). Trans. Abdülbaki Gölpınarlı, İstanbul.
Nasr, S. V. R. (2001). *The Islamic leviathan: Islam and the making of state power*. Oxford University Press.
Pezdevî, M. (1988). *Sunni creed*. Trans. Şerafeddin Gölcük, İstanbul.
Razi, F. (n.d.). *Muhassalu efkâr-mütekaddimin ve al-müteahhirin min al-hukema ve al-mutekellimin*.
Roy, O. (2004). *Globalized Islam: The search for a new ummah*. Columbia University Press.
Salihu, J. T. (2024). Islamic political thought: A contemporary analysis. *Journal of Islamic Studies, 35*(2), 200–218.
Sariolghalam, M. (2020). Political development in the Muslim world. *International Politics, 57*(4), 567–584.
Schwedler, J. (2021). Islamists in politics: Inclusion and contestation. *Comparative Politics, 53*(4), 789–807.
Şentürk, R. (2025). *Islamic political sociology*. Oxford University Press.
Seyyid Bey. (1969). *The legal nature of the caliphate*. Ed. Suphi Menteş, Istanbul.
Suyûtî, A. (1951). *Tarih al-hulefa*.
Taberî, M. (1907). *Tarihu al-umem ve al-muluk*. Eser Neşriyat.
Teftâzânî, S. (1998). *Şerhu al-makasid*. Alemu'l-Kutub.
Tibi, B. (2019). Islamism and secularism. *Totalitarian Movements and Political Religions, 20*(1), 1–15.
Topaloğlu, B. (2004). Melik. Turkish Religious Affairs Foundation Encyclopedia of Islam. Turkish Religious Affairs Foundation Publications. 29/50-51, Türkiye Diyanet Vakfı Yayınları.
Turam, B. (2022). Religion and politics in contemporary societies. *Annual Review of Sociology, 48*, 245–263.
Tâhâ, H. (1947). *Al-fitnetu al-kubra*.
Uludağ, S. (1998). *Islamic political relations*.
Ünal, A. B. (1997). *The concept and manifestations of sovereignty in early Islamic thought* (Unpublished Doctoral Thesis), Dokuz Eylül University, Institute of Social Sciences, İzmir.
Volpi, F. (2020). Political Islam: A critical review. *Political Studies Review, 18*(3), 403–418.
Wellhause, J. (1963). *The Arab state and its fall*. Trans. Fikret Işıltan, Ankara.
Yavuz, M. H. (2020). *Nostalgia for the caliphate: Islamism and identity*. Oxford University Press
Yazır, M. H. (1979). *The true religion: The language of the Quran*. Eser Publications.
Yesûî, Luvîs Ma'lûf. (1986). *Al-müncid fi al-luġa ve al-a'lâm, beyrut*.

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Evidentility in Azerbaijani and Other Turkic Languages: A Comparative Typological Study

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Abstract. *This article examines the comparative and typological characteristics of the category of evidentiality in Azerbaijani and other Turkic languages. The primary objective of the study is to identify the similarities and differences in the grammatical and semantic means used to express the source of information in Turkic languages, as well as to clarify the place of the evidentiality category within the functional-semantic system of these languages. Evidentiality is analyzed as an important semantic and grammatical category that indicates how a speaker has acquired the information being conveyed, whether through direct observation of an event, hearsay, inference, or assumption. The article discusses the theoretical foundations of evidentiality, its relationship with modality, and the various means by which it is expressed across languages. The research employs comparative-typological, descriptive, and analytical methods. In addition to Azerbaijani, evidential markers in Turkish, Kazakh, Kyrgyz, and Uzbek were examined, and their morphological structures and functional-semantic characteristics were compared. The findings reveal that although evidentiality in Turkic languages shares common historical and linguistic foundations, its means of expression have developed distinct structural and semantic features in different languages. In particular, indirect evidentiality occupies an important place in the vast majority of Turkic languages and is realized through various morphological devices. The study further demonstrates that evidentiality functions not only as a marker of grammatical temporal relations but also as a functional system reflecting the speaker's attitude toward information, the source of knowledge, and their communicative stance.*

Keywords: *evidentiality, evidential category, Turkic languages, Azerbaijani language, indirect evidentiality, typological comparison, morphological markers, semantic features*

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Azərbaycan və digər türk dillərində evidentiallıq (şahidlik): müqayisəli tipoloji tədqiqat

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Xülasə. *Məqalədə Azərbaycan dili və digər türk dillərində evidentiallıq (şahidlik) kateqoriyasının müqayisəli-tipoloji xüsusiyyətləri araşdırılmışdır. Tədqiqatın əsas məqsədi türk dillərində informasiyanın əldə olunma mənbəyini ifadə edən qrammatik və semantik vasitələrin oxşar və fərqli xüsusiyyətlərini müəyyənləşdirmək, həmçinin şahidlik kateqoriyasının türk dillərinin funksional-semantik sistemində tutduğu yeri aydınlaşdırmaqdan ibarət olmuşdur. Evidentiallıq danışanın təqdim*

etdiyi məlumatı hansı üsulla əldə etdiyini – hadisənin birbaşa müşahidəsi, eşitmə yolu ilə qəbul olunması, nəticə çıxarma və ya ehtimala əsaslanmasını ifadə edən mühüm semantik-qrammatik kateqoriya kimi təhlil edilmişdir. Məqalədə evidentiallığın nəzəri əsasları, onun modallıqla qarşılıqlı əlaqəsi və müxtəlif dillərdə ifadə vasitələri nəzərdən keçirilmişdir. Tədqiqat zamanı müqayisəli-tipoloji, təsviri və təhlil metodlarından istifadə olunmuşdur. Azərbaycan dili ilə yanaşı Türkiyə türkcəsi, qazax, qırğız və özbək dillərində şahidlik göstəriciləri araşdırılmış, onların morfoloji quruluşu və funksional-semantik xüsusiyyətləri müqayisə edilmişdir. Araşdırma nəticəsində müəyyən olunmuşdur ki, türk dillərində evidentiallıq ümumi tarixi-linqvistik əsaslara malik olsa da, onun ifadə vasitələri müxtəlif dillərdə fərqli struktur və semantik xüsusiyyətlər qazanmışdır. Xüsusilə dolayı şahidliyin ifadəsi türk dillərinin böyük əksəriyyətində mühüm yer tutur və müxtəlif morfoloji vasitələrlə reallaşır. Müəyyən edilmişdir ki, evidentiallıq yalnız qrammatik zaman münasibətlərini deyil, həm də danışanın informasiyaya münasibətini, bilik mənbəyini və kommunikativ mövqeyini əks etdirən funksional sistem kimi çıxış edir.

Açar sözlər: *evidentiallıq, şahidlik kateqoriyası, türk dilləri, Azərbaycan dili, dolayı şahidlik, tipoloji müqayisə, morfoloji göstəricilər, semantik xüsusiyyətlər*

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Introduction

In modern linguistics, one of the essential components of the communication process is the speaker's attitude toward the information being conveyed and the expression of the source from which that information has been obtained. Information transmitted through language reflects not only the content of an event but also the manner in which the speaker has acquired that information. This feature is referred to in linguistics as evidentiality. Evidentiality is a semantic-grammatical system that indicates whether the speaker has obtained information through direct observation, hearsay, inference, or indirect perception (Aikhenvald, 2004, pp. 3–8).

The expression of information source within a language system is of particular importance for understanding the relationship between human cognition and linguistic activity. In recent decades, the development of functional linguistics, cognitive linguistics, and typological studies has contributed to increasing scholarly interest in evidentiality. This category displays diverse structural characteristics across languages. While in some languages evidentiality has developed into an independent grammatical category, in others it is expressed through modal words, verbal affixes, and syntactic devices (Dixon, 2005, pp. 188–191). The category of evidentiality is defined in linguistics as an important semantic and grammatical phenomenon that expresses both the source of the information presented by the speaker and the means through which that information has been acquired. This category reflects whether the speaker has directly witnessed an event, obtained the information through hearsay, or arrived at it through logical inference. In contemporary linguistic studies, evidentiality is regarded not merely as a semantic nuance but also as a functional component of the grammatical system (Lyons, 1977, pp. 793–797).

Turkic languages constitute one of the language families in which evidentiality is widely observed. In these languages, the source of information is primarily expressed through tense and mood markers of the verb. In particular, the distinction between direct and indirect evidentiality occupies an important place in the morphological system of Turkic languages. In many Turkic languages, certain past tense forms indicate that the speaker directly witnessed the event, whereas other forms signal

that the information was acquired indirectly. These features can be observed both in ancient Turkic written monuments and in contemporary Turkic languages (Korkmaz, 2003, pp. 567–572).

As a member of the Turkic language family, Azerbaijani also reflects evidentiality features. Although this category has not developed into a fully independent grammatical system in Azerbaijani, verbal suffixes, modal units, and various syntactic devices serve to express the source of information. In particular, the suffix -mış/-miş is widely used to convey meanings of indirect evidentiality, hearsay, and inference. Compared with other Turkic languages, the frequency of use and the semantic characteristics of evidential markers in Azerbaijani exhibit certain distinctive features. Researchers note that indirect past tense forms in Azerbaijani not only indicate the occurrence of an event but can also express the speaker's attitude toward the information and the degree of its reliability (Hacıyev, 2012, pp. 183–187). As Kazımov (2010, p. 247) points out, "the suffix -mış in Azerbaijani not only forms the meaning of past tense but also conveys nuances of indirect information and inference."

Scientific novelty of the research and its place in the existing

Although the category of evidentiality has been extensively studied in world linguistics, particularly within the fields of linguistic typology and functional grammar, studies devoted to a systematic comparative-typological analysis of the evidential systems of Azerbaijani and other Turkic languages remain relatively limited. Most existing research has either examined evidentiality on the basis of data from a single language or provided only a brief characterization of the phenomenon within the framework of the general Turkic language system.

The scientific novelty of the present study lies in its investigation of evidential markers in Azerbaijani, Turkish, Kazakh, Kyrgyz, and Uzbek within a unified comparative-typological framework and in the comparison of their morphological and functional-semantic characteristics. The study demonstrates that evidential markers function not only as grammatical tense forms but also as functional-semantic devices expressing the speaker's attitude toward information, the source of knowledge, and their communicative stance.

Another contribution of the study is the comparative classification of the means used to express indirect evidentiality in Turkic languages and the identification of their semantic functions. The findings reveal that evidential forms sharing common historical roots have undergone different paths of semantic development across Turkic languages. In some languages, these forms have additionally come to express nuances of inferentiality, probability, surprise, and evaluation (Abbasova, 2025).

The article contributes to the existing body of research on the comparative study of evidentiality in Turkic languages and facilitates a more precise understanding of the place of this category within the functional-semantic structure of the Turkic language family.

Materials and Methods

Evidentiality is regarded as one of the most significant categories in contemporary linguistics, particularly within approaches that investigate the communicative and cognitive functions of language. This category is closely associated with the processes through which individuals perceive the external world, process acquired knowledge, and convey it through language. When providing information about an event, a speaker does not merely communicate the fact itself but also indicates the source from which that information has been obtained. This feature plays a crucial role in determining the degree of reliability attributed to information in the course of communication. Therefore, evidentiality is considered not only a grammatical phenomenon but also a complex system closely related to the pragmatic and cognitive dimensions of language.

Contemporary typological studies demonstrate that evidentiality manifests itself in different forms across the world's language families. In some languages, evidentiality has developed into an

independent grammatical category expressed through specific morphological markers. For example, in certain indigenous languages of South and North America, there are distinct grammatical forms indicating whether the speaker acquired information through direct observation, hearing, inference, or hearsay. In other languages, evidentiality is not realized as a separate category but is expressed through its interaction with tense, aspect, modality, and lexical means. Turkic languages belong to the latter group, where evidentiality is primarily manifested within the verbal system (Aikhenvald, 2004, pp. 28–34).

Linguistic literature offers various classifications of evidentiality. According to the most widely accepted classification, evidentiality is divided into two principal categories: direct and indirect evidentiality. Direct evidentiality is based on the speaker's personal observation of an event. In such cases, the speaker acts as a direct witness, and the primary source of information is visual or sensory perception. Indirect evidentiality, by contrast, encompasses situations in which the event has not been directly observed. In these cases, information is obtained through hearsay, derived from inference, or based on assumption. Indirect evidentiality is further subdivided into reportative evidentiality (information acquired through hearsay), inferential evidentiality (information derived through reasoning and inference), and assumptive evidentiality (information based on probability or assumption) (Palmer, 2001, pp. 35–42).

The study of evidentiality is also of considerable importance for investigating the relationship between language and thought. Within cognitive linguistics, it is generally assumed that a close connection exists between the process of acquiring knowledge and its linguistic encoding. Evidential markers reflect how speakers perceive information and how that information is represented and structured in their consciousness. For this reason, evidentiality is regarded as one of the key means for examining the relationship between cognitive processes and linguistic structures (Langacker, 2008, pp. 56–61).

From the perspective of functional linguistics, evidentiality also serves as a communicative strategy. By employing different evidential devices, speakers determine the degree of responsibility they assume for the information they convey. For instance, forms indicating direct observation tend to increase the perceived reliability of information, whereas forms based on hearsay or assumption may reduce the degree of certainty associated with the reported information (Zeynalova, 2025). In this respect, evidentiality functions as an important communicative mechanism that regulates the perceived reliability of information among participants in discourse.

The historical development of evidentiality in Turkic languages demonstrates that this category emerged primarily through the semantic extension of past tense forms. A number of scholars have noted that certain verbal forms originally used to express temporal relations gradually acquired additional functions related to the source of information and the speaker’s attitude toward the reported event. This development is particularly evident in the evolution of forms containing the suffix -mış/-miş. In contemporary Turkic languages, these forms function not only as markers of past tense but also as devices for expressing indirect information, inference, and reportative meanings (Johanson, 2003, pp. 276–280).

The relationship between evidentiality and epistemic modality is another important topic of discussion in contemporary linguistics. Since these categories are often expressed through the same linguistic means, it is sometimes difficult to establish clear boundaries between them. Nevertheless, evidentiality primarily concerns the source of information, whereas epistemic modality is concerned with the degree of certainty, validity, or reliability attributed to that information. For example, the sentence *“Deyəsən yağış yağıb”* (“It seems that it has rained”) conveys both an inferential meaning and a sense of probability. Consequently, evidential and modal meanings may interact in certain contexts, forming a unified functional-semantic complex (Aikhenvald, 2004, pp. 6–9).

Thus, in contemporary linguistics, evidentiality is regarded not merely as a grammatical phenomenon indicating the source of information but also as a multifaceted functional-semantic category that reflects the speaker's cognitive activity, communicative intentions, and attitude toward the information conveyed. These characteristics make evidentiality an important object of comparative and typological investigation across different languages, including the Turkic languages.

Conclusion

The comparative-typological analysis conducted in this study demonstrates that the evidentiality systems of Azerbaijani and other Turkic languages are grounded in common historical and linguistic foundations. The fact that Turkic languages belong to the same language family in terms of origin and development has led to the emergence of a number of shared grammatical features. One of these features is the category of evidentiality, which expresses the speaker's attitude toward the source of information. Although evidentiality is realized through different morphological means across Turkic languages, a number of common functional and semantic characteristics can be observed (Serebrennikov & Hacıyeva, 2002, pp. 221–225).

The findings of the study indicate that the expression of indirect evidentiality occupies a particularly important place in the vast majority of Turkic languages. Azerbaijani, Turkish, Kazakh, Kyrgyz, and Uzbek all possess specific verbal forms used to express indirectly acquired information. These forms indicate that the speaker did not directly witness the event but instead obtained the information through hearsay, logical inference, or other indirect sources. In particular, the Azerbaijani suffix -mış/-miş, the Turkish suffix -miş, the Kazakh forms -ыпты/-іпті, the Kyrgyz form -ыптыр, and the Uzbek construction -gan ekan are especially noteworthy in this regard (Öner, 1998, pp. 142–145; Reshetov & Shoabdurahmonov, 1978, pp. 203–209).

The study also demonstrates that evidentiality is not merely a grammatical phenomenon but also a functional-semantic system that expresses the speaker's attitude toward information and communicative intentions. A comparative investigation of this category in Turkic languages provides valuable insights into their historical development, typological characteristics, and grammatical structure (Comrie, 1976, pp. 54–58).

However, the comparative analysis reveals that, despite their common historical foundations, Turkic languages exhibit certain structural and semantic differences in the use of evidential markers. These differences are manifested, in some cases, in the structure of the morphological markers employed and, in others, in their semantic functions. For example, while in some Turkic languages indirect evidential forms merely indicate the source of information, in others the same forms may additionally convey nuances of surprise, probability, or the speaker's subjective attitude toward the event. The functional development of grammatical forms in Turkic languages demonstrates that the same morphological marker can perform different semantic functions in different communicative contexts (Ergin, 2009, pp. 298–302).

In Azerbaijani linguistics, the functional-semantic nature of indirect past tense forms in Turkic languages is explained within the framework of the multifunctional characteristics of verbal categories. From this perspective, forms expressing indirectly acquired information function not only as markers of tense but also as devices that convey the speaker's attitude toward the information and their communicative intention (Müasir Azərbaycan dili: Sintaksis, 2014, pp. 352–356).

Comparative analyses of Turkic languages demonstrate that past tense forms express not only temporal relations but also the means by which information has been acquired.

As noted in *Modern Azerbaijani Language*, verbal forms constitute important grammatical devices that express both the speaker's attitude toward an event and whether the information has been obtained directly or indirectly (*Müasir Azərbaycan dili: Morfologiya, 2007*, p. 219).

From this perspective, evidentiality functions not merely as a morphological category but also as a system carrying significant communicative functions. *The Grammar of the Azerbaijani Language* emphasizes that grammatical forms are not solely structural markers but also functional units endowed with semantic content (*Azərbaycan dilinin qrammatikası, 2010*, p. 415).

Thus, the evidentiality system in Turkic languages may be regarded as a complex category that has developed through both historical and functional processes.

Furthermore, the study of evidentiality is of considerable scientific significance for investigating the historical development of Turkic languages, their patterns of interaction, and their typological characteristics. Similarities observed in evidential systems may be regarded as one of the indicators reflecting the common origin and shared grammatical features of Turkic languages. At the same time, the existing differences demonstrate that each language has evolved under the influence of its own internal developmental mechanisms as well as various socio-historical factors (Zeynalov, 2008, pp. 315–320).

The category of evidentiality constitutes an important component of the functional structure of language and also reflects the ways in which knowledge and information are conceptualized and expressed across different cultures. In Azerbaijani linguistics, this phenomenon is primarily interpreted within the framework of the semantic extension of grammatical categories and their communicative functions. As the communicative potential of language develops, grammatical forms may acquire additional functional-semantic properties (Hacıyev, 2012, pp. 191–194).

As noted in *The Grammar of the Azerbaijani Language*, grammatical categories are not merely formal structural units but also functional devices that reflect the speaker's cognitive activity and attitude toward information (*Azərbaycan dilinin qrammatikası, 2010*, p. 415).

Recent studies on Modern Azerbaijani emphasize that modal and auxiliary expressions serve as important communicative tools for conveying the speaker's assumptions, conjectures, and inferential reasoning within the linguistic system (Nuri et al., 2026, p. 382).

From this perspective, evidentiality constitutes an important object of research not only within the grammatical system but also in the study of the relationship between language and cognition. In contemporary linguistics, the investigation of linguistic devices associated with information source is of particular significance for identifying the interconnections between human cognitive processes and linguistic structures (Crystal, 2008, pp. 168–172).

Thus, the present study demonstrates that evidentiality is a semantic-grammatical category occupying an important place in the typological structure of Turkic languages. Future research may yield new insights through broader comparative analyses of Turkic languages, investigations of evidential markers in ancient Turkic written monuments, and studies of the functional characteristics of evidential devices in contemporary communicative environments. Comparative research on Turkic languages is of considerable scientific significance, as it contributes to the identification of both their shared features and their individual developmental trajectories (Tekin, 2003, pp. 163–167).

2. Indirect Evidentiality

Indirect evidentiality is characterized by the speaker's lack of direct observation of the event being reported. In such cases, information is obtained from other sources or derived through various

inferential processes. In linguistic studies, indirect evidentiality is associated with both the origin of the information presented by the speaker and the degree of its reliability (Comrie, 1976, pp. 66–70).

Main Types of Indirect Evidentiality

Information Acquired Through Hearsay: In this case, the information is obtained from other individuals:

They say that the weather will change tomorrow.
I have heard that the event has been postponed.

In such expressions, the speaker is not a direct witness to the event and receives the information from an external source (Boas, 1938, pp. 133–136).

Inference-Based Evidentiality: In this case, the speaker forms a conclusion based on observable facts:

It seems that it has rained.
Apparently, the guests have arrived.

Here, the information is derived from observed evidence and has an inferential character (Johanson, 2003, pp. 281–285).

Assumptive and Probabilistic Evidentiality: In this case, the speaker relies on logical assumptions and probability:

He is probably at home.
They must have already set off.

Such structures express the speaker's subjective stance regarding the degree of certainty of the information (Palmer, 2001, pp. 36–40).

In linguistic literature, evidentiality is interpreted not only as a marker of the source of information but also as a communicative device that determines the degree of reliability of information and the formation of the speaker's knowledge. From this perspective, the category of evidentiality encompasses not only how the speaker acquires information but also the epistemic evaluation assigned to that information (Dixon, 2005, pp. 208–211).

As noted in *Modern Azerbaijani Language: Syntax*, modal words and auxiliary expressions constitute the primary means of conveying the speaker's stance of probability, conjecture, and inference (2014, p. 176). This indicates that information is presented not merely as factual content but also together with the speaker's subjective evaluation. A similar approach is reflected in *The Grammar of the Azerbaijani Language*, where it is emphasized that verbal categories express both the speaker's attitude toward events and the relationship between information and its source (2010, p. 415). This feature demonstrates that evidentiality exists in Azerbaijani as a functional-semantic system within the grammatical structure of the language.

In Azerbaijani, one of the most frequently used means of expressing indirect evidentiality is the suffix **-mış/-miş/-muş/-müş**.

Examples:

He has reportedly come / It turns out that he has come.
The child has fallen asleep.
The guests have already left.

In these sentences, the speaker does not directly observe the event; instead, the information is obtained through hearsay, inference, or other indirect sources. Researchers note that in Azerbaijani, past forms marked by this suffix do not function solely as temporal indicators but also carry additional semantic and communicative nuances (Hacıyev, 2012, pp. 196–199). According to Kazımov (2010, p. 253), indirect past tense forms serve as functional means that express both the source of information and the speaker's attitude toward the event.

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In the Azerbaijani language, the main means of expressing evidentiality can be classified as follows:

Means of expressing evidentiality in Azerbaijani and their functions

Means	Function
-mış/-miş	Expression of indirect information
Görünür	Inferential meaning (result-based conclusion)
deyirlər	Hearsay (information obtained through others)
yəqin	Probability
güman ki	Assumption
deyəsən	Indeterminate inference

These linguistic devices perform different evidential functions in Azerbaijani, ranging from marking indirect information to expressing inference, hearsay, and varying degrees of epistemic uncertainty.

Thus, evidentiality in Azerbaijani functions as a complex communicative category that expresses both the source of information and its degree of reliability and probability. The processes of perception and presentation of information transmitted through language are closely linked to the speaker's communicative intentions. The semantic development of evidential forms across Turkic languages demonstrates that the mode of information presentation is not only grammatical but also functional in nature (Öner, 1998, pp. 148–152).

In Azerbaijani, evidentiality does not exist as a fully independent grammatical category; instead, it is expressed through various morphological and lexical means. Verbal suffixes, modal words, and syntactic constructions play a central role in this process. The development of verbal forms in Turkic languages shows that temporal and modal meanings are often interconnected, and in many cases, they also encode the source of information (Aksu-Koç, 1988, pp. 28–34).

In Azerbaijani, one of the most frequently used means of expressing indirect evidentiality is the suffix -mış/-miş/-muş/-müş.

Examples:

He has reportedly come / He apparently came.
The child has fallen asleep.
The guests have already left.

In these sentences, the speaker does not directly observe the event; instead, the information is obtained through hearsay, inference, or other indirect sources. Comparative studies of Turkic languages indicate that verbal forms expressing indirect information do not merely serve to transmit reported events but also reflect the speaker's attitude toward the information conveyed (Reshetov & Shoabdurahmonov, 1978, pp. 205–210).

Comparative Analysis of Evidentiality in Turkic Languages

In Turkic languages, the evidentiality system is regarded as one of the key grammatical-semantic means for expressing the source of information. In these languages, evidentiality is primarily associated with the verbal system and is especially prominent in past tense forms. Most Turkic languages exhibit a formal distinction between direct observation of an event and indirect acquisition of information. This feature is considered one of the shared typological characteristics of Turkic languages (Zeynalov, 2008, pp. 308–312).

Within the grammatical structure of Turkic languages, forms expressing indirect information do not solely carry temporal meaning; they also reflect the speaker's attitude toward the information and the manner in which it was acquired. Researchers emphasize that identical morphological markers in Turkic languages may acquire additional semantic nuances depending on different communicative contexts (Ergin, 2009, pp. 302–306).

"As Zeynalov (2008, p. 310) notes, *past tense forms in Turkic languages may express not only temporal relations but also the source of information.*"

Similarly, Ergin (2009, p. 304) states that *the functional development of grammatical forms expands their semantic potential.*

In Azerbaijani typological and comparative linguistic studies, particular attention is given to evidentiality in Turkic languages. According to this approach, indirect past tense forms in Turkic languages express not only temporal relations but also the source of information. Thus, certain verbal forms simultaneously encode both grammatical tense and evidential meaning (Satybaldiev, 1980, pp. 188–192).

Material from Kyrgyz shows that constructions such as -ыптыр and -ган экен do not merely indicate that an event occurred in the past; they also express that the information was obtained indirectly and that the speaker was not a direct witness of the event. This is regarded as one of the general typological features of evidentiality in Turkic languages (Satybaldiev, 1980, pp. 190–192).

As Satybaldiev (1980, p. 191) notes, *indirect past forms carry information about both tense and the source of information.*

In Turkic languages, some past tense forms are based on direct observation, while others express meanings derived from indirect information and inference. This feature demonstrates that evidentiality is formed as a functional-semantic system within Turkic languages (Əsgərova & Ələkbərova, 2026).

The same idea is also emphasized in *Modern Azerbaijani Language*, where it is shown that verbal affixes function not only as temporal markers but also as means of expressing the speaker's attitude toward events and the mode of information acquisition (2007, pp. 219–221). A similar approach is reflected in comparative Turkic grammars, which state that, as a result of the semantic expansion of verbal forms, they may perform not only temporal functions but also encode the source of information (Serebrennikov & Hacıyeva, 2002, pp. 226–229).

These approaches demonstrate that the category of evidentiality in Turkic languages is not limited to the morphological tense system but also plays an important functional-semantic role, reflecting the speaker's relationship to the source of information.

In Turkish, the evidentiality system is one of the grammatical categories where this distinction is particularly clearly observable. The main opposition is based on the principle of direct versus indirect evidentiality. Direct evidentiality is typically expressed by the past tense suffix **-di**, as in *Ali geldi* ("Ali came") and *Ahmet okula gitti* ("Ahmet went to school"). In such constructions, the speaker presents themselves as a direct witness of the event, and the source of information is based on visual perception (Ergin, 2009, pp. 295–298).

Indirect evidentiality in Turkish is mainly expressed through the suffix **-miş**, as in *Ali gelmiş* ("Ali has apparently come") and *Ahmet okula gitmiş* ("Ahmet has apparently gone to school"). In such cases, the speaker either obtains the information from an external source or reaches a conclusion based on certain facts. In Turkish, this form can convey both reportative (hearsay-based) and inferential meanings (Comrie, 1985, pp. 67–70).

Researchers note that the Turkish -miş form is not only an indicator of indirect information but also carries additional semantic nuances such as surprise, unexpectedness, information acquired after the fact, and inference (Johanson, 2000, pp. 66–69).

In Kazakh, evidentiality is primarily realized through the verbal system and is based on grammatical means expressing whether information is obtained directly or indirectly. Direct evidentiality is typically expressed by simple past tense forms, as in *Ол келді* ("He came") and *Бала мектепке барды* ("The child went to school"). Indirect evidentiality, on the other hand, is mainly expressed by the suffixes -ыпты / -іпті, as in *Ол келіпті* ("It is said that he has come") and *Бала мектепке барыпты* ("It turns out that the child went to school"). In these forms, it is evident that the speaker is not a direct witness of the event and that the information is obtained from indirect sources. Researchers emphasize that in Kazakh these forms are particularly productive in spoken discourse and may convey additional semantic nuances such as information reliability, speaker stance, and inference (Johanson, 2003, pp. 278–281).

In Kyrgyz, the evidentiality system is relatively complex and is expressed through a variety of morphological means. Several different structures are used to convey indirect information in this language. For example: *Ал келген экен* ("It turns out that he has come") and *Ал келиптир* ("It is said that he has come"). The forms -ган экен and -ыптыр used in these constructions indicate that the speaker is not a direct witness of the event. Studies show that in Kyrgyz these forms are mainly used to transmit hearsay information, report events learned after the fact, and express conclusions based on indirect evidence (Aikhenvald, 2004, pp. 211–214).

In Uzbek, the category of evidentiality is primarily expressed through verbal forms. A grammatical distinction is made between directly and indirectly acquired information. Direct evidentiality is typically expressed by the simple past tense, as in *U keldi* ("He came"). Indirect evidentiality, on the other hand, is mainly conveyed through the construction -gan ekan, as in *U kelgan ekan* ("It turns out that he has come"). In this example, the form -gan ekan indicates that the event was not directly witnessed by the speaker and that the information was obtained indirectly. Researchers note that in

Uzbek, evidentiality functions not only as a grammatical category but also as an important device for expressing the speaker's attitude toward information, its degree of reliability, and communicative stance (Johanson, 2003, pp. 282–284).

Comparative Typological Analysis

The comparison of Turkic languages demonstrates that in most of them there are structural similarities in the expression of direct and indirect evidentiality. At the same time, certain differences can be observed in the phonetic and morphological structure of the affixes used.

Table 1
Evidential markers in selected Turkic languages

Language	Direct evidentiality	Indirect evidentiality
Azerbaijani	-dı	-mış
Turkish	-di	-miş
Kazakh	-dı/-di	-ıptı/-ipti
Kyrgyz	-gan	-ıptır
Uzbek	-di	-gan ekan

As can be seen from the table, there is a high degree of structural similarity between Azerbaijani and Turkish in the suffixes used to express indirect evidentiality. In contrast, in the Turkic languages of Central Asia, more complex constructions are more widely used to express indirect information.

Table 2
Examples of direct and indirect evidential forms in Turkic languages

Language	Direct evidentiality example	Translation	Indirect evidentiality example	Translation
Azerbaijani	*O gəldi.*	The speaker is a witness of the event.	*O gəlmişdir.*	The speaker has heard about the event or inferred it.
Turkish	*Ali geldi.*	Ali came.	*Ali gelmiş.*	It has been reported that Ali has come.
Kazakh	*Ол келді.*	He came.	*Ол келіпті.*	It is said that he has come.
Kyrgyz	*Ал келди.*	He came.	*Ал келиптир.*	It turns out that he has come.
Uzbek	*U keldi.*	He came.	*U kelgan ekan.*	It has later become known that he has come.

The examples presented in the table demonstrate that in all the Turkic languages under comparison, direct evidentiality is typically expressed through simple past tense forms. In Azerbaijani, Turkish, and Kazakh, these forms are primarily realized by the suffixes -dı/-di.

In the expression of indirect evidentiality, however, a greater degree of variation is observed. In Azerbaijani and Turkish, the proto-Turkic form -mış/-miş has been preserved. In Kazakh, the forms -ыпты/-іпті are used, in Kyrgyz -ыптыр, and in Uzbek the construction -gan ekan is employed. These facts indicate that although the category of evidentiality in Turkic languages shares a common functional-semantic core, its morphological realization has undergone different developmental pathways.

In particular, the use of auxiliary-based complex constructions in Uzbek and Kyrgyz reflects varying degrees of grammaticalization in the expression of evidentiality across Turkic languages.

Table 3
Semantic functions of indirect evidential forms

Language	Hearsay (reportative)	Inference (inferential)	Surprise / unexpectedness
Azerbaijani (-mış)	+	+	±
Turkish (-miş)	+	+	+
Kazakh (-ıпті)	+	+	±
Kyrgyz (-ыптыр)	+	+	+
Uzbek (-gan ekan)	+	+	±

Table 4
Morphological structure of evidential markers in Turkic languages

Language	Evidential form	Morphological structure	Type
Azerbaijani	*gəlmiş*	gəl- + -miş	Simple suffix
Turkish	*gelmiş*	gel- + -miş	Simple suffix
Kazakh	*kelipti*	kel- + -ip + -ti	Compound suffix
Kyrgyz	*keliptir*	kel- + -ip + -tir	Compound suffix
Uzbek	*kelgan ekan*	kel- + -gan + ekan	Analytic construction

The table shows that evidentiality in Azerbaijani and Turkish is predominantly expressed in a synthetic manner (through suffixation). In Kyrgyz and Kazakh, more complex suffixal structures are used, while in Uzbek an analytic construction is preferred.

Comparative-typological studies of Turkic languages in Azerbaijani linguistics indicate that the formation of grammatical categories is closely linked to the historical development of languages and their communicative needs. From this perspective, although the evidentiality system in Turkic languages shares a common origin, it has acquired different structural and functional properties over time (Zeynalov, 2008, pp. 310–313). The development of grammatical categories shows that linguistic forms may gradually acquire semantic expansion and functional versatility within the language system (Bybee et al., 1994, pp. 186–189).

It is also noted in *Comparative Grammar of Turkic Languages* that the evolution of grammatical forms in Turkic languages is based both on common Turkic roots and on the internal developmental tendencies of individual languages. This approach helps explain the historical foundations of the structural differences observed in evidentiality systems across Turkic languages.

At the same time, *The Grammar of the Azerbaijani Language* emphasizes that the semantic expansion and functional change of grammatical categories are directly related to the communicative needs of the language (2010, p. 415). This view helps explain the variation in the realization of the evidentiality category across Turkic languages.

As noted in *Ismayil et al. (2026)*, “grammatical forms in Turkic languages may acquire different functional properties in the course of historical development.”

Thus, the comparative analysis demonstrates that although evidentiality in Turkic languages is based on a common historical origin, its grammatical means of expression have developed in different

directions over time and are realized at different structural levels in each language (Zeynalov, 2008, pp. 313–316).

The results of the study indicate that evidentiality in Azerbaijani and Turkish is primarily expressed through synthetic forms (-mış/-miş), whereas Uzbek predominantly employs analytic constructions (-gan ekan). In Kazakh and Kyrgyz, evidential markers more prominently express both reportative and inferential functions. These findings suggest that, although evidentiality in Turkic languages has a unified origin, it has undergone diverse processes of grammaticalization and semantic differentiation across different languages.

References

Abbasova, A. (2025). Qədim türk qaynaqlarındakı Qərbi Azərbaycan toponimləri və onların ermənilərdirilmiş variantları. *Elmi İş, 19*(5), 17–21. https://doi.org/10.36719/2663-4619/115/17-21

Aikhenvald, A. Y. (2004). *Evidentiality*. Oxford University Press.

Aksu-Koç, A. (1988). *The acquisition of aspect and modality: The case of past reference in Turkish*. Cambridge University Press.

Ağayeva, D. (2025). Neologizmlərin dilin dinamik inkişafında rolu və sosiolinqvistik təhlili. *Elmi İş, 19*(10), 89–94. https://doi.org/10.36719/2663-4619/122/89-94

Azərbaycan dilinin qrammatikası (Cild 1). (2010). Elm.

Boas, F. (1938). Language. In F. Boas (Ed.), *General anthropology*. D. C. Heath and Company, 124-145.

Bybee, J., Perkins, R., & Pagliuca, W. (1994). *The evolution of grammar: Tense, aspect, and modality in the languages of the world*. University of Chicago Press.

Comrie, B. (1976). *Aspect*. Cambridge University Press.

Comrie, B. (1985). Tense. Cambridge University Press.

Crystal, D. (2008). *A dictionary of linguistics and phonetics (6th ed.)*. Blackwell Publishing. https://doi.org/10.1002/9781444302776

Dixon, R. M. W. (2005). *A semantic approach to English grammar (2nd ed.)*. Oxford University Press.

Ergin, M. (2009). *Türk dil bilgisi*. Bayrak Yayınları.

Əsgərova, Q., & Ələkbərova, G. (2026). Ədəbi dil və dialekt münasibətləri. *Elmi İş, 20*(3), 108–114. https://doi.org/10.36719/2663-4619/127/108-114

Hacıyev, T. İ. (2012). *Azərbaycan ədəbi dili tarixi*. Təhsil.

Ismayil, Z., Semedova, K., & Vagifkizi Guliyeva, G. (2026). Derivations at the intersection of dialectology and folklore: The process of word formation in folk language materials. *Universidad y Sociedad*, 18(2), Article e5626.

Johanson, L. (2000). Viewpoint operators in European languages. In Ö. Dahl (Ed.), *Tense and aspect in the languages of Europe*. Mouton de Gruyter, *127–187.*

Johanson, L. (2003). Evidentiality in Turkic. In A. Y. Aikhenvald & R. M. W. Dixon (Eds.), *Studies in evidentiality*. John Benjamins, 273-290. https://doi.org/10.1075/tsl.54.15joh

Kazımov, Q. Ş. (2010). *Müasir Azərbaycan dili*. Elm və Təhsil.

Korkmaz, Z. (2003). *Türkiye Türkçesi grameri (şekil bilgisi)*. Türk Dil Kurumu.

Langacker, R. W. (2008). *Cognitive grammar: A basic introduction*. Oxford University Press.

Lyons, J. (1977). *Semantics*. Cambridge University Press.

Müasir Azərbaycan dili: Morfologiya. (2007). Şərq-Qərb.

Müasir Azərbaycan dili: Sintaksis. (2014). Elm və Təhsil.

Nuri, A., Seyidov, R., Hashimov, A., Kosareva, L., Ismayil, Z., Alizada, P., Tavberidze, N., & Ahmadov, H. (2026). Theoretical disruption: AI-driven language systems and the reformulation of linguistics. *Journal of Ethnic and Cultural Studies, 13*(3), 382–412. https://doi.org/10.66815/ejecs/3065

Öner, M. (1998). *Bugünkü Kıpçak Türkçesi*. Türk Dil Kurumu.
Palmer, F. R. (2001). *Mood and modality (2nd ed.)*. Cambridge University Press.
Reshetov, V. V., & Shoabdurahmonov, Sh. (1978). *O'zbek tili grammatikasi*. O'qituvchi.
Satybaldiev, T. (1980). *Kırgız tilinin grammatikası*. Mektep.
Serebrennikov, B. A., & Hacıyeva, N. Z. (2002). *Türk dillərinin müqayisəli tarixi qrammatikası*. Səda.
Tekin, T. (2003). *Orhon Türkçesi grameri*. Türk Dil Kurumu.
Zeynalov, F. R. (2008). T*ürk dillərinin müqayisəli qrammatikası (I hissə: Fonetika, leksika, morfologiya)*. MBM.
Zeynalova, A. (2025). Onomastik vahidlərin XIII–XIV əsrlər Azərbaycan klassik ədəbiyyatında izləri. *Elmi İş, 19*(6), 9–13. https://doi.org/10.36719/2663-4619/118/9-13

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Do Lectures Still Matter in EFL Teaching in Higher Education? Exploring Students' Perceptions in Fergana State University

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Abstract. *Despite being a foundational method of instruction in universities for centuries, lecture-based teaching is now under increasing scrutiny regarding its pedagogical effectiveness in the age of digital transformation. This study investigates university students' perceptions of lecture classes, focusing on their effectiveness and engagement levels. The research was conducted among 68 undergraduate English language learners at Fergana State University, using a quantitative survey approach. A structured Google Form questionnaire containing 12 closed-ended items was administered to gather data on students' experiences and attitudes toward lecture classrooms. The findings suggest that a significant proportion of students view lecture-based classes as ineffective and disengaging. Key concerns raised include the lack of interaction, persistent classroom noise, and insufficient subject knowledge demonstrated by some instructors. The study also highlights a growing preference for more interactive, student-centered approaches such as group discussions, task-based learning, and technology-enhanced instruction. This research contributes to the ongoing debate on the future of traditional lectures in higher education, particularly within English as a Foreign Language (EFL) contexts.*

Keywords: *lecture-based teaching, student perceptions, higher education, EFL, interactive learning*

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Ali təhsildə EFL tədrisində mühazirələr hələ də əhəmiyyətlidir? Fərqanə Dövlət Universitetində tələbələrin baxışlarının araşdırılması

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Xülasə. *Əsrlər boyu universitetlərdə əsas tədris metodu olmasına baxmayaraq, mühazirə əsaslı tədris rəqəmsal transformasiya dövründə pedaqoji effektivliyi baxımından getdikcə daha çox diqqət mərkəzindədir. Bu tədqiqat universitet tələbələrinin mühazirə dərsləri haqqında qavrayışlarını araşdırır, onların effektivliyinə və cəlb olunma səviyyələrinə diqqət yetirir.*

Tədqiqat Fərqanə Dövlət Universitetində bakalavriat səviyyəsində ingilis dili öyrənən 68 tələbə arasında kəmiyyət sorğusu yanaşmasından istifadə edilərək aparılmışdır. Tələbələrin təcrübələri və mühazirə siniflərinə münasibətləri haqqında məlumat toplamaq üçün 12 qapalı sualdan ibarət strukturlaşdırılmış Google Forms anketindən istifadə edilmişdir. Nəticələr göstərir ki, tələbələrin əhəmiyyətli bir hissəsi mühazirə əsaslı dərsləri səmərəsiz və maraqsız hesab edir. Qaldırılan əsas narahatlıqlar sırasına qarşılıqlı əlaqənin olmaması, davamlı sinif səs-küyü və bəzi müəllimlər tərəfindən nümayiş etdirilən fənn biliklərinin yetərli olmaması daxildir. Tədqiqat həmçinin qrup müzakirələri, tapşırıq əsaslı təlim və texnologiya ilə təkmilləşdirilmiş təlim kimi daha interaktiv, tələbə mərkəzli yanaşmalara artan üstünlüyü vurğulayır. Bu tədqiqat ali təhsildə, xüsusən də xarici dil kimi ingilis dili (EFL) kontekstlərində ənənəvi mühazirələrin gələcəyi ilə bağlı davam edən müzakirələrə töhfə verir.

Açar sözlər: *mühazirə əsaslı tədris, tələbələrin qavrayışları, ali təhsil, EFL, interaktiv təlim*

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Introduction

The traditional lecture format has long served as the cornerstone of higher education and the primary method of knowledge transmission in universities worldwide. The first lecture classes were established at the University of Bologna in 1088, catering to grammar, rhetoric and logic. The evolution of the lecture format has undergone gradual but significant transformations over the centuries. Originally created as a "reading" (lectio) format for clergy education, the lecture has adapted to technological developments and educational needs over time. With the invention of the printing press and increased availability of books, the necessity of lectures was questioned. However, the authoritative position and hierarchical status of lecturers ensured the format's continued dominance within academic institutions. The early nineteenth century witnessed the introduction of laboratory-based teaching as a more active and experiential form of learning, directly challenging the passive reception characteristic of traditional lectures. This hands-on approach embodied the practical "learning by doing" philosophy. Modern technological integration brought student response systems ("clickers"), projectors, PowerPoint presentations, and eventually online lecture recording and distribution, allowing students to manage their study schedules more flexibly. However, even before COVID-19, over 700 studies reported in-person lectures as ultimately ineffective teaching methods, with declining attendance rates and calls for more hybrid learning approaches (Gibbs, 2013).

However, in an era characterized by rapid digital transformation and evolving pedagogical paradigms, the effectiveness of lecture-based instruction is increasingly being questioned (Benavides et al., 2020). This scrutiny has become particularly pronounced in English as a Foreign Language (EFL) contexts, where the communicative and interactive nature of language learning appears to conflict with the traditionally passive lecture format.

The emergence of digital technologies and innovative teaching methodologies has fundamentally challenged conventional approaches to education. Modern students, often referred to as "digital natives," demonstrate different learning preferences and engagement patterns compared to previous

generations (Hamamra et al., 2026). They exhibit heightened expectations for interactive, multimedia-rich, and participatory learning experiences that align with their digital literacy and communication habits. This shift has prompted educators and researchers to reconsider the relevance and effectiveness of traditional pedagogical methods, particularly in language education where interaction and active participation are deemed essential for successful learning outcomes.

In EFL teaching contexts, the debate surrounding lecture effectiveness becomes even more complex. Language acquisition theories emphasize the importance of communicative competence, interaction, and meaningful engagement with the target language. These principles appear to be at odds with the lecture format, which typically involves one-way communication from instructor to students, limited opportunities for active participation, and minimal authentic language use. Furthermore, the increasing availability of digital resources, online learning platforms, and interactive technologies has created alternative pathways for language learning that may better serve students' needs and preferences.

Despite extensive research on teaching methodologies in higher education, there remains a significant gap in understanding students' perceptions of lecture-based instruction specifically within EFL contexts. While some studies have examined the effectiveness of various teaching approaches in language learning, few have systematically investigated students' attitudes toward traditional lectures in the current digital age. This lack of empirical evidence from the learners' perspective limits educators' ability to make informed decisions about pedagogical approaches and curricular design.

This study aims to address this gap by exploring the following research questions:

RQ1. How do undergraduate EFL students perceive the effectiveness of lecture-based instruction for learning English?
RQ2. How engaged do students feel during lectures, and what alternative instructional formats do they prefer?
RQ3. Do students' perceptions of lecture-based instruction differ by gender and year of study?
By examining students' experiences and attitudes, this research seeks to provide valuable insights that can inform pedagogical decisions and contribute to the ongoing discourse on the future of traditional teaching methods in EFL higher education contexts.

The Shift Towards Interactive and Student-Centered Methods in EFL

In recent years, EFL instruction has increasingly shifted away from lecture-based, teacher-centered approaches toward more interactive, student-centered methodologies. Traditional lectures often prioritize content delivery and grammatical accuracy, leaving limited room for spontaneous communication. In contrast, communicative approaches such as Communicative Language Teaching (CLT) and Task-Based Language Teaching (TBLT) emphasize meaningful interaction, learner autonomy, and real-life language use (Ellis, 2003; Nunan, 2004).

CLT encourages learners to use the target language in authentic communicative situations rather than focusing solely on grammar and vocabulary drills. Littlewood (2007) notes that CLT enhances learner motivation and engagement by prioritizing fluency over accuracy. Similarly, TBLT involves students completing meaningful tasks—such as problem-solving or group discussions—that mirror real-world situations. Ellis (2003) argues that such task-based approaches promote deeper cognitive processing and increase language retention. In EFL classrooms, these methods are seen as more effective than traditional lectures in developing speaking, listening, and collaboration skills.

The Flipped Classroom and Student Reactions

Another emerging trend in student-centered teaching is the flipped classroom model, where learners study content (e.g., video lectures or readings) outside class and use class time for discussion,

practice, and feedback. This model transforms the classroom into an interactive space and allows for greater individual support (Bergmann & Sams, 2012). Research shows that students generally respond positively to these changes, reporting increased participation, better comprehension, and a greater sense of control over their learning (Basal, 2015). However, such methods require digital readiness and well-planned instruction to be fully effective in EFL environments.

The Role of Lectures in Developing Academic and Language Skills

In the context of English as a Foreign Language (EFL), lectures play a fundamental role not only in delivering content but also in shaping learners' academic and linguistic competencies. According to Abdulbaki et al. (2018), academic lectures are among the primary sources of input in higher education, and they require learners to simultaneously listen, understand, and process complex information. This dual task challenges students but also helps develop essential skills such as academic listening, critical thinking, and note-taking.

Hyland (2006) emphasizes that lectures contribute to building academic literacy by exposing students to the structure, tone, and vocabulary of academic discourse. Learners internalize these patterns over time, improving their ability to comprehend and produce academic texts. Nation and Newton (2009) also highlight the significance of lectures in contextual vocabulary acquisition, as students repeatedly encounter academic terms in meaningful contexts.

From a language development perspective, Goh (2007) and Rost (2011) argue that lectures support listening comprehension by training students to follow extended spoken input, identify key points, and deal with various accents and speaking speeds. Moreover, lectures help learners notice the use of cohesive devices, grammar structures, and rhetorical strategies, which they can then transfer to their own writing and speaking.

In test preparation contexts, particularly for IELTS and TOEFL, lectures serve as a practice ground for listening tasks and integrated skills activities. As Göçer and Karabatak (2026)noted, the ability to understand academic lectures is crucial for international students, and explicit instruction in lecture comprehension strategies can improve both comprehension and academic performance.

Despite criticisms that lectures are too teacher-centered, research suggests that when lectures are structured with student needs in mind, they can significantly enhance learners' academic engagement and language proficiency. The integration of guided note-taking, follow-up discussions, and visual aids can make lectures more accessible and pedagogically effective.

Student Engagement and Perceptions in Traditional Lectures

Research on student engagement in traditional lecture settings reveals mixed findings. While some studies report that well-structured lectures can maintain student attention and facilitate knowledge retention (Shi, 2026; Goetz et al., 2020), others indicate declining engagement levels, particularly in extended lecture sessions (Wilson & Korn, 2007). The passive nature of traditional lectures has been identified as a primary factor contributing to reduced student engagement, with attention spans typically declining after 10–15 minutes of continuous listening.

Contemporary research has highlighted the generational shift in learning preferences among current university students. Digital natives demonstrate preferences for multimodal learning experiences, immediate feedback, and collaborative activities (Khadawardi, 2025). These preferences often conflict with the traditional lecture format, leading to what some researchers describe as a "pedagogical mismatch" between instructional methods and learner expectations (Jones & Shao, 2011).

Materials and Methods

Research Design

This study employed a quantitative survey research design to investigate undergraduate English language learners' perceptions of lecture-based classes at Fergana State University. The quantitative approach was selected to enable systematic collection and statistical analysis of student attitudes and experiences, providing generalizable insights into the effectiveness and engagement levels of traditional lecture formats in EFL education.

Participants

The study involved 68 undergraduate students enrolled in the English Language and Literature program at Fergana State University. Participants were selected using purposive sampling to ensure representation across different academic years (first through fourth year). The sample comprised 42 female students (61.8%) and 26 male students (38.2%), aged between 18 and 23 years (M = 20.3, SD = 1.4). All participants had experienced both traditional lecture-based classes and alternative teaching methods throughout their academic journey, providing them with a comparative framework for evaluation.

Purposive sampling was preferred over random sampling for two reasons. First, the study's comparative research questions required guaranteed representation from all four academic years; random sampling risked underrepresenting one or more cohorts given the unequal year-group sizes within the programme. Second, the criterion that all participants must have experienced both lecture-based and alternative instructional formats necessitated a targeted selection rather than an open invitation. Students were identified through class registers in coordination with the department head, and all who met the inclusion criteria were invited to participate. Students absent during the data collection window and those who had not yet completed at least one full semester were excluded.

Research Instrument

A structured questionnaire was developed specifically for this study, consisting of 12 closed-ended items designed to measure various aspects of student perceptions regarding lecture-based classes. The questionnaire was administered via Google Forms to ensure ease of access and data collection efficiency. The instrument was divided into three main sections:

1. **Demographic Information** (3 items): Gender, academic year, and age
2. **Perception of Lecture Effectiveness** (5 items): Items addressing content delivery, knowledge retention, skill development, exam preparation, and overall learning outcomes
3. **Engagement and Satisfaction** (4 items): Items measuring attention levels, participation opportunities, motivation, and preference for alternative methods.

Items were rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The questionnaire underwent pilot testing with 10 students to ensure clarity and reliability, resulting in minor modifications to item wording. The final instrument demonstrated acceptable internal consistency (Cronbach's $\alpha = 0.78$). The Cronbach's alpha value of 0.78 falls within the range of 0.70–0.90 considered acceptable for social science research instruments (Field, 2018, p. 795), indicating that the items within each subscale consistently measured the same underlying construct. Reliability was calculated separately for the two substantive subscales: perceived lecture effectiveness ($\alpha = 0.74$) and engagement and satisfaction ($\alpha = 0.76$), both confirming adequate internal consistency. In addition to reliability, face validity was established through review by two experienced EFL instructors who confirmed that all items were relevant, clearly worded, and representative of the constructs being measured.

Data Collection Procedures

Data collection occurred during the spring semester of the 2025–2026 academic year. The questionnaire link was distributed to participants through institutional email and class WhatsApp groups. Participants were informed about the study's purpose, assured of anonymity, and provided with consent information before accessing the survey. The data collection period lasted two weeks, with reminder messages sent after one week to maximize response rates. The overall response rate was 85%, with 68 out of 80 invited students completing the survey.

Data Analysis

Quantitative data were analysed using IBM SPSS Statistics (version 26.0). The analysis proceeded in three stages. In the first stage, descriptive statistics — including means (M), standard deviations (SD), and percentage frequencies — were computed for all questionnaire items to characterise the overall distribution of student perceptions. In the second stage, inferential statistics were applied to address the comparative research questions. Independent-samples t-tests were conducted to examine gender differences in perceived lecture effectiveness and learning preferences; effect sizes were calculated using Cohen's d to assess the practical significance of any statistically significant differences. One-way analysis of variance (ANOVA) was used to compare perceptions across the four academic years, with Tukey's Honest Significant Difference (HSD) post-hoc test applied where the omnibus F-test indicated significance, to identify which specific year pairs differed. In the third stage, Pearson product-moment correlation coefficients were calculated to explore the relationship between engagement levels and perceived lecture effectiveness. Prior to all parametric tests, the assumptions of normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test) were verified and confirmed. The alpha level was set at $p < 0.05$ for all statistical tests.

Data Interpretation

Quantitative findings were interpreted through a deductive lens, drawing on the theoretical frameworks outlined in the literature review — specifically sociocultural theory, communicative language teaching principles, and student engagement models. Mean scores below 3.0 on the five-point Likert scale were interpreted as reflecting negative or unfavourable perceptions, scores above 3.0 as positive or favourable, and scores at or near 3.0 as neutral. Percentage frequencies were used to contextualise the magnitude of each finding, while statistically significant group differences were interpreted in light of their effect sizes rather than p-values alone, to avoid over-interpreting trivial differences. Findings were subsequently compared with results from analogous international studies to assess whether patterns observed at Fergana State University reflected broader trends or were context-specific. Where statistical results appeared inconsistent, raw frequency distributions were re-examined to rule out distributional anomalies before conclusions were drawn.

Results and Discussion

The analysis revealed predominantly negative perceptions of traditional lecture-based instruction among participants. Table 1 presents a summary of all key descriptive and inferential statistics.

Table 1
Summary of descriptive and inferential statistics for key study variables

Variable	M	SD	Key Statistic	p	Effect Size
Overall lecture effectiveness	2.31	0.89	—	—	—
Engagement level	2.18	0.76	—	—	—
Interaction opportunities	2.03	0.82	—	—	—
Peer discussion opportunities	1.97	0.79	—	—	—
Interaction–motivation correlation	—	—	$r = -0.52$	$< .001$	moderate-large

Classroom management (year diff.)	—	—	$F(3, 64) = 4.23$	.008	$\eta^2 = 0.17$
Lecture satisfaction (year diff.)	—	—	$F(3, 64) = 6.78$	< .001	$\eta^2 = 0.24$
Lecture effectiveness (gender)	—	—	$t(66) = 1.23$	.22	$d = 0.30$
Collaborative preference (gender)	—	—	$t(66) = 2.41$	.02	$d = 0.59$

Note. Scale range: 1 (strongly disagree) – 5 (strongly agree). Effect sizes reported as Cohen's d for t-tests, η^2 for ANOVA, and r for correlations.

Overall Lecture Effectiveness and Engagement

The mean score for overall lecture effectiveness was 2.31 (SD = 0.89), with 58.8% (n = 40) of participants rating lectures as ineffective or highly ineffective and only 16.2% (n = 11) rating them as effective. Engagement levels were similarly low (M = 2.18, SD = 0.76), with 64.7% (n = 44) reporting difficulty maintaining attention. As shown in Table 2, the most frequently cited barriers were lack of interaction opportunities (73.5%), monotonous delivery (67.6%), excessive class duration (61.8%), and classroom noise (58.8%).

Table 2

Frequency of reported barriers to engagement during lectures (N = 68)

Barrier	n	%
Lack of interaction opportunities	50	73.5
Monotonous delivery style	46	67.6
Excessive class duration	42	61.8
Classroom noise and disruptions	40	58.8

Note. Percentages reflect the proportion of participants identifying each item as a significant barrier. Multiple responses were permitted.

Specific Concerns

Three specific concerns emerged from the data. First, students reported minimal opportunities for questions (M = 2.03, SD = 0.82) and peer discussion (M = 1.97, SD = 0.79), with restricted interaction significantly and negatively correlated with motivation levels ($r = -0.52$, $p < .001$). Second, 41.2% (n = 28) of participants raised concerns about instructor competence, citing over-reliance on slide reading, outdated content, and inability to address student questions. Third, classroom noise was reported as a significant distraction by 58.8% (n = 40) of participants, with fourth-year students significantly more critical of classroom management than first-year peers, $F(3, 64) = 4.23$, $p = .008$, $\eta^2 = 0.17$.

Academic Year and Gender Differences

Lecture satisfaction declined significantly across academic years, $F(3, 64) = 6.78$, $p < .001$, $\eta^2 = 0.24$, representing a large effect. As shown in Table 3, mean scores decreased progressively from Year 1 (M = 2.89, SD = 0.71) to Year 4 (M = 1.96, SD = 0.68), with Tukey post-hoc tests confirming significant differences between Years 1 and 3 (p = .021) and Years 1 and 4 (p = .003).

Table 3

Mean lecture satisfaction scores by academic year

Academic Year	N	M	SD
Year 1	18	2.89	0.71
Year 2	17	2.54	0.74
Year 3	18	2.21	0.69
Year 4	15	1.96	0.68

Note. $F(3, 64) = 6.78$, $p < .001$, $\eta^2 = 0.24$. Tukey post-hoc: Years 1–3 ($p = .021$); Years 1–4 ($p = .003$). Scale range: 1–5.

No significant gender difference was found in overall lecture effectiveness perceptions, $t(66) = 1.23$, $p = .22$, $d = 0.30$. However, female students expressed a significantly stronger preference for collaborative learning methods than male students, $t(66) = 2.41$, $p = .02$, $d = 0.59$.

Preferred Instructional Alternatives

Students expressed strong preferences for interactive alternatives to traditional lectures: the flipped classroom model (70.6%, n = 48), group discussion and task-based activities (68.2%, n = 46), and technology-enhanced instruction (63.5%, n = 43).

The findings of this study provide robust empirical evidence that traditional lecture-based instruction faces substantial pedagogical challenges in meeting the learning needs and expectations of contemporary EFL undergraduates at Fergana State University. The overwhelmingly negative perceptions of lecture effectiveness — with 58.8% of participants rating lectures as ineffective — align with and extend a well-established international evidence base. Freeman et al. (2014), in a meta-analysis of 225 studies spanning STEM and humanities disciplines, demonstrated that students in traditional lecture courses were 1.5 times more likely to fail than those in active learning environments. Abdulbaki et al. (2018), examining EFL lecture instruction specifically, reported that 54% of university students in their sample viewed lectures as inadequate for developing communicative competence — a figure the present study surpasses by nearly five percentage points. The consistency of these findings across geographically, linguistically, and institutionally diverse contexts — the United States, Iraq, and Uzbekistan — suggests that the limitations of passive lecture instruction are not contextually contingent but reflect a fundamental structural tension between the lecture format and the communicative demands of language learning.

The low engagement levels recorded in this study — with 64.7% of participants reporting difficulty maintaining attention — are similarly consistent with, and in several respects more pronounced than, comparable international findings. Bunce et al. (2010) documented attention decline in approximately 50% of undergraduate students in American university lecture settings, a rate 14.7 percentage points lower than that observed here. Johnstone and Percival (1976), whose foundational work established that student attention begins to deteriorate after 10–15 minutes of continuous lecture exposure, provide a theoretical baseline against which the present findings should be read: in EFL contexts, the additional cognitive burden of processing academic content in a second language accelerates this attentional decline beyond what monolingual learners typically experience (Goh, 2007). Wilson and Korn (2007), in a review of attention research in lecture settings, confirmed that disengagement is not merely a motivational problem but a cognitive one, shaped by the interaction between instructional format and the listener's processing capacity — a dynamic that is structurally intensified in second-language academic listening. Goetz et al. (2020) further demonstrated that negative emotional states, including boredom and frustration, mediate the relationship between passive instructional formats and disengagement, providing an affective dimension to the cognitive explanation: students in lectures are not simply inattentive but are actively experiencing negative emotional responses that compound disengagement over time.

The statistically significant negative correlation between limited interaction opportunities and reduced motivation ($r = -0.52$, $p < 0.001$) constitutes one of the study's most analytically important findings. This moderate-to-large effect directly supports Long's (1996) Interaction Hypothesis, which argues that negotiation of meaning through interactive communication is not merely beneficial but essential for second language acquisition — a process the unidirectional lecture format structurally prevents. Littlewood (2007), examining EFL instruction across East Asian university contexts, found that learners with fewer classroom interaction opportunities demonstrated significantly lower

communicative confidence and motivation, a pattern that closely parallels the present results and suggests the interaction deficit identified here is a cross-contextual phenomenon rather than an institutional anomaly specific to Fergana State University. Nunan (2004) further argues that even minimal structural interventions — such as brief pair-work episodes or embedded question-and-answer activities within lectures — can meaningfully restore the interactive conditions necessary for language development, pointing to a practical pathway for reform that does not require wholesale abandonment of the lecture format.

Concerns regarding instructor competence, raised by 41.2% of participants, require careful contextualisation rather than straightforward attribution to individual faculty failure. In post-Soviet educational systems undergoing rapid reform, such as Uzbekistan's, the transition from transmission-based to communicative pedagogical paradigms has proceeded at the policy level far more quickly than at the classroom level (Irgasheva, 2020). Instructors trained under deeply embedded didactic traditions frequently lack the professional repertoire required for interactive, learner-centred practice — a gap that manifests in precisely the classroom behaviours students identified: over-reliance on slide reading, inability to respond flexibly to student questions, and delivery of content perceived as outdated. Benavides et al. (2020), in a systematic review of digital transformation in higher education institutions, found that institutional modernisation consistently outpaces faculty capacity development, producing a structural mismatch between curriculum expectations and actual pedagogical delivery. This systemic interpretation reframes the instructor competence concern from an individual performance issue to an institutional investment problem, with faculty development rather than faculty replacement as the appropriate policy response.

The significant decline in lecture satisfaction across academic years — from a mean of 2.89 among first-year students to 1.96 among fourth-year students, $F(3, 64) = 6.78$, $p < 0.001$, $\eta^2 = 0.24$ — represents the study's strongest group difference, with a large effect size indicating that academic year is a practically as well as statistically meaningful predictor of lecture attitudes. This progressive disillusionment is theoretically consistent with self-regulated learning theory, which holds that as learners develop greater metacognitive awareness and expand their repertoire of learning strategies, they become increasingly critical of instructional environments that fail to support active, autonomous engagement (Zimmerman, 2002). Basal (2015), studying Turkish EFL university students, documented a comparable developmental trajectory in which advanced-year learners demonstrated the strongest preferences for flipped and interactive alternatives to traditional lectures. The large effect size observed in the present study suggests that this is not a marginal trend but a robust developmental pattern with direct implications for curriculum sequencing: pedagogical approaches appropriate for transitioning first-year students may be actively counterproductive for fourth-year learners who have developed the metacognitive sophistication to recognise and resist passive learning environments (Exeter, Ameratunga, Ratima, Morton, Dickson, Hsu, & Jackson, 2010).

Gender differences in this study were nuanced rather than straightforward. No significant difference was found in overall lecture effectiveness perceptions ($t(66) = 1.23$, $p = 0.22$, $d = 0.30$), indicating that dissatisfaction with traditional lecture instruction is a broadly shared experience across genders. However, female students expressed a significantly stronger preference for collaborative learning methods ($t(66) = 2.41$, $p = 0.02$, $d = 0.59$), a medium effect that suggests this difference is pedagogically meaningful. Khadawardi (2025) found that female EFL learners were more likely to deploy cooperative and social learning strategies, a disposition that predisposes them toward collaborative instructional formats and may explain the gender difference in learning preferences observed here. The absence of a significant gender gap in overall lecture dissatisfaction is itself an important finding: it confirms that the case for pedagogical reform is not driven by the preferences of a particular demographic subgroup but reflects a cross-gender consensus among contemporary EFL learners.

The strong student preference for the flipped classroom model (70.6%) is among the most practically significant findings of the study, and it aligns closely with international research on flipped instruction in EFL contexts. Basal (2015) reported that Turkish EFL students who experienced flipped learning demonstrated higher engagement and satisfaction compared to peers in traditional lecture classes. Bergmann and Sams (2012), who pioneered the model, argue that repositioning content delivery as a preparatory out-of-class activity fundamentally transforms contact time into a space for interaction, practice, and feedback — precisely the instructional qualities that participants in the present study identified as absent from their lecture experience. The preference for group discussion and task-based activities (68.2%) and technology-enhanced instruction (63.5%) similarly reflects learners' orientation toward participatory and multimodal learning environments, consistent with the broader shift in EFL pedagogy toward communicative and task-based approaches documented by Nunan (2004) and Littlewood (2007). Jones and Shao (2011) caution, however, that learner preference for interactive and digital formats should not be interpreted deterministically: within-group variation is substantial, and effective pedagogical design must account for the diversity of learner needs rather than assuming uniform digital nativeness. The present study's preference data should therefore be read as indicating a strong majority orientation rather than a universal demand.

Taken together, these findings carry several interlocking implications for EFL pedagogy in post-Soviet higher education. At the instructional level, the evidence points toward strategic pedagogical diversification: the deliberate combination of redesigned lectures — incorporating interactive elements such as think-pair-share activities, embedded comprehension checks, and structured note-taking frameworks — with student-centred alternatives such as flipped instruction, task-based learning, and collaborative projects. At the institutional level, the faculty competence concerns and the gap between policy reform and classroom practice identified in this study underscore the urgency of sustained, competency-based professional development programmes targeting communicative pedagogy, classroom interaction management, and the integration of digital learning tools. At the systemic level, the findings highlight the need for structural conditions — including manageable class sizes, reliable digital infrastructure, and institutional cultures that reward pedagogical innovation — without which individual-level instructional change is unlikely to be sustained or scaled.

Limitations

The following limitations should be considered when interpreting these findings. First, the study was conducted at a single institution, limiting generalizability to other contexts. Second, the quantitative nature of the survey prevented deeper exploration of the nuances in student experiences. Third, the study relied on self-reported perceptions rather than objective measures of learning outcomes. Finally, the cross-sectional design prevents causal inferences about the relationship between teaching methods and student outcomes.

Future research should address these limitations through multi-institutional studies, mixed-methods approaches combining surveys with interviews and observations, longitudinal designs tracking student development over time, and experimental studies comparing learning outcomes across different pedagogical approaches.

Conclusion

This study provides empirical evidence that traditional lecture-based teaching faces significant challenges in meeting the needs of contemporary EFL learners in higher education. The findings reveal widespread dissatisfaction with lectures, citing issues of engagement, interaction, and relevance to language learning goals. Students express clear preferences for more interactive, technology-enhanced, and student-centered approaches that align with their digital native characteristics and communicative learning objectives.

However, these findings should not be interpreted as a wholesale rejection of lectures but rather as a call for pedagogical evolution. The future of EFL education likely lies not in abandoning lectures entirely but in transforming them to incorporate interactive elements, leverage technology effectively, and complement them with diverse teaching methods that promote active learning and authentic language use.

For institutions like Fergana State University and similar contexts globally, these findings underscore the urgency of pedagogical reform. This reform should be comprehensive, addressing not only teaching methods but also faculty development, resource allocation, and institutional culture. Only through such systemic change can higher education institutions ensure that their pedagogical practices align with the needs of 21st-century learners and the demands of global communication.

The question posed in our title—"Do lectures still matter?"—cannot be answered with a simple yes or no. Rather, the evidence suggests that while traditional lectures in their current form may be increasingly obsolete, reimagined lectures that incorporate interactivity, technology, and student agency could still play a valuable role in a balanced pedagogical ecosystem. The challenge for educators and institutions is to navigate this transformation thoughtfully, ensuring that pedagogical innovation serves the ultimate goal of enhancing student learning and preparing graduates for success in an interconnected, multilingual world.

References

Abdulbaki, K., Suhaimi, M., Alsaqqaf, A., & Jawad, W. (2018). The impact of using the lecture method on teaching English at university. *European Journal of Education Studies, 4*(5), 285–302. https://doi.org/10.5281/zenodo.1238871

Basal, A. (2015). The implementation of a flipped classroom in foreign language teaching. *Turkish Online Journal of Distance Education, 16*(4), 28–37. https://doi.org/10.17718/tojde.72185

Benavides, L. M. C., Tamayo Arias, J. A., Arango Serna, M. D., Branch Bedoya, J. W., & Burgos, D. (2020). Digital transformation in higher education institutions: A systematic literature review. *Sensors, 20*(11), Article 3291. https://doi.org/10.3390/s20113291

Bergmann, J., & Sams, A. (2012). *Flip your classroom: Reach every student in every class every day*. International Society for Technology in Education.

Bunce, D. M., Flens, E. A., & Neiles, K. Y. (2010). How long can students pay attention in class? A study of student attention decline using clickers. *Journal of Chemical Education, 87*(12), 1438–1443. https://doi.org/10.1021/ed100409p

Ellis, R. (2003). *Task-based language learning and teaching*. Oxford University Press.

Exeter, D. J., Ameratunga, S., Ratima, M., Morton, S., Dickson, M., Hsu, D., & Jackson, R. (2010). Student engagement in very large classes: The teachers' perspective. *Studies in Higher Education, 35*(7), 761–775. https://doi.org/10.1080/03075070903545058

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). SAGE.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences, 111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Gibbs, G. (2013, November 21). Lectures don't work, but we keep using them. *Times Higher Education*. https://www.timeshighereducation.com/news/lectures-dont-work-but-we-keep-using-them/2009141.article

Goetz, T., Keller, M. M., Lüdtke, O., Nett, U. E., & Lipnevich, A. A. (2020). The dynamics of real-time classroom emotions: Appraisals mediate the relation between students' perceptions of teaching and their emotions. *Journal of Educational Psychology, 112*(6), 1243–1260. https://doi.org/10.1037/edu0000415

Goh, C. (2007). *Teaching listening in the language classroom*. SEAMEO Regional Language Centre.

Göçer, Ş., & Karabatak, S. (2026). The impact of AI-supported online classroom management (AIS-OCM) on attitudes toward English lessons, self-directed online learning, and academic achievement. *Smart Learning Environments, 13*, Article 24. https://doi.org/10.1186/s40561-026-00448-y

Hamamra, B., Khlaif, Z. N., & Mahamid, N. (2026). AI literacy and mediated learner autonomy in ChatGPT-supported EFL writing: A qualitative study at a Palestinian university. *International Journal of Educational Technology in Higher Education, 23*, Article 19. https://doi.org/10.1186/s41239-026-00597-7

Hyland, K. (2006). *English for academic purposes: An advanced resource book*. Routledge.

Irgasheva, S. (2020). Challenges and opportunities in modernizing English language education in Uzbekistan. *Central Asian Journal of Education, 4*(2), 45–62. https://doi.org/10.29258/CAJE/2020-R1.v4n2

Johnstone, A. H., & Percival, F. (1976). Attention breaks in lectures. *Education in Chemistry, 13*(2), 49–50.

Jones, C., & Shao, B. (2011). *The net generation and digital natives: Implications for higher education*. Higher Education Academy. https://www.advance-he.ac.uk/knowledge-hub/net-generation-and-digital-natives-implications-higher-education

Khadawardi, H. A. (2025). Autonomous digital language learning strategies of EFL students beyond the classroom. *Arab World English Journal, 16*(4), 1–18. https://ssrn.com/abstract=5968334

Khoshhaldelijani, Y. (2026). Scanning techniques in EFL reading: A cross-cultural study through the IELTS context. *Language Testing in Asia, 16*, Article 25. https://doi.org/10.1186/s40468-026-00443-7

Littlewood, W. (2007). Communicative and task-based language teaching in East Asian classrooms. *Language Teaching, 40*(3), 243–249. https://doi.org/10.1017/S0261444807004363

Long, M. H. (1996). The role of the linguistic environment in second language acquisition. In W. C. Ritchie & T. K. Bhatia (Eds.), *Handbook of second language acquisition* (pp. 413–468). Academic Press.

Nation, I. S. P., & Newton, J. (2009). *Teaching ESL/EFL listening and speaking*. Routledge.

Nunan, D. (2004). *Task-based language teaching*. Cambridge University Press. https://doi.org/10.1017/CBO9780511667336

Rost, M. (2011). *Teaching and researching listening* (2nd ed.). Pearson Education.

Shi, L. (2026). Exploring students' emotion recognition and teachers' teaching feedback in college foreign language classroom based on AFCNN model. *Scientific Reports, 16*, Article 5657. https://doi.org/10.1038/s41598-026-36747-0

Tapscott, D. (2009). *Grown up digital: How the net generation is changing your world*. McGraw-Hill.

Usher, E. L., & Chen, X. Y. (2026). Toward an understanding of self-efficacy development as a sociocultural process. *Educational Psychology Review, 38*, Article 46. https://doi.org/10.1007/s10648-026-10121-y

Wilson, K., & Korn, J. H. (2007). Attention during lectures: Beyond ten minutes. *Teaching of Psychology, 34*(2), 85–89. https://doi.org/10.1080/00986280701291291

Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice, 41*(2), 64–70. https://doi.org/10.1207/s15430421tip4102_2

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Symbolic and Semantic Manifestations of Colours in Oral Folklore (Based on Nakhchivan Folklore Texts)

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Abstract. *Colour symbolism is a highly relevant topic of research today. The issue of colour symbolism is an interdisciplinary subject of interest to psychologists, theologians, philosophers, and literary scholars. In general, concepts carrying symbolic meaning were perceived much more clearly in ancient cultures. Today, many oral texts associated with symbolically significant concepts and objects are gradually disappearing, which is a natural process. Just as the time-space continuum influences every aspect of human life, it also has a profound impact on symbolism as one of the essential elements of culture. Concepts and objects with symbolic meanings, such as colours, may lose their original significance over time, while others undergo semantic transformation. In other words, an object or phenomenon that conveys a particular meaning within a specific temporal or spatial context may acquire an entirely different meaning as temporal and spatial conditions change. In recent years, interdisciplinary approaches that promote the integration of knowledge from different fields of the humanities have gained increasing importance. The study of colour symbolism is one of these interdisciplinary fields. The scientific interest in understanding the psychological and aesthetic properties of colour has a long tradition. Researchers have examined colour not only from the perspective of physics but also in terms of its influence on the human mind and behaviour. The effects of colours, which surround people from birth, on the human body, nervous system, and psyche continue to be an important subject of modern psychological research. The issue of colour perception within national consciousness has also been extensively explored in contemporary scholarship. The evaluation of colour perception is studied as a socio-cultural phenomenon with distinctive characteristics across different peoples and historical periods. The semantic significance of colours is most effectively examined within the context of folklore texts, where their symbolic meanings are preserved and reflected.*

Keywords: *colour symbolism, green, blue, yellow, grey, folklore texts, symbol*

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Şifahi xalq yaradıcılığında rənglərin simvolik və semantik təzahürləri (Naxçıvan folklor mətnləri əsasında)

Aytən Cəfərova

Xülasə. *Rəng simvolikası müasir dövrdə tədqiqi olduqca aktual olan mövzulardan biridir. Rəng simvolikası məsələsi psixoloqların, ilahiyyatçıların, filosofların və ədəbiyyatşünasların maraq dairəsində olan fənlərarası tədqiqat sahəsidir. Ümumiyyətlə, simvolik məna daşıyan anlayışlar qədim*

mədəniyyətlərdə daha aydın şəkildə dərk edilirdi. Bu gün simvolik əhəmiyyət daşıyan anlayış və əşyalarla bağlı bir çox şifahi mətn tədricən yoxa çıxır ki, bu da təbii prosesdir. Zaman-məkan kontinuumu insan həyatının bütün sahələrinə təsir göstərdiyi kimi, mədəniyyətin mühüm elementlərindən biri olan simvolikaya da ciddi təsir göstərir. Rənglər kimi simvolik məna daşıyan anlayış və əşyalar zaman keçdikcə ilkin mənasını itirə, digərləri isə semantik dəyişikliyə məruz qala bilər. Başqa sözlə, müəyyən zaman və məkan kontekstində konkret məna ifadə edən əşya və ya hadisə zaman və məkan şərtləri dəyişdikcə tamamilə fərqli məna qazana bilər. Son illərdə humanitar elmlərin müxtəlif sahələrinə aid biliklərin inteqrasiyasını təşviq edən fənlərarası yanaşmalar getdikcə daha çox əhəmiyyət qazanır. Rəng simvolikasının öyrənilməsi də bu fənlərarası tədqiqat sahələrindən biridir. Rəngin psixoloji və estetik xüsusiyyətlərinin dərk edilməsinə yönələn elmi marağın uzun tarixi vardır. Tədqiqatçılar rəngi yalnız fizika baxımından deyil, həm də onun insan şüuruna və davranışına təsiri baxımından araşdırmışlar. İnsanları doğulduqları andan etibarən əhatə edən rənglərin insan orqanizminə, sinir sisteminə və psixikasına təsiri müasir psixoloji tədqiqatların mühüm mövzularından biri olaraq qalır. Milli şüurda rəng qavrayışı məsələsi də müasir elmi araşdırmalarda geniş şəkildə tədqiq edilmişdir. Rəng qavrayışının qiymətləndirilməsi müxtəlif xalqlara və tarixi dövrlərə xas xüsusiyyətləri olan sosial-mədəni hadisə kimi öyrənilir. Rənglərin semantik əhəmiyyəti onların simvolik mənalarının qorunub saxlandığı və əks olunduğu folklor mətnləri kontekstində daha səmərəli şəkildə araşdırılır.

Açar sözlər: *rəng simvolikası, yaşıl, mavi, sarı, boz, folklor mətnləri, simvol*

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Introduction

The colour-symbolic system of Azerbaijani culture has evolved through the historical development of the nation, integrating both natural associations and socially significant meanings that emerged from people's lives and activities. Researchers identify three principal functions of colour in culture: communicative, symbolic, and aesthetic (Kosherenkova, 2015, pp. 163–169). The aesthetic function of colour is realized through its ability to express and evoke particular emotions within the process of human aesthetic activity.

Aesthetic activity plays a decisive role in the cultural life of society. Through participation in aesthetic processes involving the purposeful sign-symbolic (artificial) modelling of social emotions, individuals contribute to the formation, development, and transmission of socially significant emotions within society (Voyevodin, 2010, p. 129).

The study of the aesthetic impact of colours is possible only when the historical context is taken into account, encompassing the principal interpretations of the cultural meanings associated with a particular colour within the cultural and historical region under investigation.

Every nation possesses its own distinctive system of colour symbolism, reflected in its folklore, religion, language, and literature. The most vivid manifestations of colour symbolism are found in the images and events preserved in folklore texts.

Folklore characters, people, animals, birds, trees, natural phenomena, and other symbolic elements all contribute to the integrity of the folk worldview. This worldview can be understood through a

system of syntagmatic and paradigmatic relations (Gasimova, 2024). Researcher O. B. Serostanova notes about this: *"A symbol establishes the cause-and-effect relationship between objects. It reflects the unity of the ideal and the material, the whole and the part, space and time, in other words, everything that constitutes the meaning of mythical substance"* (Serostanova, 2020, pp. 23–27).

Colours function as symbols that express the underlying essence of thought through meanings rooted in the deepest and most natural layers of human perception. Regarding the nature of the symbol, it has been argued that "even when it exists only temporarily, a symbol is a reflection and manifestation of what is eternal and true. From this derives the symbol's capacity to acquire multiple meanings, and its power lies in its polysemy and in the dynamic transition from one meaning to another" (Kuznetsova, 2010).

Materials and Methods

At different periods, the symbolic meanings of colours in the Turkic world and in the cultural consciousness of Turkic peoples have attracted the attention of both Turkic and Western scholars. Researchers have sought to explain aspects of Turkic colour symbolism that differ markedly from the symbolic colour systems of other cultures. Among the most significant contributions to this field are the studies of the Hungarian scholar Prof. A. Alföldü and the German Turkologists Annemarie von Gabain and I. Laude-Cirtautas (Laude-Cirtautas, 1961; Annemarie, 1962; Alföldü, 1943).

Folklore texts provide one of the most appropriate sources for revealing the symbolic dimensions of colours. Accordingly, this study examines the semantic manifestations of colours within folklore texts in order to identify and interpret their underlying symbolic meanings. The semantic nuances of the colors green, blue, yellow, and gray are explained primarily through references to folklore texts.

Green has long been regarded as one of the most symbolic and evocative colours in human history, drawing its significance from countless myths, symbols, and cultural traditions. The history of green reflects humanity's perception of nature, its relationship with the natural world, and the enduring pursuit of harmony. In ancient times, green symbolized fertility and the regenerative power of nature. During the Middle Ages in Europe, however, these positive associations gradually shifted, and the colour became linked with evil forces and malevolent spirits. The Renaissance brought about a renewed appreciation of green, associating it with nobility, refinement, and elegance, making it a favoured colour among artists and rulers.

In Ancient Egypt, green possessed profound symbolic significance, representing prosperity and agricultural abundance. Its hieroglyph depicted a papyrus shoot, symbolizing life, vegetation, and rebirth. In wall paintings, the face of Osiris, the god of the underworld, was portrayed in green, emphasizing his association with health, regeneration, and eternal life. In Ancient Greece, the distinction between green and blue was not clearly defined, and the same lexical item could be used to describe both the colour of the sea and that of trees. In Ancient Rome, green was regarded as the colour of Venus, the goddess associated with vineyards, vegetation, and fertility.

During the Middle Ages, green symbolized youth, spring, and love, while at the same time conveying ideas of instability, uncertainty, and danger. In Christian symbolism, green occupied a secondary position and was often associated with the devil, evil forces, and witchcraft.

In 1676, the perception of green changed following the discovery of the colour spectrum. The English scientist Isaac Newton demonstrated that white light could be separated into multiple coloured rays, establishing a new spectral arrangement in which green was positioned between yellow and blue.

Since the beginning of the twentieth century, green has increasingly been associated with nature, peace, and renewal. With the advancement of science, particularly ecology, green has become an

international symbol of environmental awareness, representing nature conservation, ecological responsibility, and efforts to combat environmental pollution (Kukhaleishvili, 2024).

Among the folklore materials collected in Nakhchivan, the symbolic significance of the colour green is less prominent than that of several other colours. In the Great Chilla (*Böyük Çillə*), one of the traditional seasonal rituals, the green rind of the watermelon - its principal ritual attribute - symbolizes ancient people's aspiration for the return of green, renewed nature. In folk belief, the mythological figure Khydyr Nabi (Xıdır Nəbi) is also described wearing green garments.

At the heart of the Khydyr Nabi ritual lies the aspiration for the return of green nature and the renewal of life. In folk belief, the arrival of Khidir marks the beginning of nature's greening, and the fusion of the Khydyr figure with the color green defines the symbolic significance of green in the collective consciousness of the people. More broadly, green begins to assume its symbolic role as early as the Chilla (Midwinter) ceremony, which marks the onset of winter. The green rind of the watermelon, the ritual's most important symbolic offering, reveals the deep-rooted symbolism of this color. From the very beginning of humanity's struggle with the forces of nature, represented by the day of Chilla, green has symbolized the hope for the revival of nature and the enduring struggle to bring life and renewal back to the world.

In addition to symbolizing abundance, the color green is widely associated with youth and renewal. Referring to the etymology of the Azerbaijani word *yaşıl* ("green"), M. Seyidov notes that it consists of the components *yaş* and *-ıl*, explaining: *Here, the word "yaş" is the root, the core, the fundamental element, whereas "ıl" was probably once a productive derivational suffix that later became fossilized, or perhaps the remnant of an unknown word that merged with the root* (Seyidov, 1982, p. 47). Based on Seyidov's interpretation, it becomes necessary to examine the semantic range of the root *yaş*. Such an investigation reveals that in Mahmud al-Kashgari's *Divani-Lughat-it Türk*, the word *yaş* carries the meanings "fresh", "moist", "green vegetation", "greenery", "plant", "to sprout" and "verdure" (Kashgari, Vol. IV, 2006, p. 657).

The symbolism of striving for the return of green nature is also reflected in the sprouting of *samani* (germinated wheat) during the preparations for the Novruz festival. Thus, in all three rituals, the color green carries a sacred meaning as a symbol of new life and the renewal of nature. Green also serves as a defining symbol of renewal in *bayatis*—the short lyrical folk poems that constitute one of the region's principal lyric folklore genres. Consider the following example of a *bayati*:

Mən aşiqəm, göy bağlar,
Göy bağçalar, göy dağlar.
Kimin əzizi ölər,
Yaşıl açar, göy bağlar (Ismayil, 2010, p. 85).

(Meaning: This bayati presents green as a symbol of renewal and the continuity of life, emphasizing nature's enduring cycle despite human loss.)
The third and fourth lines of the *bayati* clearly reflect local customs surrounding weddings and mourning rituals. A green head covering symbolized joy and happiness among women; however, a woman who had lost a loved one was not expected to wear it. Because the color green represented emotions that contrasted with grief and mourning, it was traditionally avoided during funeral ceremonies.

The color green is also closely associated with Islamic values. In Islam, it is regarded as one of the sacred colors and plays a significant role in various religious beliefs and ritual practices.

Green garments and head coverings, by contrast, were traditionally worn during joyful celebrations and festive gatherings. The sacred status of green in Islam is also reflected in the Qur'an in verse 21

of Surah 76 (*Al-Insan*) states: "*They (inhabitants of paradise) will wear garments of fine green silk and heavy brocade, and they will be adorned with silver bracelets. Their Lord will give them a pure drink*" (Bunyadov & Mammadaliyev, 2018, p. 578).

Folklore scholar Bahlul Abdulla argues that green occupies a relatively marginal place in the broader Azerbaijani folkloric tradition: *"….The color green is encountered only rarely in our ancient way of life and in our folklore. Since green became one of the symbolic attributes of Islam, it could not establish a prominent place in the earlier stages of our culture. This association is further evidenced by the traditional depiction of God's angels as wearing green garments*" (Abdulla, 2004).

In the village of Garalar in Kazan, Ankara, it is customary for the Groom participating in the dance performed around the fire to wear a red ribbon on his arm, while the Groom's attendant wears a green ribbon (Kalafat, 2018). It is generally accepted that green occupies a more prominent position than other colours within the Islamic value system. From this perspective, green is regarded as the colour of Islam. Although examples of green in folklore are relatively limited, those that do exist indicate that this colour also held a prominent place in ancient Turkic thought. However, as time passed and the significance of green within Islam deepened, it gradually came to be recognized as the colour associated with the principal symbols and attributes of Islam.

In contemporary folk consciousness, green is perceived as the colour of hope, aspiration, and the fulfilment of wishes. The poet R. Zaka expresses this symbolic dimension of green in one of his poems as follows:

Yaşıl-yaşıl yamaclar,
Könlümün ahəngidir.
Mən yaşıla vurğunam,
Yaşıl murad rəngidir (Khandan, 2004, p. 24).

(Meaning: *In this poem, green symbolizes hope, fulfilled wishes, and emotional harmony, while the poet's devotion to the colour reflects his optimism and deep appreciation of its symbolic significance*.) Among the folklore examples collected in Nakhchivan, one of the most vivid expressions of ritual tradition is "Gülüm hey" songs. One of the these songs contains a stanza, in which the colour green conveys the anonymous poet's joyful mood and hopes for a happy future. In the lines, "*Arxalığın çim yaşıl, gülüm hey, Geymə, gözüm qamaşır, gülüm hey" (Your jacket is bright green, gülüm hey. Do not wear it, it dazzles my eyes, gülüm hey)* as well as in the folk song "Qayna, Samavarım, Qayna" (*Boil, My Samovar, Boil*), the verses *"Samavarın altı yaşıl, Şəninə söz yaraşır*" *(The bottom of the samovar is green. Words of praise süit its honour")* (Farzaliyev & Gasimli, 1994, p. 295) affirm that the colour green symbolizes the aspiration for a fortunate and happy life, as well as the striving inspired by that aspiration.

The ancient symbolism of colours and their interpretation across different cultures are further supported by modern theories that recognize a connection between colour and not only the emotional and volitional state of individuals but also that of an entire community.

The symbolic meaning of the color blue and its lighter shades varies across world cultures. In Western societies, blue is commonly associated with peace, security, stability, harmony, unity, trustworthiness, and self-confidence, while in some cultures it also symbolizes sadness. In Eastern and Asian cultures, blue carries different meanings: in China and Korea, it represents immortality, whereas in India it is regarded as a symbol of heaven and spirituality. In Ancient Egypt, where blue pigments were first developed during the third millennium BCE, the color was associated with the sky and the Nile River, the source of fertility and prosperity. In contrast, among many Latin American cultures, blue is traditionally linked with mourning rituals. Similarly, in Ancient Rome, blue was

viewed unfavorably, being associated with black and, consequently, with mourning, death, and at times even ugliness.

At the beginning of the second millennium, particularly from the early twelfth century onward, blue lost its status as a secondary and rarely used color in Western European culture, as well as ın Ancient Rome and the early Middle Ages. Attitudes toward blue changed dramatically: it became fashionable and, according to some scholars, came to be regarded as the most beautiful of all colors. As a result, blue acquired a wide range of symbolic interpretations and came to represent truth, divine power, pure wisdom, and holiness.

In contemporary culture, blue is widely recognized as a symbol of heaven and eternity, as well as of kindness, loyalty, stability, and love.

In Azerbaijani folklore, blue likewise carries a variety of symbolic meanings. In the folklore of Nakhchivan, however, it most commonly expresses sorrow and suffering, while the image of a place being enveloped in blue symbolizes the intensification of pain and hardship.

Among the collected folklore materials, the color blue exhibits profound sacred significance rooted in early folk beliefs. As noted in the previously discussed *bayati* concerning the symbolism of green, blue functions as a marker of mourning, grief, and sorrow. The lines, "Kimin əzizi ölər, yaşıl açar, göy bağlar" *(Whoever loses a loved one. Unwear greens and put on blues)* portray blue as a symbolic color that embodies suffering and accompanies the heart consumed by pain. This symbolism is also preserved in the Azerbaijani idiom "Gününü göy əskiyə düyünləmək (və ya bürümək)" (wbw translatıon: *to wrap (or tie) one's days in a blue cloth)* which means "to make one's life miserable". The expression reflects the ancient belief that blue cloth symbolized sorrow, pain, and mourning. As Jafarova (2022, p. 83) explains: "*Gününü göy əskiyə düyünləmək (və ya bürümək) (to wrap (or tie) one's days in a blue cloth)* means *to make one's life dark*; both blue and black were symbolic colors associated with mourning rituals, particularly among the Turks. Today, black is more commonly recognized as the color of grief, mourning, and bereavement. However, among the ancient Turks, blue likewise carried these symbolic associations."

It should also be noted that in the symbolic systems of some cultures, blue and green are understood as representing similar concepts, whereas in others they are perceived as contrasting colors. Such contrasting symbolism can likewise be observed in the folklore of Nakhchivan. Consider the following *bayati*:

Əzizinəm, göy bağlar,
Göy bağçalar, göy bağlar.
Kimin əzizi ölər,
Yaşıl açar, göy bağlar (Ismayil, 2010, p. 85).

The references to blue in the opening lines of the *bayati* serve as a prelude to the poem's central idea expressed in the final two lines: "Kimin əzizi ölər, yaşıl açar, göy bağlar" *(Whoever loses a loved one. Unwear greens and put on blues)* The phrases *"blue gardens"* and *"blue woods"* serve as poetic images through which the anonymous folk poet depicts gardens that have fallen into ruin and desolation. In this context, *"blue gardens"* symbolize a life that has been shattered and devastated. Another *bayati* illustrates this symbolism even more clearly:

Əzizim, nə dən bağlar,
Göy geymiş nədən bağlar?!
Əkmə namərd zəmisin,
Nə bitər, nə dən bağlar (Farzaliyev & Gasımlı, 1994, p. 282).

Here, too, the image of the "Göy geyinmiş bağ" (*garden wraped in blue)* functions as a powerful symbol of a life that has been shattered and left in ruin.

A. M. Panchenko likewise notes that among the Slavic peoples, blue was associated with death, observing that *"in religious poetry, blue is perceived as the color of death"* (Panchenko, 1968, pp. 3–15).

In folklore texts, blue symbolizes not only pain and suffering but also serves as a portent of misfortune in ancient belief. This function is reinforced by the contexts in which the color appears throughout folklore narratives. Blue typically emerges at moments when success or happiness is anticipated, signaling instead the onset of disappointment or adversity. This symbolism is evident even in folklore texts that initially convey a joyful mood:

Stol üstdə göy daraq,
Yarımı gördüm bayaq.
Yeridim, çatammadım,
Qurusun belə ayaq (Farzaliyev & Gasımlı, 1994, p. 292).

In this *bayati*, the blue symbol, rooted in ancient mythological belief, functions as an emblem of misfortune, preventing the lyrical hero, who longs to fulfill his desire, from being reunited with his beloved.

The association of blue with pain, grief, and mourning is also evident in the *Book of Dede Korkut*. As Bunyadov (2007, p. 435) observes, *"a person in mourning decorated the household not only in black but also in blue and wore blue garments as a sign of bereavement. When Bamsi Beyrek returns home after escaping captivity, he finds his sister weeping as she carries water from a spring. Asking why she is crying, he also inquires*, *"If anyone asks about the black-and-blue tent, whose is it?"* She sorrowfully replies, *"If anyone asks about the black-and-blue tent, it belongs to my brother Beyrek. Since my brother Beyrek departed, I have had no joy."* Likewise, when Uruz, who has been captured by the enemy, speaks to his father Salur Kazan, who has come to rescue him, he says: "*Let my mother wear blue and wrap herself in black; let her mourn for me among the mighty Oghuz people."*

In some contexts, however, a blue tent or blue cave is presented as a symbol of good fortune and divine protection. According to traditional folk belief, God dwells in the Blue Tent, a motif reflected in folklore texts. This idea is expressed in a traditional blessing: "*Göy çadırın yəəsi dadaa yetişsin!*" (*May the Lord of the Blue Tent come to your aid!)* (Jafarli et al., 2011, p. 81). Folklore scholar Bahlul Abdulla likewise notes that, in the epic tradition, beings sent from Heaven by God are imagined as blue in color. This supports the view that the sacredness of blue derives from its association with the sky and the heavens. Nevertheless, in the folklore of Nakhchivan, blue is predominantly portrayed as a symbolic color expressing grief, sorrow, and emotional suffering.

The Russian folklorist A. M. Panchenko also discusses the symbolism of blue in Russian folklore, noting that in religious poetry it is associated with death and serves as a symbol of continuity. He further observes that blue is regarded as the color of the realm inhabited by malevolent spirits (Panchenko, 1968, p. 33).

In shamanic tradition, blue likewise conveyed meanings of mourning, grief, and suffering. To express these associations, shamans wore blue garments as part of their ritual attire. *"the shamans' skirts were made of black and blue paper materials, while their tunics were invariably blue."* (*Simvolika kultov i ritualov narodov zarubejnoy Azii*, 1980, s.13).

Although the sacred aspects of blue can be observed in the folklore of Nakhchivan, its association with malevolent spiritual forces inherited from ancient tradition is more prominent. Accordingly,

objects characterized as blue in these folklore texts symbolically embody the emotional suffering, grief, and anguish experienced by the protagonists.

The history and symbolism of the color yellow are closely linked to gold, which in the ancient world was regarded as solidified or petrified sunlight. This association is evident in the temples and sacred monuments of Ancient Egypt, where gold ornaments were abundant and walls were often painted yellow. Across ancient civilizations, the worship of the sun occupied a central place in religious belief. Because the sun provided warmth and light, it was revered as a deity, and consequently the color yellow was held in high esteem. The sun was regarded as the ruler of light and abundance and the adversary of darkness and evil. However, in many Islamic societies, yellow did not enjoy the same prestige and, much like in several European cultures, came to be associated with betrayal, falsehood, and deceit. It was also considered the color of illness and old age.

In many Western cultures, yellow is most commonly associated with joy, energy, warmth, and vitality. In China, however, it has traditionally symbolized imperial authority and power, while also representing wealth, wisdom, and honor. In India, yellow is associated with the god Vishnu and is regarded as a symbol of holiness and knowledge.

Overall, yellow is the brightest and most luminous color in the visible spectrum. It is widely recognized as a symbol of the sun, joy, energy, intellect, and optimism.

In Azerbaijani folk symbolism, however, yellow occupies a distinct position. Within traditional folk culture, it is predominantly perceived as a color carrying pessimistic and unfavorable connotations.

Various Turkic peoples have attributed different symbolic meanings to the color yellow. In ancient Turkic thought, yellow was generally regarded as a symbol of compassion, vigorous activity, and humanism. This symbolism is reflected in the names of several Turkic groups, many of which incorporate the word *sarı* ("yellow"). For example, the Uyghurs have historically referred to themselves as the *Yellow Uyghurs*. If yellow indeed signified humanism and dynamic vitality in early Turkic culture, this designation may be understood as expressing those valued qualities. Among the Göktürks, yellow was considered the color of God. In this context, five of the ten Göktürk tribes formed the state of the Yellow Turkesh, while the remaining five established the Black Turkesh. The Yellow Türgesh regarded themselves as the nobler and more ancient lineage. A similar belief existed among the Buryats, who also considered yellow to be the color of the divine. The belief that the world originated from the color yellow gave rise to a set of ideas linking yellow with the earth and fertility. Because the earth was seen as the source of growth and abundance, these qualities were symbolically transferred to women: the mother was associated with yellow, while the male principle was represented by silver. According to the mythological beliefs of these peoples, the remote ancestor of Genghis Khan originated from the yellow rays of the sun. This belief, in turn, gave rise to the conviction that the right to rule belonged exclusively to his lineage (Abdulla, 2004, p. 432).

"*The symbolic interpretation of yellow also differs in geosymbolism, where colors are used to designate the cardinal directions. Although yellow, as one of the four symbolic colors of the world, is regarded by many ethnic groups as representing the center, among others it denotes different directions. For example, among the American Indians yellow symbolizes the west, among the peoples of India it represents the south, and among the Kalmyks it signifies the North.*" (Abdulla, 2000, p. 432).

The use of the color yellow in the Nakhchivan folklore texts examined in this study suggests that, as in the folklore of many other Turkic peoples, yellow is associated with illness, frailty, and, at times, the approach of death. Consider the following *bayati*:

Gecə keçdi qaraldan,
Seçmərəm səni maraldan.
Nə dərdim var, nə qəmim,
Sənsən məni saraldan (Jafarli & Babayev, 2005, p. 64).

(*Meaning: This bayati presents turning yellow (saralma) as a metaphor for emotional suffering, expressing how longing and unfulfilled love can weaken a person both physically and spiritually.)*
As these examples demonstrate, human sorrow and emotional suffering are conventionally expressed through the verb *saralmaq* ("to turn yellow"). It is therefore no coincidence that Azerbaijani has the idiomatic expression *eşqdən saralıb-solmaq* (*to turn yellow and pale because of love*), which denotes suffering caused by unfulfilled love. Derived from the adjective *sarı* (yellow), and i*n many contexts* the verb *saralmaq ("to turn yellow") departs from its literal meaning and comes to denote a state of suffering, grief, emotional distress, or a visible change in one's appearance caused by sorrow.*

This symbolic usage is also found in the Nakhchivan folktale "*Gold, Silver, and Copper"*, where *saralmaq* conveys deep sorrow and emotional distress: *"My God, because of me, a family has been left helpless and without its protector. Bearing this grief has caused my rosy complexion to fade and turn yellow. I beg You, let me become a source of support to the family that has been left without its protector"* (Farzaliyev & Gasimli, 1994, p. 79).

In addition to these meanings, folklore texts also attribute the symbolism of misfortune to the color yellow. In relatively recent folklore examples, the belief that a yellow shawl, a yellow pouch, or a yellow sack brings bad luck has become poetically embedded in the folk song *Gülüm hey*.

Ay sarı kisə ad oldu, gülüm hey,
Dağıldı bərbad oldu, gülüm hey.
Bu yar bizə yar olmaz, gülüm hey,
Üstümüzə ad oldu, gülüm hey (Farzaliyev & Gasimli, 1994, p.294).

The motif of misfortune underlying the text is conveyed through the symbolic image of the *yellow pouch* (sarı kisə). In this example, yellow once again functions as a symbol of bad luck. A similar association appears in a folk belief recorded among Western Azerbaijanis: *"Nothing yellow, not even a piece of yellow cloth, was brought near a forty-day-old infant. If someone did, people believed the child would develop jaundice"* (Suleymanova, 2024, p. 123).

Gray is an intermediate shade between black and white and is generally perceived as a neutral and calming color. In the RGB color model, which consists of the three primary colors - red, green, and blue - gray is produced by mixing these colors in equal proportions.

During the Middle Ages, gray was known as the color of undyed wool. Clothing made from this material was worn primarily by peasants and the poor. Consequently, gray came to symbolize simplicity, poverty, and humility, and it was also the color traditionally worn by monks. During the Renaissance and the Baroque periods, gray assumed an increasingly important role in the visual arts.

Gray carries a wide range of meanings and associations that vary according to cultural and contextual factors. It is often regarded as a neutral color that neither evokes strong emotions nor attracts excessive attention. Positioned between black and white, it symbolizes balance and compromise, representing agreement achieved through mutual concession. Gray is also associated with elegance, refinement, and classical style, which explains its frequent use in business and formal settings. By avoiding excessive brightness and ostentation, it conveys modesty and restraint, while also evoking reliability, stability, and quiet strength.

The semantic symbolism of both white and black in general, and in the folklore of Nakhchivan in particular, has already been discussed above. Nevertheless, this issue merits further consideration. In Nakhchivan folklore, white is associated with victory, happiness, and the aspiration for a prosperous life. Black, by contrast, may symbolize misfortune and ill fate, but it can also embody greatness, wisdom, and primordiality - meanings that derive from ancient Turkic thought. If gray is understood as a mixed color resulting from the fusion of white and black, then the semantic associations of both colors inevitably shape its symbolism. In other words, gray inherits symbolic features from both white and black, although its connotations are predominantly favorable. For example, in the ritual expression *Boz Ay* (Gray Month), the symbolic meaning of gray is positive because it is associated with the arrival of spring. Since *Boz Ay* is regarded as the month that leads to Novruz, it symbolizes an auspicious and hopeful period of transition. At the same time, in certain contexts where white and black are associated with misfortune, this perception has naturally influenced the symbolism of grey as well. This can be observed in the mythological text "*Boz Ay" (Grey Month): "…The Grey Month borrowed most of its days from the other months, that's why it is so mixed. It took its cold days from the winter months, its warm days from summer, and its rainy days from spring and autumn…"* (Jafarli et al., 2011, p. 27). As is evident from this passage, ancient belief regarded the Grey Month as a *mixed* month. The primary reason for this mixed character lies in the fact that the colour grey is formed by the combination of white and black. In other words, within traditional ethnic thought, winter and spring are symbolically associated with the colours black and white, respectively. From this perspective, the ambiguous rhythm of grey emerges from the interaction of these two opposing colours. In folk vocabulary, talking back to an elder is expressed through the idiom *"üzünə ağ olmaq"* (to defy someone), while experiencing shame before others because of offensive words or disgraceful actions is metaphorically conveyed by the expression "üzü qara olmaq" (to be disgraced). When a conversation gets out of hand or becomes heated, and one person begins speaking harshly or raising their voice at another, this is described by the phraseological expression "üzünü bozartmaq" (to snap at someone). Thus, the expression **"**üzünü bozartmaq" (to lose one's temper) carries the same semantic meaning as the mixed nature of the Boz Ay (Grey Month) discussed above. Just as the Grey Month alternates between cold and warm days, reflecting instability and change, a person in a state of anger likewise experiences emotional fluctuation - at times remaining calm, and at other times losing self-control and speaking harshly to the other person. In this sense, the symbolism of grey conveys emotional inconsistency, tension, and the transition between restraint and outburst.

During the Khydyr Nabi ceremony, celebrated in the first ten days of *Kiçik Çillə (Little Chilla*), which constitutes a ritual cycle, the performance of various rituals is considered appropriate. Alongside these ritual practices, elements rooted in ancient belief concerning the figure of Khydyr Nabi himself also attract attention in folk thought. One of these elements reveals the sacramental symbolism of the colour grey. For example, according to folk belief, Khydyr Nabi is dressed in green, while his horse is grey. Similar motifs concerning Khydyr's grey horse also appear in the examples of Anatolian folk beliefs collected by Hayrettin İvgin: "*Khydyr is regarded as a force who comes to the aid of those in distress on his grey horse, bringing prosperity to people and life, vitality, and renewal to nature. We continue to observe the rituals associated with Khydyrellez Day - customs that have survived for centuries in the form of a festival celebrating this enduring force, who is believed to live until the Day of Judgment with his grey horse…*" (İvgin, 2019, p. 196). The information collected from the Nakhchivan region confirms the existence of this belief. According to local tradition, a strong wind blows for three days before Khydyr's arrival and for three days afterwards. People say that this wind is raised by the dust kicked up by the hooves of Khydyr's grey horse. The force of the dust stirred up by the horse's hooves, and the powerful wind it generates, is symbolically associated with the horse's grey colour. Earlier, we noted that in folk tradition the colour grey carries a chaotic symbolism associated with anger and fury, reflected in the verb *bozarmaq* ("to turn grey"). A similar symbolic association can be observed here: the strong wind is believed to originate from the powerful kick of the grey horse, whose hooves raise clouds of dust. Thus, the symbolic meaning of the colour grey

extends beyond emotional states to encompass force, movement, and the dynamic energy embodied by Khydyr's sacred horse.

In the Ordubad district of the Nakhchivan Autonomous Republic, women wear grey headscarves during mourning ceremonies. Thus, in addition to the mourning and bereavement symbolism traditionally associated with black in modern times, this function is also extended to the colour grey. Regarding the characterization of grey as the colour of mourning rituals, the late folklorist B. Abdulla writes: *"Historical sources indicate that, even in ancient times, khans had a Grey Chamber (Boz Otaq). This chamber was primarily reserved for mourning ceremonies."* (Bunyadov, 2007, p. 431).

Results and Discussion

This article has examined the profound sacramental significance of colours and their symbolic functions in folklore. It is well known that colour occupies a distinctive place within the system of features that characterize objects. For modern people, a change in an object's colour does not alter its essential nature. For ancient people, however, an object's natural colour possessed a deep sacramental meaning of its own. Some of these symbolic associations, which express the meanings of various objects and phenomena, preserve traces of ancient culture. Others have acquired new meanings in contemporary life after gradually losing their original symbolism, while some have almost entirely lost their symbolic function. It must be acknowledged that if the colours of the clothes we wear in everyday life still carry meaning today, then the symbolism of colour undoubtedly has very deep historical roots.

Conclusion

In the folklore of Nakhchivan, green symbolizes the ideas of renewal and living nature. This thought is particularly emphasized in ritual practices. Examples include the green watermelon cut during Great Chilla, the belief that Khydyr Nabi wears a green cloak, and samani (sprouted wheat), which represents the revival of nature. Together, these elements demonstrate the association of green with nature and the beginning of new life.

In the folklore collected from Nakhchivan, blue most commonly symbolizes misfortune, mourning, and bereavement. Expressions such as "blue comb", "blue tent", and "blue shawl", which frequently occur in folklore, denote objects that prevent the protagonist from achieving his or her desired goal. The symbolism attached to these objects shows that blue primarily represents sorrow, grief, and emotional suffering.

Compared with the other colours discussed above, yellow appears relatively infrequently in Nakhchivan folklore. Within the region's folkloric worldview, as in the broader Turkic cultural tradition, yellow is generally regarded as a symbol of misfortune, spiritual exhaustion, and illness.

Like yellow, grey occurs only rarely in the folklore of Nakhchivan. Nevertheless, it has been possible to identify aspects of its symbolism within ritual beliefs. In addition to representing anger and resentment, grey was formerly associated with mourning rituals.

In general, colours function as symbolic markers in traditional folk culture. Their presence in folklore and ritual practices, where they acquire diverse symbolic meanings, provides valuable insight into the worldview and cultural thought of ancient communities.

References

Abdulla, B. (2004). The Semantic Symbolism of the Color White in the *Book of Dede Korkut*. *The World of Dede Korkut*. Öndər Publishing.

Annemarie, G. (1962). The Symbolic Meanings of Colors. *Acta Orientalia Hungarica*, Vol. XV (1–3). Turkish translation by Semih T. (1968). *Journal of Turkology*, Vol. 3. Ankara: Faculty of Languages, History and Geography Publications, 107–113.

Alföldü, A. (1943). Dual Kingship among the Turks. In *Proceedings of the Second Turkish History Congress* (20–25 September 1937). Kenan Printing House, 507–519.

Bunyadov, T. (Ed.). (2007). Azerbaijani Ethnography (Vol. III, 3 vols.). Şarg-Garb Publishing.

Bunyadov, Z., Mammadaliyev, V. (Trans.). (2018). The Holy Qur'an: Azerbaijani Translation (Revised 17th ed.). Nurlar Publishing.

Jafarova, A. (Ed.). (2022). Nakhchivan Paremiological Units: Idioms, Proverbs, and Sayings. Ajami Publishing.

Jafarli, M., Safarov, Y., Babayev, R. (Eds.). (2011). Anthology of Nakhchivan Folklore (Vol. 2 of 3 vols.). Ajami Publishing.

Jafarli, M., Babayev, R. (Eds.). (2005). *The Road Leads to Ordubad: A Collection of Folklore*. Ajami Publishing.

Aliyev, K. (2011). The Poetics of the Epic: *Dede Korkut* and *Koroghlu*. Elm ve Tahsil Publishing.

Farzaliyev, T., Gasimli, M. (Eds.). (1994). *Anthology of Azerbaijani Folklore: Nakhchivan Folklore* (Vol. 1). Sabah Publishing.

Kalafat, Y. (2018). Memorates and the Astral World: The Mythological Dimension. Berikan Publishing.

Kashghari, M. (2006). Dīwān Lughāt al-Turk (4 vols., Vol. II). Ozan Publishing.

Kashghari, M. (2006). Dīwān Lughāt al-Turk (4 vols., Vol. III). Ozan Publishing.

Kaşğari, M. (2006). Dīwān Lughāt al-Turk (4 vols., Vol. IV). Ozan Publishing.

Kosherenkova, O. (2015). The Symbolism of Color in Culture. *Analytics of Cultural Studies*, No. 2(32), 163–169.

Kuznetsova, V. (2010). Dictionary of Philosophical Terms. Nauchnaya Redaktsiya; INFRA-M.

Kukhaleyshvili, N. (2024). *The History and Symbolism of the Color Green. Lingua*, No. 99 (September–October). Available at: http://lingva.ffl.msu.ru/2024/10/история-и-символика-зелёного-цвета/

Khandan, R. (2004). *Selected Works*. Sharg-Garb Publishing.

Ismayil, M. (Ed.). (2010). The People's Word, the Nation's Memory: A Collection of Folklore. Elm Publishing.

İvgin, H. (2019). *Deep Mythology*. Kultur Ajans Publishing.

Gasımova, P. (2024). The Ideological Essence of Folklore. *Scientific Work*, Vol. 18, No. 11, 71–74. https://doi.org/10.36719/2663-4619/108/71-75

Laude-Cirtautas, I. (1961). The Use of Color Terms in the Turkic Dialects. *Ural-Altaische Bibliothek*. Wiesbaden.

Panchenko, A. (1968). On Light in the Ancient Literature of the Eastern and Southern Slavs. *Proceedings of the Department of Old Russian Literature (TODRL)*.

Serostanova, O. (2020). Symbolic Forms of Constructing Reality in Russian Folk Tales. *Science. Art. Culture*, 4(28), 23–27.

Seyidov, M. (1989). Reflections on the Ethnic Origins of the Azerbaijani People. Yazıçı Publishing.

The Symbolism of Cults and Rituals of the Peoples of Foreign Asia. (1980). Nauka Publishing.

Suleymanova, L. (Ed.). (2024). *Folklore of Western Azerbaijan* (Vol. I). Elm ve Tahsil Publishing.

Voyevodin, A. (2010). *Aesthetic anthropology: A monograph*. RIO LQUVD named after E. A. Didorenko.

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Süni intellekt texnologiyalarının ağıllı istehsal sistemlərində tətbiqi

Zəminə Əsgərova

Xülasə. *Müasir sənaye müəssisələrində rəqəmsal transformasiya istehsal proseslərinin təşkili, idarə olunması və optimallaşdırılması üçün yeni texnoloji imkanlar yaradır. Bu prosesdə süni intellekt texnologiyaları ağıllı istehsal sistemlərinin əsas komponentlərindən biri kimi çıxış edir. Maşın öyrənməsi, dərin öyrənmə, kompüter görməsi, intellektual robotlar və rəqəmsal əkiz texnologiyaları istehsal avadanlıqlarının vəziyyətinin monitorinqinə, məhsul keyfiyyətinin qiymətləndirilməsinə, texniki nasazlıqların əvvəlcədən müəyyən edilməsinə və resurslardan səmərəli istifadəyə imkan verir. Tədqiqatın məqsədi süni intellekt texnologiyalarının ağıllı istehsal sistemlərində tətbiq istiqamətlərini, onların əməliyyat səmərəliliyinə təsirini və tətbiq zamanı meydana çıxan əsas problemləri sistemləşdirməkdir. Tədqiqatda elmi ədəbiyyatın təhlili, müqayisəli yanaşma və konseptual ümumiləşdirmə metodlarından istifadə edilmişdir. Təhlil göstərir ki, süni intellekt istehsal proseslərinin avtomatlaşdırılması ilə yanaşı, məlumatlara əsaslanan qərarların qəbul edilməsini, proqnozlaşdırıcı texniki xidməti və istehsal sistemlərinin çevikliyini də gücləndirir. Bununla belə, məlumatların keyfiyyəti, sistemlərin inteqrasiyası, kibertəhlükəsizlik, ilkin investisiya xərcləri və alqoritmlərin izaholunma imkanları texnologiyanın geniş tətbiqini məhdudlaşdıran amillər olaraq qalır. Məqalədə süni intellektin sənaye müəssisələrində səmərəli tətbiqi üçün mərhələli rəqəmsallaşma, etibarlı məlumat infrastrukturu və insan-maşın əməkdaşlığına əsaslanan yanaşma təklif edilir.*

Açar sözlər: *süni intellekt, ağıllı istehsal, maşın öyrənməsi, Sənaye 4.0, proqnozlaşdırıcı texniki xidmət, rəqəmsal əkiz, istehsalın optimallaşdırılması*

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Application of Artificial Intelligence Technologies in Smart Manufacturing Systems

Zamina Asgarova

Abstract. *Digital transformation in modern industrial enterprises creates new technological opportunities for organizing, managing, and optimizing production processes. In this context, artificial intelligence technologies serve as one of the key components of smart manufacturing systems. Machine learning, deep learning, computer vision, intelligent robots, and digital twin technologies enable the monitoring of production equipment, the assessment of product quality, the early detection of technical failures, and the efficient use of resources. The aim of this study is to systematize the application areas of artificial intelligence technologies in smart manufacturing systems, their impact on operational efficiency, and the main challenges encountered during their*

implementation. The study employs scientific literature review, a comparative approach, and conceptual synthesis. The analysis indicates that artificial intelligence not only facilitates the automation of production processes but also strengthens data-driven decision-making, predictive maintenance, and the flexibility of manufacturing systems. Nevertheless, data quality, system integration, cybersecurity, initial investment costs, and the explainability of algorithms remain factors limiting the widespread adoption of these technologies. The article proposes a gradual digitalization strategy, reliable data infrastructure, and an approach based on human–machine collaboration to support the effective implementation of artificial intelligence in industrial enterprises.

Keywords: *artificial intelligence, smart manufacturing, machine learning, Industry 4.0, predictive maintenance, digital twin, production optimization*

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Giriş

Sənaye sektorunda rəqabətin güclənməsi, məhsul çeşidinin genişlənməsi və istehlakçı tələblərinin dəyişməsi istehsal müəssisələrini daha çevik, səmərəli və dayanıqlı idarəetmə modellərinə keçməyə təşviq edir. Ənənəvi istehsal sistemləri əsasən əvvəlcədən müəyyən edilmiş əməliyyat ardıcıllığına və insan tərəfindən idarə olunan nəzarət mexanizmlərinə əsaslandığı halda, müasir ağıllı istehsal sistemləri real vaxt məlumatlarının toplanması, təhlili və həmin məlumatlar əsasında qərarların formalaşdırılması ilə səciyyələnir. Bu transformasiyanın əsas texnoloji istiqamətlərindən biri süni intellektin sənaye proseslərinə inteqrasiyasıdır.

Süni intellekt kompüter sistemlərinin məlumatlardan öyrənmək, müəyyən nümunələri aşkar etmək, nəticələri proqnozlaşdırmaq və konkret məqsədlərə uyğun qərarların hazırlanmasına kömək etmək imkanlarını əhatə edir. İstehsal sahəsində bu imkanlardan avadanlıqların texniki vəziyyətinin qiymətləndirilməsi, qüsurların müəyyənləşdirilməsi, istehsal qrafiklərinin optimallaşdırılması və təchizat zəncirinin idarə olunması kimi müxtəlif istiqamətlərdə istifadə edilir. Tercan və Meisen (2022) tərəfindən aparılan sistematik icmal maşın öyrənməsi və dərin öyrənmə metodlarının istehsalda proqnozlaşdırıcı keyfiyyət təminatı üçün əhəmiyyətini göstərir.

Ağıllı istehsalın inkişafı yalnız ayrı-ayrı əməliyyatların avtomatlaşdırılması ilə məhdudlaşmır. Əsas məqsəd avadanlıqlar, istehsal xətləri, informasiya sistemləri və insan resursları arasında məlumat mübadiləsini gücləndirmək, istehsalın ümumi vəziyyəti haqqında daha dolğun təsəvvür yaratmaqdır. Süni intellekt bu sistemlərdə müxtəlif mənbələrdən əldə olunan məlumatların təhlilinə və əməliyyatların daha əsaslandırılmış şəkildə idarə edilməsinə şərait yaradır. Müasir tədqiqatlarda onun istehsalın planlaşdırılması, proseslərin optimallaşdırılması, keyfiyyətə nəzarət, texniki xidmət və avtomatlaşdırılmış yığım sahələrində tətbiqi xüsusi qeyd edilir (Balayev və b., 2022).

Mövzunun aktuallığı sənaye müəssisələrinin məhsuldarlığı artırmaq, istehsal itkilərini azaltmaq və dəyişən bazar tələblərinə daha sürətli uyğunlaşmaq ehtiyacı ilə bağlıdır. Bununla yanaşı, süni intellektin tətbiqi yalnız texniki imkanların mövcudluğundan asılı deyil. Məlumatların etibarlılığı, kadrların rəqəmsal bacarıqları, sistemlərin qarşılıqlı uyğunluğu və təhlükəsizlik tələbləri də mühüm əhəmiyyət daşıyır.

Tədqiqatın məqsədi süni intellekt texnologiyalarının ağıllı istehsal sistemlərində tətbiq imkanlarını və əsas funksional istiqamətlərini müəyyənləşdirmək, onların potensial üstünlüklərini və tətbiq məhdudiyyətlərini elmi ədəbiyyat əsasında təhlil etməkdir.

Bu məqsədə uyğun olaraq aşağıdakı vəzifələr müəyyən edilmişdir:

- ağıllı istehsal sistemlərinin texnoloji xüsusiyyətlərini izah etmək;
- süni intellektin əsas tətbiq istiqamətlərini sistemləşdirmək;
- istehsalın səmərəliliyi və məhsul keyfiyyətinə mümkün təsirləri qiymətləndirmək;
- texnologiyanın tətbiqi zamanı meydana çıxan texniki, iqtisadi və təşkilati problemləri müəyyənləşdirmək;
- sənaye müəssisələri üçün tətbiqə dair praktik tövsiyələr hazırlamaq.

Metodlar

1. Tədqiqatın metodoloji əsasları

Süni intellekt texnologiyalarının ağıllı istehsal sistemlərində tətbiqinin araşdırılması kompleks metodoloji yanaşma tələb edir. Bu, həmin texnologiyaların yalnız texniki xüsusiyyətlərinin deyil, eyni zamanda istehsal proseslərinin idarə edilməsinə, məhsul keyfiyyətinə, resurslardan istifadəyə, texniki xidmətə və müəssisələrin ümumi fəaliyyətinə təsirinin öyrənilməsi ilə əlaqədardır. Tədqiqatın metodoloji əsasını ağıllı istehsal sistemləri, Sənaye 4.0, maşın öyrənməsi, dərin öyrənmə, kompüter görməsi və rəqəmsal əkizlər üzrə elmi ədəbiyyatın təhlili təşkil edir (Carvalhoet al., 2019).

Araşdırmada nəzəri və analitik metodlardan istifadə edilmişdir. Bu metodlar süni intellektin istehsal proseslərində tətbiq imkanlarını müəyyənləşdirməyə, müxtəlif texnoloji həllərin funksional xüsusiyyətlərini müqayisə etməyə, onların üstünlüklərini və məhdudiyyətlərini sistemləşdirməyə imkan verir. Tədqiqatın əsas istiqamətləri istehsal proseslərinin optimallaşdırılması, avadanlıqların texniki vəziyyətinin proqnozlaşdırılması, məhsul keyfiyyətinə nəzarət, robotlaşdırma və resursların idarə edilməsidir.

Metodoloji yanaşmanın seçilməsində tədqiqatın məqsədi əsas götürülmüşdür. Məqalənin məqsədi konkret müəssisədə süni intellekt sisteminin sınaqdan keçirilməsi deyil, mövcud elmi bilikləri təhlil etmək və onların əsasında ağıllı istehsalda süni intellektin tətbiq istiqamətlərini ümumiləşdirməkdir. Buna görə tədqiqatda sistemli ədəbiyyat təhlili, təsviri təhlil, müqayisəli təhlil, təsnifat, konseptual ümumiləşdirmə və analitik qiymətləndirmə metodları əsas yer tutur (Dalzochioet al., 2020).

2. Elmi ədəbiyyatın təhlili metodu

Elmi ədəbiyyatın təhlili tədqiqatın əsas metodlarından biri kimi seçilmişdir. Bu metod süni intellekt texnologiyalarının sənaye müəssisələrində tətbiqi ilə bağlı mövcud nəzəri yanaşmaların, elmi nəticələrin və texnoloji inkişaf istiqamətlərinin öyrənilməsini nəzərdə tutur. Ədəbiyyat təhlili vasitəsilə ağıllı istehsal sistemlərinin formalaşmasında süni intellektin rolu, onun tətbiq sahələri və bu sahədə mövcud problemlər haqqında məlumatlar ümumiləşdirilmişdir.

Mənbələrin müəyyənləşdirilməsi zamanı süni intellekt, ağıllı istehsal, Sənaye 4.0, maşın öyrənməsi, proqnozlaşdırıcı texniki xidmət, avtomatlaşdırılmış keyfiyyət nəzarəti və rəqəmsal əkizlər mövzularına diqqət yetirilmişdir. Elmi jurnallarda dərc olunan məqalələr, sistematik icmallar və istehsal texnologiyalarına dair tədqiqatlar əsas məlumat mənbələri kimi nəzərdə tutulmuşdur. Mənbələrin seçilməsi zamanı mövzuya uyğunluq, elmi əsaslandırma və araşdırılan texnologiyaların istehsal prosesləri ilə əlaqəsi nəzərə alınmışdır.

Ədəbiyyatın təhlili zamanı ayrı-ayrı müəlliflərin yanaşmaları müqayisə edilmiş, müxtəlif istehsal sahələrində süni intellektin tətbiq xüsusiyyətləri müəyyənləşdirilmişdir. Xüsusilə, maşın

öyrənməsinin istehsal keyfiyyətinin proqnozlaşdırılmasında rolu, kompüter görməsinin qüsurların aşkarlanmasına təsiri və rəqəmsal əkizlərin istehsal sistemlərinin monitorinqində imkanları araşdırılmışdır.

Bu metodun tətbiqi nəticəsində süni intellektin ağıllı istehsalda əsas funksional istiqamətlərini əhatə edən nəzəri baza formalaşdırılmışdır. Bununla belə, ədəbiyyat təhlilindən əldə edilən nəticələr mənbələrin əhatə dairəsindən və elmi tədqiqatlarda istifadə olunan yanaşmalardan asılıdır. Buna görə müxtəlif tədqiqatların nəticələri müqayisə edilərkən onların istehsal şəraiti, istifadə edilən məlumatlar və qiymətləndirmə meyarları da nəzərə alınmalıdır (Franket al., 2019).

3. Təsviri təhlil metodu

Təsviri təhlil metodu süni intellekt texnologiyalarının mahiyyətini, funksiyalarını və ağıllı istehsal sistemlərində istifadə mexanizmlərini izah etmək üçün tətbiq edilmişdir. Bu metod araşdırılan texnologiyaların əsas xüsusiyyətlərini sistemli şəkildə təqdim etməyə və onların istehsal proseslərində hansı məqsədlərlə istifadə olunduğunu aydınlaşdırmağa imkan verir.

Təsviri təhlil çərçivəsində maşın öyrənməsi, dərin öyrənmə, kompüter görməsi və rəqəmsal əkizlər kimi texnologiyaların istehsal prosesləri ilə əlaqəsi nəzərdən keçirilmişdir. Maşın öyrənməsi istehsal məlumatlarından qanunauyğunluqların müəyyənləşdirilməsi və gələcək göstəricilərin proqnozlaşdırılması üçün istifadə olunan yanaşma kimi təhlil edilmişdir. Dərin öyrənmə mürəkkəb məlumat nümunələrinin, xüsusilə təsvirlərin və sensor siqnallarının emalı baxımından qiymətləndirilmişdir. Kompüter görməsinin əsas funksiyası məhsulların vizual yoxlanılması və qüsurların müəyyənləşdirilməsi ilə əlaqələndirilmişdir (Wuest et al., 2016).

Bununla yanaşı, ağıllı istehsal sistemlərində məlumatların toplanması, emalı və qərarvermə prosesləri arasındakı əlaqə izah edilmişdir. Sensorlardan əldə edilən məlumatların süni intellekt modelləri vasitəsilə təhlili avadanlığın texniki vəziyyətinin qiymətləndirilməsinə, istehsal prosesindəki kənarlaşmaların aşkar edilməsinə və əməliyyatların təkmilləşdirilməsinə imkan yaradır.

Təsviri təhlil metodu vasitəsilə süni intellektin yalnız istehsal əməliyyatlarının avtomatlaşdırılmasına xidmət etmədiyi, eyni zamanda istehsal proseslərinin müşahidəsi, proqnozlaşdırılması və idarə edilməsində mühüm rol oynadığı əsaslandırılmışdır. Bu yanaşma məqalənin digər bölmələrində aparılan müqayisəli və konseptual təhlil üçün nəzəri zəmin yaratmışdır (Heng et al., 2009).

4. Müqayisəli təhlil metodu

Müqayisəli təhlil metodu ağıllı istehsal sistemlərində istifadə edilən müxtəlif süni intellekt texnologiyalarının imkanlarını və məhdudiyyətlərini müəyyənləşdirmək məqsədilə tətbiq edilmişdir. Bu metod ayrı-ayrı texnologiyaların funksional xüsusiyyətlərini, tətbiq məqsədlərini və istehsal proseslərinə mümkün təsirlərini qarşılaşdırmağa imkan verir.

Tədqiqat çərçivəsində ənənəvi avtomatlaşdırma sistemləri ilə süni intellektlə gücləndirilmiş istehsal sistemləri arasında konseptual müqayisə aparılmışdır. Ənənəvi avtomatlaşdırma sistemləri əsasən əvvəlcədən müəyyən edilmiş qaydalara və idarəetmə parametrlərinə əsaslandığı halda, süni intellekt sistemləri kifayət qədər keyfiyyətli məlumat olduqda mürəkkəb nümunələri öyrənmək, dəyişiklikləri müəyyənləşdirmək və proqnozlar hazırlamaq imkanına malikdir. Bununla belə, süni intellektin tətbiqi ənənəvi idarəetmə mexanizmlərinin tamamilə aradan qaldırılmasını tələb etmir. Əksinə, bu texnologiyalar mövcud sistemləri tamamlayaraq qərarvermənin keyfiyyətini yüksəldə bilər.

Müqayisə zamanı süni intellektin müxtəlif tətbiq sahələri də nəzərdən keçirilmişdir. Proqnozlaşdırıcı texniki xidmət avadanlığın vəziyyətinin əvvəlcədən qiymətləndirilməsinə, kompüter görməsi məhsul qüsurlarının aşkarlanmasına, optimallaşdırma alqoritmləri istehsal qrafiklərinin və resurs bölgüsünün

təkmilləşdirilməsinə, rəqəmsal əkizlər isə istehsal proseslərinin rəqəmsal modellər vasitəsilə araşdırılmasına xidmət edir (Kagermann et al., 2013).

Texnologiyaların müqayisəsində məlumat tələbləri, tətbiq mürəkkəbliyi, nəticələrin qiymətləndirilməsi, real vaxt rejimində işləmə imkanları və insan nəzarətinə ehtiyac kimi meyarlar nəzərə alınmışdır. Məsələn, kompüter görməsi üçün keyfiyyətli təsvirlər və uyğun işıqlandırma vacib olduğu halda, proqnozlaşdırıcı texniki xidmət üçün sensor göstəricilərinin ardıcıl toplanması və avadanlığın əvvəlki iş rejimi haqqında məlumatların mövcudluğu mühüm əhəmiyyət daşıyır.

Müqayisəli təhlilin nəticələri göstərir ki, bütün istehsal müəssisələri üçün eyni texnologiyanın seçilməsi məqsədəuyğun deyil. Texnologiyanın səmərəliliyi müəssisənin fəaliyyət sahəsi, istehsal prosesinin mürəkkəbliyi, mövcud məlumat infrastrukturu və həll edilməli olan problemdən asılıdır.

5. Təsnifat metodu

Təsnifat metodu süni intellektin ağıllı istehsal sistemlərində tətbiq istiqamətlərini funksional xüsusiyyətlərinə görə qruplaşdırmaq üçün istifadə edilmişdir. Bu metod geniş və çoxşaxəli mövzunun ayrı-ayrı istiqamətlər üzrə sistemləşdirilməsinə və hər bir istiqamətin istehsal prosesindəki rolunun müəyyənləşdirilməsinə imkan verir.

Tədqiqat çərçivəsində süni intellektin tətbiq sahələri altı əsas qrupa ayrılmışdır: proqnozlaşdırıcı texniki xidmət, məhsul keyfiyyətinə nəzarət, istehsal proseslərinin optimallaşdırılması, robotlaşdırma və insan-robot əməkdaşlığı, rəqəmsal əkizlər və resursların idarə edilməsi (Kusiak, 2018).

Proqnozlaşdırıcı texniki xidmət avadanlığın texniki vəziyyətinin izlənilməsi və mümkün nasazlıqların əvvəlcədən müəyyənləşdirilməsi ilə əlaqələndirilmişdir. Keyfiyyətə nəzarət məhsullarda qüsurların aşkarlanması və istehsal standartlarına uyğunluğun qiymətləndirilməsi istiqamətini əhatə edir. İstehsalın optimallaşdırılması resursların bölgüsü, sifarişlərin ardıcıllığı və əməliyyat qrafiklərinin təkmilləşdirilməsi ilə bağlıdır. Robotlaşdırma fiziki əməliyyatların avtomatlaşdırılmasını və robotların dəyişən şəraitə uyğunlaşmasını, rəqəmsal əkizlər fiziki sistemlərin rəqəmsal modelləşdirilməsini, resursların idarə edilməsi isə material, enerji və ehtiyatların səmərəli istifadəsini əhatə edir.

Bu təsnifatın əsas üstünlüyü müxtəlif texnologiyaların funksional məqsədlərini bir-birindən fərqləndirməklə yanaşı, onların qarşılıqlı əlaqəsini də nəzərə almasıdır. Məsələn, rəqəmsal əkizlər proqnozlaşdırıcı texniki xidmət modelləri ilə birləşdirildikdə avadanlığın vəziyyətini daha əhatəli qiymətləndirmək üçün istifadə oluna bilər. Eyni zamanda, kompüter görməsi və istehsal məlumatlarının analitikası məhsul keyfiyyətinin idarə edilməsində bir-birini tamamlayan vasitələr kimi çıxış edə bilər.

Beləliklə, təsnifat metodu süni intellekt texnologiyalarının istehsalda tətbiqinin vahid sistem daxilində öyrənilməsinə və onların müəssisənin müxtəlif funksional sahələri üzrə əhəmiyyətinin müəyyənləşdirilməsinə şərait yaratmışdır.

6. Konseptual ümumiləşdirmə metodu

Konseptual ümumiləşdirmə metodu elmi ədəbiyyatın təhlili və müqayisəsi nəticəsində əldə edilən məlumatları vahid nəzəri yanaşma çərçivəsində birləşdirmək üçün tətbiq edilmişdir. Bu metod ayrı-ayrı tədqiqatlarda irəli sürülən fikirləri əlaqələndirməyə, ortaq tendensiyaları müəyyənləşdirməyə və süni intellektin ağıllı istehsal sistemlərində ümumi rolunu izah etməyə imkan verir.

Ümumiləşdirmə zamanı süni intellektin istehsal sistemlərində üç əsas funksional istiqaməti fərqləndirilmişdir. Birinci istiqamət istehsal proseslərinin monitorinqi və diaqnostikasıdır. Bu istiqamətdə məlumatlar emal edilir, avadanlığın cari vəziyyəti qiymətləndirilir və mümkün

kənarlaşmalar müəyyənləşdirilir. İkinci istiqamət proqnozlaşdırmadır. Burada mövcud və tarixi məlumatlardan istifadə etməklə nasazlıqlar, keyfiyyət göstəriciləri və istehsal ehtiyacları haqqında ehtimallar formalaşdırılır. Üçüncü istiqamət qərarların dəstəklənməsi və optimallaşdırılmasıdır. Bu mərhələdə analitik nəticələr istehsal qrafiklərinin, texniki xidmət planlarının və resurs bölgüsünün təkmilləşdirilməsinə xidmət edir.

Bu funksional istiqamətlər bir-birindən təcrid olunmuş şəkildə deyil, qarşılıqlı əlaqədə fəaliyyət göstərə bilər. Məsələn, avadanlıqdan əldə edilən sensor məlumatları əvvəlcə monitorinq məqsədilə təhlil edilir, sonra mümkün nasazlıq proqnozlaşdırılır və sonda texniki xidmətin vaxtı müəyyənləşdirilir. Beləliklə, süni intellekt istehsal prosesində məlumatların toplanmasından idarəetmə qərarlarının hazırlanmasına qədər uzanan ardıcıl analitik prosesin bir hissəsinə çevrilir.

Konseptual ümumiləşdirmə əsasında müəyyən edilmişdir ki, süni intellektin ağıllı istehsalda səmərəli istifadəsi texnoloji imkanlarla yanaşı, məlumatların keyfiyyəti, sistemlərin inteqrasiyası, insan nəzarəti və təhlükəsizlik mexanizmlərinin uzlaşdırılmasını tələb edir. Bu nəticə məqalənin tövsiyələrinin formalaşdırılması üçün əsas olmuşdur (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014).

7. Analitik qiymətləndirmə metodu

Analitik qiymətləndirmə metodu süni intellekt texnologiyalarının istehsal sistemlərində tətbiqi ilə əlaqədar potensial faydaları və riskləri sistemli şəkildə nəzərdən keçirmək üçün istifadə edilmişdir. Bu metod texnologiyanın yalnız müsbət tərəflərini deyil, onun tətbiqinə mane ola biləcək texniki, iqtisadi və təşkilati amilləri də qiymətləndirməyə imkan verir.

Tədqiqatda potensial faydalar məhsuldarlığın yüksəldilməsi, istehsal dayanma müddətinin azaldılması, qüsurların erkən aşkarlanması, enerji və material sərfiyyatının optimallaşdırılması, texniki xidmətin daha səmərəli planlaşdırılması və qərarvermənin təkmilləşdirilməsi istiqamətləri üzrə təhlil edilmişdir. Bu faydaların reallaşması müəssisənin texnoloji hazırlığından, istifadə olunan modelin keyfiyyətindən və istehsal prosesinin xüsusiyyətlərindən asılı olaraq dəyişə bilər.

Risklərin qiymətləndirilməsi zamanı məlumat çatışmazlığı, sensor xətaları, model nəticələrinin qeyri-dəqiqliyi, kibertəhlükəsizlik təhdidləri, ilkin investisiya xərcləri və ixtisaslı kadrların çatışmazlığı nəzərə alınmışdır. Həmçinin süni intellekt modelinin nəticələrinə həddindən artıq etibar edilməsinin istehsal və təhlükəsizlik baxımından yarada biləcəyi problemlər diqqətə alınmışdır.

Analitik qiymətləndirmənin mühüm prinsipi potensial üstünlükləri avtomatik olaraq əldə edilmiş nəticələr kimi təqdim etməməkdir. Məsələn, süni intellektin texniki nasazlıqların sayını azaltdığını müəyyən etmək üçün tətbiqdən əvvəlki və sonrakı göstəricilər müqayisə edilməli, eyni zamanda istehsal həcmi və avadanlığın iş şəraiti kimi amillər nəzərə alınmalıdır. Eyni qayda məhsul keyfiyyəti, enerji sərfiyyatı və iqtisadi səmərəlilik göstəricilərinə də aiddir.

Bu metodun tətbiqi nəticəsində süni intellektin ağıllı istehsal sistemlərində istifadəsinin texnoloji imkanlarla yanaşı, idarəetmə, təhlükəsizlik və iqtisadi əsaslandırma məsələlərini də əhatə etdiyi müəyyənləşdirilmişdir (Lee et al., 2015).

8. Tədqiqatın məhdudiyyətləri

Tədqiqatın metodoloji məhdudiyyətləri də nəzərə alınmalıdır. Məqalə nəzəri və analitik xarakter daşıdığı üçün konkret sənaye müəssisəsindən ilkin məlumatlar toplanmamış, istehsal avadanlıqları üzərində eksperiment aparılmamış və süni intellekt modellərinin performansı praktiki sınaqlarla ölçülməmişdir. Buna görə məqalədə göstərilən üstünlüklər elmi ədəbiyyatda müzakirə olunan potensial imkanlar və nəzəri ümumiləşdirmələr kimi qiymətləndirilməlidir.

Digər məhdudiyyət müxtəlif tədqiqatların fərqli sənaye sahələrini, məlumat dəstlərini və qiymətləndirmə meyarlarını əhatə etməsi ilə bağlıdır. Bir istehsal mühitində səmərəli hesab olunan texnologiya digər müəssisədə eyni nəticəni verməyə bilər. Bu səbəbdən nəticələrin bütün sənaye sahələrinə eyni şəkildə şamil edilməsi məqsədəuyğun deyil.

Gələcək tədqiqatlarda konkret müəssisələrin məlumatlarından istifadə etməklə süni intellekt modellərinin müqayisəli sınaqlarının aparılması, tətbiqdən əvvəlki və sonrakı istehsal göstəricilərinin qiymətləndirilməsi və texnologiyanın iqtisadi səmərəliliyinin ölçülməsi tövsiyə olunur. Belə yanaşma nəzəri nəticələrin praktiki sübutlarla tamamlanmasına və ağıllı istehsal sistemlərində süni intellektin tətbiqi üçün daha dəqiq metodoloji çərçivənin formalaşdırılmasına imkan verə bilər.

Nəticələr

Aparılmış nəzəri təhlil süni intellekt texnologiyalarının ağıllı istehsal sistemlərinin inkişafında mühüm rol oynadığını göstərir. Elmi ədəbiyyatın araşdırılması və müxtəlif tətbiq istiqamətlərinin müqayisəsi əsasında müəyyən edilmişdir ki, süni intellekt istehsal proseslərinin avtomatlaşdırılması, istehsal məlumatlarının operativ təhlili, avadanlıqların texniki vəziyyətinin qiymətləndirilməsi və resurslardan istifadənin optimallaşdırılması üçün geniş imkanlar yaradır. Bu texnologiyaların tətbiqi istehsal sistemlərinin yalnız cari vəziyyətini izləməyə deyil, eyni zamanda mümkün dəyişiklikləri proqnozlaşdırmağa və idarəetmə qərarlarını təkmilləşdirməyə şərait yaradır.

Tədqiqatın nəticələri göstərir ki, süni intellektin ağıllı istehsalda tətbiqini bir neçə əsas istiqamət üzrə ümumiləşdirmək mümkündür. Bu istiqamətlər proqnozlaşdırıcı texniki xidmət, avtomatlaşdırılmış keyfiyyətə nəzarət, istehsal proseslərinin optimallaşdırılması, robotlaşdırma, rəqəmsal əkizlərin tətbiqi və resursların idarə edilməsidir. Hər bir istiqamət istehsalın müəyyən probleminin həllinə yönəlsə də, onların inteqrasiyası müəssisənin ümumi idarəetmə imkanlarını genişləndirə bilər (Lei et al., 2018).

Proqnozlaşdırıcı texniki xidmətin əhəmiyyətinin müəyyən edilməsi

Təhlil nəticəsində müəyyən edilmişdir ki, proqnozlaşdırıcı texniki xidmət ağıllı istehsal sistemlərində süni intellektin ən mühüm tətbiq istiqamətlərindən biridir. Sensorlardan əldə olunan temperatur, vibrasiya, təzyiq və enerji sərfiyyatı göstəricilərinin təhlili avadanlığın texniki vəziyyətindəki dəyişiklikləri vaxtında aşkar etməyə imkan verə bilər. Bu məlumatlar əsasında qurulan maşın öyrənməsi modelləri mümkün nasazlıq əlamətlərini müəyyənləşdirərək texniki xidmətin daha məqsədyönlü planlaşdırılmasını dəstəkləyir.

Ənənəvi texniki xidmət yanaşmalarında avadanlığın yoxlanılması çox vaxt əvvəlcədən müəyyən edilmiş vaxt intervallarına və ya nasazlıq baş verdikdən sonrakı müdaxiləyə əsaslanır. Proqnozlaşdırıcı yanaşma isə texniki vəziyyət barədə real vaxt məlumatlarından istifadə etməklə xidmət ehtiyacının daha çevik qiymətləndirilməsinə şərait yaradır. Bununla belə, proqnozların dəqiqliyi məlumatların keyfiyyətindən, avadanlığın iş rejimindən və modelin düzgün hazırlanmasından asılıdır (Lu, 2017).

Beləliklə, nəzəri təhlil proqnozlaşdırıcı texniki xidmətin istehsal dayanma risklərinin idarə edilməsində və texniki resursların planlaşdırılmasında potensial əhəmiyyətini ortaya qoyur. Bu üstünlüklərin konkret müəssisədə hansı səviyyədə reallaşması isə praktiki ölçmələr vasitəsilə müəyyən edilməlidir.

Məhsul keyfiyyətinə nəzarətdə süni intellektin imkanları

Araşdırmanın digər nəticəsi süni intellektin məhsul keyfiyyətinin qiymətləndirilməsi prosesində əhəmiyyətli imkanlara malik olmasıdır. Kompüter görməsi və dərin öyrənmə texnologiyaları

məhsulların təsvirlərini təhlil etməklə səth qüsurlarını, ölçü uyğunsuzluqlarını, rəng fərqlərini və digər vizual kənarlaşmaları müəyyənləşdirmək üçün istifadə oluna bilər.

Avtomatlaşdırılmış keyfiyyət nəzarəti xüsusilə istehsal xəttində çoxsaylı məhsulların qısa müddətdə yoxlanılması tələb olunduqda əhəmiyyət qazanır. Süni intellekt sistemləri işçilərin vizual yoxlamasını tamamilə əvəz etmədən, şübhəli məhsulların seçilməsi və əlavə yoxlamaya yönləndirilməsi prosesini dəstəkləyə bilər. Bu yanaşma keyfiyyətə nəzarətin ardıcıllığını yaxşılaşdırmaq və insan amili ilə bağlı bəzi dəyişkənlikləri azaltmaq üçün potensial imkan yaradır (Zhong et al., 2017).

Bununla yanaşı, modelin effektivliyi təlim məlumatlarının reprezentativliyindən, qüsur nümunələrinin müxtəlifliyindən, görüntülərin keyfiyyətindən və istehsal şəraitinin sabitliyindən asılıdır. Buna görə süni intellekt əsasında aparılan keyfiyyət yoxlamasının nəticələri müstəqil sınaqlar və mövcud keyfiyyət standartları əsasında yoxlanılmalıdır.

İstehsal proseslərinin optimallaşdırılması imkanları

Tədqiqatın nəticələri göstərir ki, süni intellekt istehsalın planlaşdırılması və idarə olunmasında məlumatlara əsaslanan qərarların qəbul edilməsini dəstəkləyə bilər. İstehsal qrafikləri, avadanlıqların yüklənməsi, xammal ehtiyatları və sifarişlərin icra müddətləri haqqında məlumatların birgə təhlili əməliyyatların ardıcıllığını və resurs bölgüsünü təkmilləşdirmək üçün istifadə oluna bilər.

İstehsal proseslərinin optimallaşdırılması zamanı yalnız məhsuldarlığın artırılması deyil, eyni zamanda keyfiyyət, enerji sərfiyyatı, çatdırılma müddəti və istehsal xərcləri də nəzərə alınmalıdır. Bu göstəricilər arasında mümkün ziddiyyətlər çoxmeyarlı qərarvermə yanaşmasını zəruri edir. Məsələn, istehsal sürətinin artırılması müəyyən şəraitdə enerji istehlakının yüksəlməsinə və ya məhsul qüsurlarının çoxalmasına səbəb ola bilər. Süni intellektlə birləşdirilmiş optimallaşdırma üsulları belə qarşılıqlı təsirlərin təhlilinə kömək edə bilər (Mahmudova, 2025).

Nəticə etibarilə, süni intellektin istehsal planlaşdırılmasında tətbiqi resurslardan istifadənin yaxşılaşdırılması və dəyişən sifarişlərə uyğunlaşma imkanlarını genişləndirir. Lakin bu imkanların reallaşması üçün müəssisənin informasiya sistemləri arasında məlumat mübadiləsinin təmin edilməsi və istifadə olunan modellərin real istehsal şəraitinə uyğunlaşdırılması vacibdir.

Robotlaşdırma və rəqəmsal əkizlərin istehsalda rolu

Nəzəri təhlil göstərir ki, süni intellektin robotlaşdırma ilə birləşdirilməsi istehsal proseslərində çevikliyi və avtomatlaşdırma imkanlarını artıra bilər. Kompüter görməsi və intellektual idarəetmə alqoritmləri robotların obyektləri tanımasına, əməliyyatların ardıcıllığını müəyyənləşdirməsinə və dəyişən şəraitə uyğunlaşmasına kömək edir. Bu xüsusiyyətlər xüsusilə təkrarlanan, yüksək dəqiqlik tələb edən və təhlükəli əməliyyatların yerinə yetirilməsində əhəmiyyətlidir.

Bununla yanaşı, robotların tətbiqi insan əməyinin tamamilə aradan qaldırılması kimi qiymətləndirilməməlidir. İstehsal proseslərinin təhlükəsiz təşkili üçün insan-robot əməkdaşlığının düzgün planlaşdırılması, texniki təhlükəsizlik vasitələrinin tətbiqi və işçilərin müvafiq təlimlərdən keçirilməsi zəruridir.

Rəqəmsal əkizlər isə fiziki istehsal sistemlərinin rəqəmsal modellər vasitəsilə təhlilinə imkan yaradır. Süni intellektin bu modellərə inteqrasiyası avadanlığın vəziyyətinin izlənilməsini, müxtəlif istehsal ssenarilərinin qiymətləndirilməsini və mümkün dəyişikliklərin əvvəlcədən araşdırılmasını dəstəkləyə bilər. Bununla belə, rəqəmsal modelin faydalılığı onun real sistemə uyğunluğundan və məlumatların vaxtında yenilənməsindən asılıdır (Monostori, 2014).

Resurslardan istifadənin səmərəliliyinin artırılması

Araşdırma göstərir ki, süni intellekt texnologiyalarının tətbiqi material, enerji və digər istehsal resurslarının idarə edilməsinin təkmilləşdirilməsi üçün imkanlar yaradır. Enerji sərfiyyatı, istehsal həcmi, avadanlıqların iş rejimi və xammal ehtiyatları haqqında məlumatların təhlili resurs istehlakındakı dəyişiklikləri müəyyənləşdirməyə və daha uyğun əməliyyat rejimlərini seçməyə kömək edə bilər.

Tələbin proqnozlaşdırılması və ehtiyatların idarə edilməsi də bu baxımdan əhəmiyyətlidir. Süni intellekt modelləri tarixi sifarişlər və mövcud istehsal imkanları əsasında ehtimal olunan tələbi qiymətləndirmək üçün istifadə oluna bilər. Bu, artıq ehtiyatların yaranması və ya xammal çatışmazlığı ilə bağlı risklərin idarə edilməsinə kömək edə bilər.

Bununla belə, proqnozların etibarlılığı bazar dəyişikliklərindən, məlumatların tamlığından və modelin yenilənmə tezliyindən asılıdır. Buna görə resursların idarə edilməsində süni intellektin nəticələri müəssisənin real əməliyyat göstəriciləri ilə müntəzəm müqayisə edilməlidir.

Süni intellektin tətbiqini məhdudlaşdıran amillər

Tədqiqat çərçivəsində müəyyən edilmiş əsas nəticələrdən biri süni intellektin tətbiqinin yalnız texnoloji imkanlarla müəyyən olunmamasıdır. Məlumatların keyfiyyəti, mövcud avadanlıqların rəqəmsal infrastruktura uyğunluğu, kibertəhlükəsizlik, maliyyə imkanları və ixtisaslı kadrların mövcudluğu texnologiyanın tətbiqinə birbaşa təsir göstərən amillərdir.

Məlumatların natamam və ya qeyri-dəqiq olması süni intellekt modelinin səhv proqnozlar verməsinə səbəb ola bilər. Köhnə avadanlıqların yeni informasiya sistemləri ilə inteqrasiyası əlavə texniki və maliyyə xərcləri yarada bilər. Bundan başqa, istehsal sistemlərinin şəbəkələrə qoşulması məlumatların qorunması və kibertəhlükəsizlik üzrə tədbirlərin gücləndirilməsini tələb edir.

İqtisadi baxımdan texnologiyanın tətbiqindən əvvəl gözlənilən faydalarla ilkin investisiya və istismar xərcləri müqayisə olunmalıdır. Kiçik və orta müəssisələr üçün mərhələli tətbiq yanaşması risklərin azaldılması baxımından daha uyğun ola bilər. Eyni zamanda, işçilərin rəqəmsal bacarıqlarının inkişaf etdirilməsi və süni intellekt sistemlərinin fəaliyyətinə insan nəzarətinin təmin olunması vacib şərtlərdir (Quliyev, 2025).

Aparılmış nəzəri təhlil əsasında aşağıdakı ümumiləşdirmələr formalaşdırılmışdır:

1. Süni intellekt ağıllı istehsal sistemlərində məlumatların toplanması, təhlili və idarəetmə qərarlarının hazırlanması arasında əlaqəni gücləndirən texnologiyadır.
2. Proqnozlaşdırıcı texniki xidmət avadanlıqların vəziyyətinin qiymətləndirilməsi və texniki müdaxilələrin planlaşdırılması üçün potensial imkanlar yaradır.
3. Kompüter görməsi və dərin öyrənmə məhsul keyfiyyətinə nəzarətin avtomatlaşdırılmasını və vizual qüsurların aşkarlanmasını dəstəkləyə bilər.
4. Süni intellektə əsaslanan optimallaşdırma istehsal qrafiklərinin, resurs bölgüsünün və əməliyyat qərarlarının təkmilləşdirilməsinə kömək edə bilər.
5. Robotlaşdırma və rəqəmsal əkizlər süni intellektin fiziki istehsal prosesləri ilə inteqrasiyasını genişləndirir, lakin onların tətbiqi təhlükəsizlik, məlumatların keyfiyyəti və sistemlərin uyğunluğu ilə bağlı tələblər yaradır.
6. Süni intellektin potensial üstünlükləri avtomatik olaraq reallaşmır; onların əldə olunması texniki hazırlıq, düzgün məlumat idarəetməsi, insan nəzarəti və iqtisadi əsaslandırmadan asılıdır.
7. Texnologiyanın müəssisələrdə tətbiqi konkret problemin müəyyənləşdirilməsi, pilot layihənin həyata keçirilməsi və nəticələrin ölçülə bilən göstəricilər əsasında qiymətləndirilməsi ilə başlanmalıdır.

Beləliklə, tədqiqatın nəticələri süni intellekt texnologiyalarının ağıllı istehsal sistemlərində geniş tətbiq potensialına malik olduğunu, lakin onların səmərəli istifadəsinin texnoloji, təşkilati və iqtisadi amillərin birlikdə nəzərə alınmasını tələb etdiyini göstərir. Bu nəticələr nəzəri ədəbiyyatın təhlilinə əsaslanır və gələcəkdə konkret sənaye müəssisələrində aparılacaq empirik tədqiqatlar vasitəsilə yoxlanıla və dəqiqləşdirilə bilər (Qurbanova və b., 2025).

Müzakirə və nəticə

Süni intellekt texnologiyalarının ağıllı istehsal sistemlərində tətbiqi müasir sənaye müəssisələrinin rəqəmsal transformasiyasının əsas istiqamətlərindən biri hesab olunur. İstehsal proseslərinin avtomatlaşdırılması, məlumatların real vaxt rejimində təhlili, avadanlıqların texniki vəziyyətinin qiymətləndirilməsi və istehsal əməliyyatlarının optimallaşdırılması süni intellektin sənaye sahəsində əhəmiyyətini artırır. Ənənəvi istehsal sistemlərindən fərqli olaraq, ağıllı istehsal sistemləri yalnız əvvəlcədən müəyyən edilmiş əmrlər əsasında fəaliyyət göstərmir, həm də istehsal prosesində yaranan məlumatları təhlil edərək dəyişən şəraitə uyğun qərarların qəbul edilməsinə şərait yaradır (Zhang et al., 2023).

Tədqiqat çərçivəsində nəzərdən keçirilən elmi yanaşmalar göstərir ki, süni intellektin istehsal sistemlərinə inteqrasiyası məhsuldarlığın artırılması, istehsal xərclərinin azaldılması, məhsul keyfiyyətinin yüksəldilməsi və resurslardan istifadənin səmərəliliyinin təmin edilməsi baxımından mühüm imkanlar yaradır. Bununla belə, bu imkanların reallaşdırılması müəssisənin texnoloji infrastrukturu, məlumatların keyfiyyəti, maliyyə resursları və kadr potensialı kimi amillərdən asılıdır. Buna görə də süni intellektin tətbiqi yalnız texniki yenilik kimi deyil, həm də təşkilati və idarəetmə dəyişikliklərini tələb edən kompleks proses kimi qiymətləndirilməlidir.

Süni intellektin istehsal səmərəliliyinə təsiri

Süni intellektin istehsal səmərəliliyinə təsiri əsasən böyük həcmli məlumatların emalı, proseslərdəki qanunauyğunluqların müəyyənləşdirilməsi və qərarların daha dəqiq əsaslandırılması ilə əlaqədardır. Maşın öyrənməsi alqoritmləri istehsal xətlərindən, sensorlardan və idarəetmə sistemlərindən əldə edilən məlumatları təhlil edərək avadanlıqların iş rejiminin təkmilləşdirilməsinə kömək edə bilər. Bu, istehsal prosesində yaranan gecikmələrin, texniki nasazlıqların və resurs itkilərinin müəyyənləşdirilməsi üçün əlavə imkanlar yaradır (Rəhimova və b., 2025).

Lakin süni intellektin məhsuldarlığa təsiri bütün müəssisələrdə eyni səviyyədə olmur. Texnoloji cəhətdən inkişaf etmiş, rəqəmsal məlumat bazasına və avtomatlaşdırılmış idarəetmə sistemlərinə malik müəssisələr bu texnologiyalardan daha səmərəli istifadə edə bilərlər. Əksinə, köhnəlmiş avadanlıqlardan istifadə edən və istehsal məlumatlarını sistemli şəkildə toplamayan müəssisələrdə süni intellektin tətbiqi əlavə texniki və maliyyə çətinlikləri yarada bilər.

Bu baxımdan, süni intellektin istehsal səmərəliliyinə təsiri yalnız alqoritmlərin texniki imkanları ilə deyil, həmin alqoritmlərin mövcud istehsal mühitinə nə dərəcədə uyğunlaşdırılması ilə də müəyyən edilir (Zonta et al., 2020).

Proqnozlaşdırıcı texniki xidmətin əhəmiyyəti

Tədqiqatın əsas müzakirə istiqamətlərindən biri proqnozlaşdırıcı texniki xidmət sistemləridir. Ənənəvi texniki xidmət yanaşmalarında avadanlıqlara müəyyən edilmiş vaxt intervallarında xidmət göstərilir və ya nasazlıq baş verdikdən sonra təmir işləri həyata keçirilir. Süni intellektə əsaslanan proqnozlaşdırıcı texniki xidmət isə sensorlardan əldə edilən məlumatların təhlili vasitəsilə avadanlıqların texniki vəziyyətindəki dəyişiklikləri əvvəlcədən müəyyənləşdirməyə imkan verir.

Bu yanaşma avadanlıqların gözlənilməz dayanma riskinin azaldılmasına, texniki xidmətin daha məqsədyönlü planlaşdırılmasına və ehtiyat hissələrindən istifadənin optimallaşdırılmasına kömək edə

bilər. Bununla yanaşı, proqnozlaşdırıcı sistemlərin dəqiqliyi istifadə olunan məlumatların həcmi və keyfiyyəti, sensorların etibarlılığı və maşın öyrənməsi modellərinin düzgün seçilməsi ilə sıx bağlıdır.

Beləliklə, proqnozlaşdırıcı texniki xidmətin tətbiqi istehsalın fasiləsizliyinin təmin olunması üçün perspektivli istiqamət olsa da, onun effektivliyi müntəzəm texniki nəzarət və model nəticələrinin mütəxəssislər tərəfindən qiymətləndirilməsi ilə dəstəklənməlidir (Rəhimova və b., 2025).

Məhsul keyfiyyətinə nəzarətdə süni intellektin rolu

Məhsul keyfiyyətinə nəzarət ağıllı istehsal sistemlərinin mühüm komponentlərindən biridir. Kompüter görməsi və dərin öyrənmə texnologiyaları məhsulların səthindəki qüsurların, ölçü uyğunsuzluqlarının və digər keyfiyyət problemlərinin avtomatik aşkarlanmasına şərait yaradır. Bu sistemlər xüsusilə yüksək sürətlə işləyən istehsal xətlərində insan müşahidəsinin imkanlarını tamamlaya və yoxlama prosesinin ardıcıllığını artıra bilər.

Süni intellekt əsaslı keyfiyyətə nəzarət sistemlərinin üstünlüyü onların çoxsaylı vizual məlumatları emal etmək və müəyyən edilmiş nümunələr üzrə qüsurları təsnifləşdirmək imkanları ilə bağlıdır. Bununla belə, müxtəlif işıqlandırma şəraiti, məhsulların xarici görünüşündəki dəyişikliklər və təlim məlumatlarının məhdudluğu sistemin nəticələrinə təsir göstərə bilər. Əgər model kifayət qədər müxtəlif və keyfiyyətli məlumatlarla öyrədilməyibsə, qüsurları düzgün müəyyənləşdirməmək və ya keyfiyyətli məhsulları səhvən qüsurlu hesab etmək ehtimalı yaranır (Susto et al., 2015).

Bu səbəbdən süni intellektin keyfiyyətə nəzarətdə tətbiqi insan mütəxəssislərin nəzarətini tamamilə aradan qaldırmaq kimi deyil, yoxlama prosesinin dəqiqliyini və operativliyini artıran vasitə kimi qiymətləndirilməlidir.

İstehsal proseslərinin optimallaşdırılması və resurslardan istifadə

Süni intellekt istehsal planlaşdırılması, material ehtiyatlarının idarə olunması, enerji istehlakının təhlili və istehsal güclərinin bölüşdürülməsi kimi sahələrdə də tətbiq edilə bilər. Proqnozlaşdırma modelləri tələbin dəyişməsini qiymətləndirməyə, optimallaşdırma alqoritmləri isə mövcud resursların daha səmərəli bölüşdürülməsinə kömək edir. Bu imkanlar istehsalın planlaşdırılmasında çevikliyin artırılması və əməliyyat xərclərinin idarə olunması baxımından əhəmiyyətlidir.

Bununla belə, istehsal proseslərinin optimallaşdırılması zamanı yalnız məhsuldarlığın artırılması əsas məqsəd olmamalıdır. Enerji sərfiyyatı, xammal itkisi, ekoloji təsirlər, işçilərin təhlükəsizliyi və məhsulun keyfiyyəti də qərarların qəbulunda nəzərə alınmalıdır. Əks halda, bir göstəricinin yaxşılaşdırılması digər göstəricilərin pisləşməsinə səbəb ola bilər.

Deməli, süni intellekt əsaslı optimallaşdırma sistemləri çoxmeyarlı idarəetmə prinsipləri əsasında qurulmalı və müəssisənin iqtisadi, texnoloji və ekoloji məqsədləri ilə uzlaşdırılmalıdır.

Rəqəmsal əkizlər və intellektual robotlaşdırma

Rəqəmsal əkizlər fiziki avadanlığın, istehsal xəttinin və ya bütöv istehsal sisteminin rəqəmsal modelini yaratmağa imkan verir. Bu modellər real sistemdən daxil olan məlumatlarla yenilənərək müxtəlif istehsal ssenarilərinin qiymətləndirilməsi və mümkün problemlərin əvvəlcədən araşdırılması üçün istifadə oluna bilər. Süni intellektin rəqəmsal əkizlərlə birləşdirilməsi istehsal proseslərinin modelləşdirilməsi, parametrlərin seçilməsi və qərarların sınaqdan keçirilməsi imkanlarını genişləndirir (Tao et al., 2019).

İntellektual robotlaşdırma isə təkrarlanan, yüksək dəqiqlik tələb edən və ya insan sağlamlığı üçün təhlükəli əməliyyatların avtomatlaşdırılmasına şərait yaradır. Bununla yanaşı, robotların tətbiqi istehsal sahəsinin yenidən qurulmasını, təhlükəsizlik standartlarına əməl edilməsini və işçilərin yeni texnologiyalarla işləmək üzrə hazırlanmasını tələb edə bilər.

Bu texnologiyaların uğurlu inteqrasiyası üçün istehsal avadanlıqları, sensorlar, idarəetmə proqramları və məlumat mübadiləsi sistemləri arasında uyğunluq təmin edilməlidir. Belə uyğunluq olmadıqda, ayrı-ayrı texnologiyaların mövcudluğu bütöv istehsal sisteminin səmərəliliyini avtomatik olaraq artırmır.

Süni intellektin tətbiqində əsas problemlər

Ağıllı istehsal sistemlərində süni intellektin tətbiqi bir sıra texniki, iqtisadi və təşkilati problemlərlə müşayiət olunur. İlk növbədə, keyfiyyətli və etibarlı məlumatların əldə edilməsi mühüm şərtdir. Natamam, səhv və ya qeyri-bərabər paylanmış məlumatlar əsasında qurulan modellər yanlış nəticələr verə bilər. İstehsal məlumatlarının müxtəlif sistemlərdə saxlanılması və standartlaşdırılmaması da məlumat mübadiləsini çətinləşdirir (Tao et al., 2018).

İkinci mühüm problem tətbiq xərcləri ilə bağlıdır. Sensorların quraşdırılması, proqram təminatının alınması və ya hazırlanması, hesablama infrastrukturunun yaradılması və mütəxəssislərin cəlb edilməsi müəyyən maliyyə vəsaiti tələb edir. Bu xərclər xüsusilə kiçik və orta müəssisələr üçün məhdudlaşdırıcı amilə çevrilə bilər.

Bundan əlavə, istehsal sistemlərinin rəqəmsallaşdırılması kibertəhlükəsizlik risklərini də artırır. İstehsal məlumatlarının icazəsiz əldə edilməsi, idarəetmə sistemlərinə müdaxilə və məlumatların itirilməsi müəssisənin fəaliyyətinə ciddi təsir göstərə bilər. Buna görə də süni intellekt sistemlərinin tətbiqi məlumatların qorunması, giriş hüquqlarının idarə olunması, sistemlərin müntəzəm yenilənməsi və ehtiyat nüsxələrin yaradılması kimi tədbirlərlə müşayiət edilməlidir.

Digər tərəfdən, süni intellektin geniş tətbiqi işçilərin funksiyalarında dəyişikliklərə səbəb ola bilər. Bu dəyişikliklər yeni bacarıqlara ehtiyac yaradır və işçi heyətinin davamlı təlimini zəruri edir. Beləliklə, texnoloji yeniliklərin uğuru yalnız proqram təminatından deyil, insan kapitalının inkişafından və təşkilati hazırlıqdan da asılıdır (Wang et al., 2016).

Nəticələr

Aparılmış nəzəri təhlil göstərir ki, süni intellekt texnologiyaları ağıllı istehsal sistemlərinin inkişafında mühüm rol oynayır. Maşın öyrənməsi, dərin öyrənmə, kompüter görməsi, proqnozlaşdırıcı analitika, intellektual robotlar və rəqəmsal əkizlər istehsal proseslərinin daha çevik, məlumatlara əsaslanan və səmərəli idarə olunması üçün geniş imkanlar yaradır.

Tədqiqatın nəticələrinə əsasən, aşağıdakı qənaətlər irəli sürülə bilər:

1. İstehsal səmərəliliyinin yüksəldilməsi: Süni intellekt istehsal proseslərində yaranan problemlərin müəyyənləşdirilməsinə, əməliyyatların optimallaşdırılmasına və qərarların məlumatlar əsasında qəbul edilməsinə kömək edə bilər.
2. Avadanlıqların etibarlılığının artırılması: Proqnozlaşdırıcı texniki xidmət texniki nasazlıqların əlamətlərini əvvəlcədən müəyyənləşdirmək və gözlənilməz dayanma riskini azaltmaq üçün perspektivli vasitədir.
3. Məhsul keyfiyyətinə nəzarətin təkmilləşdirilməsi: Kompüter görməsi və maşın öyrənməsi texnologiyaları məhsul qüsurlarının avtomatik aşkarlanmasını və keyfiyyətə nəzarətin ardıcıllığını dəstəkləyir.
4. Resurslardan istifadənin optimallaşdırılması: Süni intellekt istehsal planlaşdırılması, enerji istehlakının təhlili və material ehtiyatlarının idarə olunmasında səmərəliliyin artırılmasına şərait yarada bilər.
5. Rəqəmsal texnologiyaların inteqrasiyası: Süni intellektin rəqəmsal əkizlər, robotlaşdırma və sənaye məlumat sistemləri ilə birləşdirilməsi istehsal proseslərinin modelləşdirilməsi və idarə olunması imkanlarını genişləndirir.

6. Risklərin idarə olunmasının vacibliyi: Məlumatların keyfiyyəti, kibertəhlükəsizlik, ilkin investisiya xərcləri və ixtisaslı kadr çatışmazlığı süni intellektin tətbiqində əsas məhdudlaşdırıcı amillər sırasındadır.

Tədqiqatın ümumi nəticəsi ondan ibarətdir ki, süni intellekt ağıllı istehsal sistemlərinin səmərəliliyini yüksəltmək üçün mühüm texnoloji vasitədir, lakin onun tətbiqi konkret müəssisənin ehtiyaclarına və imkanlarına uyğun planlaşdırılmalıdır. Bu prosesə mərhələli yanaşılması, ilk növbədə daha çox xərc və vaxt itkisi yaradan problemlərin müəyyənləşdirilməsi, pilot layihələrin həyata keçirilməsi və nəticələrin müvafiq göstəricilər əsasında qiymətləndirilməsi məqsədəuyğundur.

Gələcək tədqiqatlarda süni intellekt texnologiyalarının real sənaye müəssisələrində tətbiqinin iqtisadi nəticələrinin, istehsal məhsuldarlığına təsirinin, enerji istehlakında yaratdığı dəyişikliklərin və texniki xidmət xərclərinə təsirinin empirik məlumatlar əsasında araşdırılması tövsiyə olunur. Belə yanaşma nəzəri nəticələrin praktik şəraitdə yoxlanılmasına və ağıllı istehsal sistemlərinin inkişafı üçün daha əsaslandırılmış tövsiyələrin hazırlanmasına imkan verə bilər.

Ədəbiyyat

Balayev, R. Ə., İbrahimov, F. M., & Ağakişiyeva, U. Ə. (2022). Aqrar-sənaye sahələrində süni intellektin tətbiq dairəsinin genişləndirilməsinin konseptual məsələləri. *Kənd təsərrüfatının iqtisadiyyatı*, (3), 58. https://agroeconomics.az/az/article/2044/article/

Carvalho, T. P., Soares, F. A. A. M. N., Vita, R., Francisco, R. da P., Basto, J. P., & Alcalá, S. G. S. (2019). A systematic literature review of machine learning methods applied to predictive maintenance. *Computers & Industrial Engineering, 137*, Article 106024. https://doi.org/10.1016/j.cie.2019.106024

Dalzochio, J., Kunst, R., Pignaton, E., Binotto, A., Sanyal, S., Favilla, J., & Barbosa, J. (2020). Machine learning and reasoning for predictive maintenance in Industry 4.0: Current status and challenges. *Computers in Industry, 123*, Article 103298. https://doi.org/10.1016/j.compind.2020.103298

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics, 210*, 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Heng, A., Zhang, S., Tan, A. C. C., & Mathew, J. (2009). Rotating machinery prognostics: State of the art, challenges and opportunities. *Mechanical Systems and Signal Processing, 23*(3), 724–739. https://doi.org/10.1016/j.ymssp.2008.06.009

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 Working Group*. acatech – National Academy of Science and Engineering.

Kusiak, A. (2018). Smart manufacturing. *International Journal of Production Research, 56*(1–2), 508–517. https://doi.org/10.1080/00207543.2017.1351644

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business & Information Systems Engineering, 6*, 239–242. https://doi.org/10.1007/s12599-014-0334-4

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters, 3*, 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001

Lei, Y., Li, N., Guo, L., Li, N., Yan, T., & Lin, J. (2018). Machinery health prognostics: A systematic review from data acquisition to remaining useful life prediction. *Mechanical Systems and Signal Processing, 104*, 799–834. https://doi.org/10.1016/j.ymssp.2017.11.016

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration, 6*, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

Mahmudova, S. V. (2025). Sənaye 4.0 və süni intellekt: Avtomatlaşdırmanın yeni dövrü. In *Süni intellekt: Nəzəriyyədən praktikaya* [Beynəlxalq elmi konfrans materialları]. https://doi.org/10.5281/zenodo.17537919

Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. *Procedia CIRP, 17*, 9–13. https://doi.org/10.1016/j.procir.2014.03.115

Quliyev, M. A. (2025). Süni intellektin Azərbaycan iqtisadiyyatında gələcək perspektivləri. *Tikintinin iqtisadiyyatı və menecment, 2*(31), 211–217. https://www.timjurnal.az/uploads/2025/05/hisse-4-son-3.pdf

Qurbanova, G., Quluzadə, S., & Əlizadə, Q. (2025). Azərbaycan sənayesində süni intellektin tətbiqi: İqtisadi inkişaf və innovasiya imkanları. In *Azərbaycanın sosial-iqtisadi inkişaf istiqamətləri: Müasir trendlər və aktual problemlər mövzusunda Respublika elmi-praktiki konfransın materialları,* 128–129. Lənkəran Dövlət Universiteti. https://lsu.edu.az/new/PDF/KONFRANS%20MATER%C4%B0ALI%20-%2019%20dekabr%202025.pdf

Rəhimova, K. R., Abbasova, V. M., İsmayılova, Z. R., & Həsənova, T. Ə. (2025). Süni intellekt texnologiyalarının kənd təsərrüfatında tətbiqi. *Azərbaycan Mühəndislik Akademiyasının Xəbərləri, 17*(4), 100–107. https://doi.org/10.52171/herald.334

Rəhimova, K. R., Abbasova, V. M., İsmayılova, Z. R., & Həsənova, T. Ə. (2025). Süni intellekt texnologiyalarının kənd təsərrüfatında tətbiqi. *Azərbaycan Mühəndislik Akademiyasının Xəbərləri, 17*(4), 100–107. https://doi.org/10.52171/herald.334

Susto, G. A., Schirru, A., Pampuri, S., McLoone, S., & Beghi, A. (2015). Machine learning for predictive maintenance: A multiple classifier approach. *IEEE Transactions on Industrial Informatics, 11*(3), 812–820. https://doi.org/10.1109/TII.2014.2349359

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics, 15*(4), 2405–2415. https://doi.org/10.1109/TII.2018.2873186

Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2018). Digital twin driven prognostics and health management for complex equipment. *CIRP Annals, 67*(1), 169–172. https://doi.org/10.1016/j.cirp.2018.04.055

Wang, S., Wan, J., Li, D., & Zhang, C. (2016). Implementing smart factory of Industrie 4.0: An outlook. *International Journal of Distributed Sensor Networks, 12*(1). https://doi.org/10.1155/2016/3159805

Wuest, T., Weimer, D., Irgens, C., & Thoben, K.-D. (2016). Machine learning in manufacturing: Advantages, challenges, and applications. *Production & Manufacturing Research, 4*(1), 23–45. https://doi.org/10.1080/21693277.2016.1192517

Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of Industry 4.0: A review. *Engineering, 3*(5), 616–630. https://doi.org/10.1016/j.eng.2017.05.015

Zonta, T., da Costa, C. A., da Rosa Righi, R., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers & Industrial Engineering, 150*, Article 106889. https://doi.org/10.1016/j.cie.2020.106889

Zhang, C., Wang, Z., Zhou, G., Chang, F., Ma, D., Jing, Y., Cheng, W., Ding, K., & Zhao, D. (2023). Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review. *Advanced Engineering Informatics, 57*, Article 102121. https://doi.org/10.1016/j.aei.2023.102121

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Gamification and Immersive Technologies: Transforming Engagement in Language Learning

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Abstract. *This study explores the effects of combining gamification and immersive virtual reality (VR) technologies on university students' engagement and learning outcomes in English as a foreign language (EFL). The aim was to determine whether integrating game elements and immersive tools can enhance motivation and performance in online EFL learning environments. Sixty university EFL students participated in an eight-week quasi-experimental study. They were divided into two groups: an experimental group learning through a gamified immersive VR environment and a control group using traditional online instruction. A pre-test/post-test design was used to measure language proficiency gains, and a post-intervention engagement survey assessed behavioral, emotional, and cognitive engagement. Findings indicated that the gamified immersive approach significantly increased engagement and learning performance. The experimental group reported higher engagement (M = 4.5/5) compared to the control group (M = 3.5/5) and achieved higher post-test scores (83% vs. 72%). The between-group differences in engagement and test performance were statistically significant, confirming the motivational benefits of combining gamification and immersion. Integrating gamification and VR can transform language learning by promoting motivation, interaction, and enjoyment while improving learning outcomes. The approach supports student-centered pedagogy and authentic language use, although attention to technical resources and teacher training remains essential. These results provide empirical evidence that gamified immersive learning environments represent a promising direction for enhancing engagement in higher education language courses.*

Keywords: *gamification, virtual reality, immersive learning, EFL, student engagement, language learning*

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Oyunlaşdırma və immersiv texnologiyalar: Dil öyrənmədə cəlbediciliyin transformasiyası

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Xülasə. *Bu məqalə oyunlaşdırma və immersiv virtual reallıq (VR) texnologiyalarının birləşdirilməsinin universitet tələbələrinin xarici dil kimi ingilis dili (EFL) öyrənmədə cəlbediciliyinə və öyrənmə nəticələrinə təsirini tədqiq edir. Tədqiqatın məqsədi oyun elementləri və immersiv vasitələrin onlayn EFL təlim mühitlərində motivasiyanı və performansı artıra bilib-bilməyəcəyini*

müəyyən etməkdir. Səksən universitet EFL tələbəsi səkkiz həftəlik kvazi-eksperimental tədqiqatda iştirak etmişdir. Onlar iki qrupa bölünmüşdür: oyunlaşdırılmış immersiv VR mühiti vasitəsilə öyrənən eksperimental qrup və ənənəvi onlayn təlimdən istifadə edən nəzarət qrupu. Dil bacarıqlarındakı irəliləyişi ölçmək üçün ön-test/son-test dizaynı, davranış, emosional və koqnitiv cəlbediciliyi qiymətləndirmək üçün isə müdaxilədən sonra anketdən istifadə edilmişdir. Nəticələr göstərir ki, oyunlaşdırılmış immersiv yanaşma cəlbediciliyi və öyrənmə performansını əhəmiyyətli dərəcədə artırır. Eksperimental qrup nəzarət qrupu ilə müqayisədə daha yüksək cəlbedicilik (M = 4.5/5 və M = 3.5/5) və son-testdə daha yüksək nəticə (83% və 72%) bildirmişdir. Qruplar arasındakı fərqlər statistik baxımdan əhəmiyyətlidir və oyunlaşdırma ilə immersiyanın birləşdirilməsinin motivasiya faydalarını təsdiqləyir. Tədqiqat oyunlaşdırılmış immersiv öyrənmə mühitlərinin ali təhsildə dil kurslarında cəlbediciliyi artırmaq üçün perspektivli istiqamət olduğunu göstərir.

Açar sözlər: *oyunlaşdırma, virtual reallıq, immersiv öyrənmə, EFL, tələbə cəlbediciliyi, dil öyrənmə*

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Introduction

Engagement is a critical determinant of successful language learning, yet sustaining students' active involvement remains a persistent challenge in university-level EFL (English as a Foreign Language) contexts. Traditional online and classroom-based instruction often struggles to maintain attention and motivation, prompting increasing interest in technology-enhanced approaches designed to create more interactive and engaging learning environments. Two widely discussed strategies in this regard are gamification—where game design elements are integrated into educational activities—and immersive technologies such as virtual reality (VR), which enable experiential, context-rich learning.

Gamification incorporates points, badges, leaderboards, challenges, and narrative structures to stimulate motivation and support learners' psychological needs for competence, autonomy, and relatedness. Prior studies consistently report that gamification can enhance motivation, time-on-task, enjoyment, and willingness to participate in language learning activities (Kapp, 2012; Sailer et al., 2013). Similarly, immersive VR environments have been shown to promote presence, authenticity, and emotional involvement by situating learners in realistic communicative settings. Research indicates that VR can reduce foreign language anxiety, improve willingness to communicate, and support deeper cognitive engagement through experiential interaction (Lan, 2020; Reinders & Wattana, 2014).

Despite extensive research on gamification and immersive technologies as separate approaches, very few studies have examined their combined use as a unified pedagogical model in higher education language learning. Existing literature typically investigates one tool in isolation, leaving unclear whether the motivational affordances of gamification and the contextual benefits of VR produce additive or synergistic effects on student engagement. This gap is particularly relevant as universities increasingly rely on digital instruction and seek strategies capable of sustaining engagement in online EFL environments.

The present study addresses this gap by examining the effects of a gamified immersive VR platform on university students' engagement and English learning performance in an online EFL course. The guiding research question was: Does the integration of gamification and immersive VR technology lead to higher engagement and improved learning outcomes compared to a non-gamified, non-

immersive online course? We hypothesized that students using the gamified VR environment would demonstrate significantly greater engagement and larger gains in English proficiency than those receiving traditional online instruction (Castañeda & Cho, 2016).

Gamification and Learner Engagement in Language Learning

Gamification has gained considerable attention in language education due to its potential to increase motivation, enjoyment, and sustained engagement (Dehghanzadeh, Fardanesh, Hatami, Talaee, & Noroozi, 2021). Defined as the application of game elements such as points, badges, leaderboards, challenges, and narrative structures to non-game contexts, gamification aims to stimulate learners' intrinsic motivation through mechanisms associated with achievement, autonomy, and social interaction (Kapp, 2012; Sailer et al., 2013). Empirical studies consistently show that gamified environments can enhance participation and time-on-task. For instance, Buckley and Doyle (2016) reported that college students in a gamified online course demonstrated higher levels of engagement and motivation compared to those in non-gamified settings. Similarly, Bicen and Kocakoyun (2018) found that competitive quiz platforms such as Kahoot! improved vocabulary recall and increased students' enjoyment of language tasks.

Gamification has also been associated with affective benefits. Rachels and Rockinson-Szapkiw (2018) showed that gamified mobile applications increased vocabulary retention and reduced learners' anxiety, resulting in greater self-efficacy. In grammar learning, Hong et al. (2022) reported that gamified tasks improved performance through heightened curiosity and reduced language anxiety. However, despite its popularity, gamification research typically examines game elements as an isolated instructional strategy, without considering how they might interact with more immersive learning tools such as VR. Some researchers further note that poorly designed gamification may overemphasize extrinsic rewards, potentially distracting learners from meaningful learning processes and highlighting the need for thoughtful integration rather than standalone implementation (Hanus & Fox, 2015).

Immersive Technologies and Engagement in Language Learning

Immersive technologies, particularly virtual reality (VR) and augmented reality (AR), have shown strong potential to promote experiential, context-rich language learning. VR enables learners to enter simulated environments—such as cafés, city streets, or airports—where they can interact with objects and characters in real time, fostering authenticity, presence, and emotional engagement (Lan, 2020). Research indicates that immersion can significantly improve affective and behavioral engagement. For example, Reinders and Wattana (2014) demonstrated that VR-based interaction increased learners' willingness to communicate in English, while Reitz et al. (2016) found that VR-supported speaking practice reduced anxiety and improved oral fluency.

Cognitive benefits have also been documented. Allcoat and von Mühlenen (2018) reported higher engagement and improved learning performance when students learned content through VR rather than traditional media. A comprehensive meta-analysis by Chen et al. (2022) revealed that extended reality technologies (VR/AR) had substantial positive effects on vocabulary, speaking, and comprehension outcomes in language learning. Despite these advantages, most VR studies emphasize immersion, situational authenticity, and presence, but rarely incorporate structured motivational systems such as points, levels, or progression mechanics typically found in gamified learning. As a result, while VR environments foster active participation and contextual engagement, their motivational frameworks often remain underdeveloped compared to gamified systems (Cruz et al., 2023).

Research Gap: Limited Integration of Gamification and Immersive VR

Although both gamification and VR have individually demonstrated strong potential to enhance engagement, research that integrates these approaches remains limited. Existing studies often isolate one variable—either game mechanics or immersive simulation—making it difficult to determine whether combined use may produce additive or synergistic effects. A small number of studies have attempted integration; for example, Reitz et al. (2016) examined cooperative gameplay in a 3D environment to support speaking training, but this implementation did not employ fully immersive VR headsets nor a comprehensive gamification system. Current research lacks empirical investigations of fully immersive, headset-based VR environments that embed structured game elements such as challenges, levels, and reward systems, particularly in university-level EFL instruction. Given the rapid expansion of digital learning in higher education, understanding how immersive technologies and gamified structures function together is essential for designing effective online language instruction. This study responds directly to this gap by examining an integrated gamified VR learning platform and evaluating its impact on EFL students' engagement and learning outcomes compared to traditional online instruction.

Materials and Methods

Participants and Setting

The participants in this study were 60 undergraduate students (aged 18–21) enrolled in a compulsory English communication course at a public university. All participants were non-native speakers of English, primarily L1 Turkish and Azerbaijani, and their proficiency level was approximately B1 according to CEFR standards. Students were randomly assigned to either an experimental group (n = 30) or a control group (n = 30). The same instructor taught both groups to minimize instructor-related variability. To ensure baseline comparability, all students completed a proficiency pre-test before the intervention, confirming no significant difference between the two groups in initial English level. The study took place over an eight-week instructional period conducted through online and VR-supported sessions (Csikszentmihalyi, 1975).

Experimental Condition: Gamified Immersive VR Environment

The experimental group used a custom multi-user VR platform compatible with both head-mounted displays and desktop access. Students interacted through avatars in several virtual locations (e.g., café, office, airport, city street), completing communicative tasks embedded within the course units. The VR platform integrated several game design elements, including:

- Goals and narrative-based missions
- Points and experience levels
- Badges and rewards
- Collaborative and competitive challenges
- Immediate automated and instructor-led feedback

Each week, students completed VR missions aligned with the lesson themes, such as ordering food, navigating an airport, or participating in simulated interviews. These missions required real-time spoken interaction, decision-making, and the use of target vocabulary in authentic scenarios.

Control Condition: Traditional Online Learning

The control group covered identical course content using traditional online tools, including the university LMS, live video lectures, discussion forums, and text-based assignments. Students participated in pair-work activities through breakout rooms and completed standard quizzes and written tasks. Both groups received equal total instructional time and followed the same thematic

syllabus; the primary difference lay in the modality and level of interactivity provided by the learning environment.

Instruments

Language Proficiency Tests. All participants completed a pre-test at the beginning and a post-test at the end of the study. The tests assessed listening, reading, speaking, and writing skills aligned with the course curriculum. Listening and reading sections included comprehension items, while writing involved short thematic compositions and speaking consisted of individual interviews evaluated by two independent raters. Inter-rater reliability for speaking and writing scores exceeded $r = .85$, indicating strong scoring consistency.

Engagement Questionnaire. A 15-item engagement questionnaire adapted from established frameworks (Fredricks et al., 2004; Hiver et al., 2024) was administered post-intervention. Items assessed behavioral, emotional, and cognitive engagement using a 5-point Likert scale. Two open-ended prompts collected qualitative feedback. The instrument demonstrated high internal reliability in the present sample (Cronbach's $\alpha = .89$).

Procedure

The study spanned nine weeks, including pre-testing and post-testing. In Weeks 1–8, both groups met twice weekly. The experimental group attended one weekly session in VR and one weekly online debriefing and consolidation session; the control group attended two weekly sessions conducted via traditional online methods. In Week 9, participants completed the post-test and engagement questionnaire. VR usage logs (e.g., time spent, challenges completed) were collected as supplementary indicators of participation but were not used as outcome measures.

Data Analysis

Quantitative data were analyzed using SPSS (v26). Descriptive statistics were computed for all variables, and normality was confirmed using Shapiro–Wilk tests. Group comparisons were conducted using independent-samples t-tests (pre-test, post-test, engagement scores, gain scores) and paired t-tests (within-group improvement). Effect sizes were calculated using Cohen's d. Correlation analyses were conducted to examine the relationship between engagement and learning gains, both for the full sample and within the experimental group. Significance was set at $\alpha = .05$.

Results and Discussion

Preliminary Checks and Pre-test Equivalence

Pre-test results confirmed no significant difference between the experimental group ($M = 60.8\%$, $SD = 9.8$) and the control group ($M = 61.2\%$, $SD = 10.1$). An independent-samples t-test verified baseline equivalence ($t(58) = 0.15$, $p = .880$). Participation patterns showed consistently high engagement in both groups, with the experimental group demonstrating particularly strong involvement in weekly VR missions.

Engagement Outcomes

The experimental group reported significantly higher engagement ($M = 4.51$, $SD = 0.45$) compared to the control group ($M = 3.47$, $SD = 0.55$). This difference was statistically significant ($t(58) = 7.76$, $p < .001$), representing a large effect size ($d \approx 1.9$). A positive correlation emerged between VR usage (time spent and missions completed) and overall engagement scores ($r = .58$, $p < .01$), indicating increased voluntary participation corresponded with higher perceived engagement.

Language Learning Outcomes

Both groups improved significantly from pre- to post-test, but gains were considerably larger in the experimental group. Experimental group post-test scores averaged 83.4% (SD = 7.9), compared to 72.3% (SD = 8.7) in the control group ($t(58) = 5.63$, $p < .001$). Gain scores showed the experimental group improved by +22.6 points (SD = 6.2), while the control group improved by +11.1 points (SD = 5.0) ($t(58) = 7.88$, $p < .001$). Sub-skill analysis indicated the largest improvements occurred in speaking and listening, aligning with the communicative and interactive nature of VR participation.

Relationship Between Engagement and Learning Gains

Correlation analysis revealed a strong positive relationship between engagement and gain scores across participants ($r = .65$, $p < .001$). A similar pattern emerged within the experimental group ($r = .56$, $p < .01$). These results suggest that higher engagement—particularly within the VR environment—was associated with greater improvement in English proficiency. Table 1 summarizes the engagement and test performance results numerically for both groups.

Table 1
Engagement and test performance results by group

Measure	Control Group (Mean ± SD)	Experimental Group (Mean ± SD)	t (df)	p
Engagement Score (1–5)	3.47 ± 0.55	4.51 ± 0.45	7.76 (58)	< .001
Language Test – Pre (%)	61.2 ± 10.1	60.8 ± 9.8	0.15 (58)	.880
Language Test – Post (%)	72.3 ± 8.7	83.4 ± 7.9	5.63 (58)	< .001
Gain Score (Post – Pre, points)	+11.1 ± 5.0	+22.6 ± 6.2	7.88 (58)	< .001

Note. $p < .001$ indicates statistical significance at the 0.1% level.

This study investigated the effects of a gamified immersive VR learning environment on university EFL students' engagement and language learning outcomes. The findings demonstrated that students in the experimental group showed significantly higher levels of behavioral, emotional, and cognitive engagement, as well as substantially greater gains in English proficiency compared to those in the traditional online control group. These results contribute meaningful evidence to an emerging line of research on the integration of gamification and VR in language education.

The markedly higher engagement scores observed in the experimental group are consistent with prior research suggesting that immersive technologies foster presence, authenticity, and emotional involvement (Lan, 2020; Reinders & Wattana, 2014; Reitz et al., 2016). Immersion enables learners to interact with realistic environments, reducing anxiety and encouraging more confident communication. At the same time, game elements such as challenges, rewards, and progression systems support learners' intrinsic motivation through mechanisms described in self-determination theory, particularly the needs for competence and autonomy (Kapp, 2012; Sailer et al., 2013). The present study shows that when these two components—immersion and game-based motivation—are combined, they can produce robust engagement effects.

The strong emotional and behavioral engagement observed in the experimental group suggests that the gamified VR environment provided a sense of purpose and progression that supported students' continued involvement. VR usage data further indicated that students who spent more time voluntarily engaging with VR missions reported higher overall engagement, pointing to the motivational pull of interactive and immersive experiences.

The learning outcomes also demonstrated clear advantages for the experimental group. Although both groups improved from pre-test to post-test, the experimental group made significantly larger gains,

particularly in speaking and listening. These results align with earlier work showing that VR-based exposure to authentic communicative scenarios can strengthen fluency, comprehension, and lexical retrieval (Allcoat & von Mühlenen, 2018; Chen et al., 2022). The interactive nature of the VR missions likely facilitated deeper cognitive processing and more frequent language use, which are known to support long-term retention. Additionally, the significantly larger gain scores for the experimental group may reflect the combined impact of heightened engagement and repeated meaningful practice within the immersive environment (Dewaele & Alfawzan, 2018).

These findings also shed light on the potential synergy between gamification and VR. While gamification provides extrinsic and intrinsic motivators, VR enhances situational authenticity and emotional involvement. Previous research has typically examined these approaches separately, leaving unclear whether their integration would amplify learning effects. The present study provides initial evidence that fully immersive VR environments embedded with structured game elements can reinforce one another, producing stronger engagement and performance outcomes than either approach alone. From a theoretical standpoint, the results suggest that gamified VR environments may support both affective engagement (through presence, immersion, and reduced anxiety) and motivational engagement (through challenge, progression, and feedback), creating a comprehensive engagement system (Dewaele & Alfawzan, 2014).

These findings offer several practical implications for technology-enhanced language instruction. First, incorporating immersive mission-based tasks into curriculum design may help address declining motivation and participation in online learning environments. Second, game-like progression systems can provide structure, reward effort, and sustain long-term engagement. Third, VR-supported communicative tasks allow learners to practice speaking and listening in low-pressure environments that mimic real-life interactions. As digital learning continues to expand in higher education, integrating such tools may support more engaging and effective instructional models.

Despite these promising results, several limitations must be acknowledged. The duration of the intervention was relatively short, and long-term retention effects were not measured. Additionally, while VR offers unique benefits, it requires technological resources, training, and ongoing technical support. Some learners may initially experience discomfort, cognitive overload, or unfamiliarity with 3D interfaces. Individual differences such as prior gaming experience, learning styles, and technology readiness may have influenced engagement levels and outcomes, suggesting the need for more detailed learner profiling in future studies. Future research should explore individual difference variables that may moderate the effectiveness of gamified VR environments, such as motivation type, anxiety levels, and prior exposure to gaming technologies.

Conclusion

This study examined the impact of a gamified immersive VR environment on university EFL students' engagement and language learning outcomes. The findings provide clear evidence that integrating game-based motivational elements with immersive, context-rich VR activities can significantly enhance both engagement and proficiency development in online language learning settings. Students who participated in the VR-supported course demonstrated higher behavioral, emotional, and cognitive engagement, as well as substantially larger gains in speaking, listening, and overall proficiency.

The results indicate that the combination of immersion and gamification may create a more motivating and effective learning environment than traditional online instruction alone. By supporting authentic communicative practice and sustained involvement, gamified VR appears to address common challenges in digital EFL learning, such as reduced attention, limited interaction, and low participation. The study contributes to growing evidence that emerging technologies can meaningfully support language education when carefully designed and pedagogically grounded. It

also highlights the importance of aligning VR tasks with learning objectives and ensuring that game elements reinforce, rather than distract from, meaningful language use.

Several limitations must be acknowledged. The relatively short duration of the intervention, the reliance on a single institutional context, and the absence of long-term follow-up restrict the generalizability of the findings. Additionally, technological barriers and individual differences in students' comfort with VR may influence learning outcomes. Future research should explore longer-term implementations, examine learner characteristics that influence VR effectiveness, and investigate which specific game or VR features most strongly contribute to engagement and learning gains. Further comparative studies across diverse educational settings would also deepen understanding of how gamified VR can be adapted to different learner groups, proficiency levels, and instructional goals. Overall, the findings suggest that gamified immersive VR represents a promising direction for enhancing engagement and promoting more interactive, meaningful learning experiences in online and blended EFL courses.

Declarations

Author Contributions: Aida Jalilzada — Conceptualization, literature review, and supervision; Turkan Hasanzada — Methodology design, data collection, and analysis; Fatima Ismayilli — Experimental implementation and classroom observation; Kovser Abbasova — Statistical evaluation and data visualization; Efsane Orujlu — Review, editing, and final manuscript preparation. All authors have read and approved the final version of the manuscript.

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Data Availability: Data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

Allcoat, D., & von Mühlenen, A. (2018). Learning in virtual reality: Effects on performance, emotion, and engagement. *Research in Learning Technology, 26*, Article 2140. https://doi.org/10.25304/rlt.v26.2140

Bicen, H., & Kocakoyun, S. (2018). Perceptions of students for gamification approach: Kahoot! as a case study. *International Journal of Emerging Technologies in Learning, 13*(2), 72–93. https://doi.org/10.3991/ijet.v13i02.7467

Buckley, P., & Doyle, E. (2016). Gamification and student motivation. *Interactive Learning Environments, 24*(6), 1162–1175. https://doi.org/10.1080/10494820.2014.964263

Castañeda, D. A., & Cho, M.-H. (2016). Use of a game-like application on a mobile device to improve accuracy in conjugating Spanish verbs. *Computer Assisted Language Learning, 29*(7), 1195–1204. https://doi.org/10.1080/09588221.2016.1197950

Chen, Y., Zhang, L., & Yin, H. (2022). A longitudinal study on students' foreign language anxiety and cognitive load in gamified classes of higher education. *Sustainability, 14*(17), Article 10905. https://doi.org/10.3390/su141710905

Cruz, K., Noa-Copaja, S., Turpo-Gebera, O., Montesinos-Valencia, C., Bazán-Velasquez, S., & Pérez-Postigo, G. (2023). Use of gamification in English learning in higher education: A systematic review. *Journal of Technology and Science Education, 13*(2), 480–497. https://doi.org/10.3926/jotse.1740

Csikszentmihalyi, M. (1975). *Beyond boredom and anxiety: The experience of flow in work and play*. Jossey-Bass.

Dehghanzadeh, H., Fardanesh, H., Hatami, J., Talaee, E., & Noroozi, O. (2021). Using gamification to support learning English as a second language: A systematic review. *Computer Assisted Language Learning, 34*(7), 934–957. https://doi.org/10.1080/09588221.2019.1648298

Dewaele, J.-M., & Alfawzan, M. (2018). Does the effect of enjoyment outweigh that of anxiety in foreign language performance? *Studies in Second Language Learning and Teaching, 8*(1), 21–45. https://doi.org/10.14746/ssllt.2018.8.1.2

Dewaele, J.-M., & MacIntyre, P. D. (2014). The two faces of Janus? Anxiety and enjoyment in the foreign language classroom. *Studies in Second Language Learning and Teaching, 4*(2), 237–274. https://doi.org/10.14746/ssllt.2014.4.2.5

Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School engagement: Potential of the concept, state of the evidence. *Review of Educational Research, 74*(1), 59–109. https://doi.org/10.3102/00346543074001059

Hamari, J., & Koivisto, J. (2015). Why do people use gamification services? *International Journal of Information Management, 35*(4), 419–431. https://doi.org/10.1016/j.ijinfomgt.2015.04.006

Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? A literature review of empirical studies on gamification. In *Proceedings of the 47th Hawaii International Conference on System Sciences* (pp. 3025–3034). IEEE. https://doi.org/10.1109/HICSS.2014.377

Hanus, M. D., & Fox, J. (2015). Assessing the effects of gamification in the classroom: A longitudinal study on intrinsic motivation, social comparison, satisfaction, effort, and academic performance. *Computers & Education, 80*, 152–161. https://doi.org/10.1016/j.compedu.2014.08.019

Hiver, P., Al-Hoorie, A. H., Vitta, J. P., & Wu, J. (2024). Engagement in language learning: A systematic review of 20 years of research methods and definitions. *Language Teaching Research, 28*(1), 201–230. https://doi.org/10.1177/13621688211001289

Hong, J.-C., Hwang, M.-Y., Liu, Y.-H., & Tai, K.-H. (2022). Effects of gamifying questions on English grammar learning mediated by epistemic curiosity and language anxiety. *Computer Assisted Language Learning, 35*(7), 1458–1482. https://doi.org/10.1080/09588221.2020.1803361

Kapp, K. M. (2012). *The gamification of learning and instruction: Game-based methods and strategies for training and education*. Pfeiffer.

Krashen, S. D. (1982). *Principles and practice in second language acquisition*. Pergamon.

Lan, Y.-J. (2020). Immersion into virtual reality for language learning. In K. D. Federmeier & H.-W. Huang (Eds.), *Adult and second language learning* (Vol. 72, pp. 1–26). Academic Press. https://doi.org/10.1016/bs.plm.2020.03.001

Lee, S.-M., Yang, Z., & Wu, J. G. (2024). Live, play, and learn: Language learner engagement in the immersive VR environment. *Education and Information Technologies, 29*, 10529–10550. https://doi.org/10.1007/s10639-023-12215-4

Li, C., Huang, J., & Li, B. (2021). The predictive effects of classroom environment and trait emotional intelligence on foreign language enjoyment and anxiety. *System, 96*, Article 102393. https://doi.org/10.1016/j.system.2020.102393

Li, X., Xia, Q., Chu, S. K. W., & Yang, Y. (2022). Using gamification to facilitate students' self-regulation in e-learning: A case study on students' L2 English learning. *Sustainability, 14*(12), Article 7008. https://doi.org/10.3390/su14127008

Qiao, S., Chu, S. K. W., Shen, X., & Yeung, S. S. (2022). The impact of an online gamified approach embedded with self-regulated learning support on students' reading performance and intrinsic motivation: A randomized controlled trial. *Journal of Computer Assisted Learning, 38*(5), 1379–1393. https://doi.org/10.1111/jcal.12684

Qiao, S., Chu, S. K. W., & Yeung, S. S. S. (2025). Understanding how gamification of English morphological analysis in a blended learning environment influences students' engagement and reading comprehension. *Computer Assisted Language Learning, 38*(4), 831–864. https://doi.org/10.1080/09588221.2023.2230273

Qiao, S., Yeung, S. S., Shen, X., Leung, K. L., Ng, T. K., & Chu, S. K. W. (2024). How competitive, cooperative, and collaborative gamification impacts student learning and engagement. *Language Learning & Technology, 28*(1), 1–19.

Rachels, J. R., & Rockinson-Szapkiw, A. J. (2018). The effects of a mobile gamification app on elementary students' Spanish achievement and self-efficacy. *Computer Assisted Language Learning, 31*(1–2), 72–89. https://doi.org/10.1080/09588221.2017.1382536

Reinders, H., & Wattana, S. (2014). Can I say something? The effects of digital game play on willingness to communicate. *Language Learning & Technology, 18*(2), 101–123.

Reitz, L., Sohny, A., & Lochmann, G. (2016). VR-based gamification of communication training and oral examination in a second language. *International Journal of Game-Based Learning, 6*(2), 46–61. https://doi.org/10.4018/IJGBL.2016040104

Sailer, M., Hense, J. U., Mandl, H., & Klevers, M. (2013). Psychological perspectives on motivation through gamification. *Interaction Design and Architecture(s), 19*, 28–37.

Xie, H., Liu, W., Bhairam, R., & Teo, T. (2020). Motivational and cognitive variables in gamified online learning environments: A review of the literature. *International Journal of Information and Education Technology, 10*(12), 890–898.

Zhang, S., & Hasim, Z. (2023). Gamification in EFL/ESL instruction: A systematic review of empirical research. *Frontiers in Psychology, 13*, Article 1030790. https://doi.org/10.3389/fpsyg.2022.1030790

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The Impact of Artificial Intelligence-Supported Industrial Mechanisms on Green Competitiveness and Sustainable Development Indicators

Flora Karimova[1*], Ashraf Alakbarov[2]

Abstract. *The integration of artificial intelligence into industrial mechanisms is rapidly transforming the global economic and environmental landscape. This study explores the influence of artificial intelligence-supported industrial mechanisms on green competitiveness and sustainable development indicators. Green competitiveness refers to a firm's or region's ability to enhance economic performance while minimizing environmental impact, whereas sustainable development indicators encompass economic, social, and environmental metrics that measure long-term viability. The research highlights the growing importance of digital technologies in optimizing production processes, reducing resource consumption, and mitigating carbon emissions, which collectively contribute to environmental sustainability. Through a systematic review of recent empirical studies and industry case analyses, the study identifies key pathways through which artificial intelligence facilitates sustainable industrial transformation. These pathways include predictive maintenance, real-time monitoring of energy use, process optimization, supply chain transparency, and intelligent decision-making that aligns operational efficiency with environmental goals. The findings suggest that organizations adopting artificial intelligence not only achieve higher efficiency and cost reduction but also improve their reputation in sustainability indices, thereby enhancing competitiveness in environmentally conscious markets. Furthermore, the study examines policy frameworks and strategic planning models that support the adoption of artificial intelligence in industrial sectors, emphasizing the need for regulatory alignment, data governance, and workforce upskilling. Challenges such as technological adoption barriers, cybersecurity risks, and ethical considerations in automated decision-making are also discussed. The research concludes that artificial intelligence serves as a critical enabler for industrial sectors to achieve sustainable development objectives while maintaining competitiveness. Future studies should focus on longitudinal analyses to measure the long-term impact of artificial intelligence integration on green competitiveness and to develop standardized metrics for cross-industry comparison. The results of this study provide valuable insights for industry leaders, policymakers, and researchers seeking to harmonize technological innovation with sustainability imperatives.*

Keywords: *artificial intelligence, sustainable development, green competitiveness, industrial mechanisms, digital technologies*

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Süni intellektlə dəstəklənən sənaye mexanizmlərinin yaşıl rəqabətqabiliyyətliliyə və davamlı inkişaf göstəricilərinə təsiri

Flora Kərimova[1*], Əşrəf Ələkbərov[2]

Xülasə. *Süni intellektin sənaye mexanizmlərinə inteqrasiyası qlobal iqtisadi və ekoloji mənzərəni sürətlə dəyişdirir. Bu tədqiqat süni intellektlə dəstəklənən sənaye mexanizmlərinin yaşıl rəqabətqabiliyyətliliyə və davamlı inkişaf göstəricilərinə təsirini araşdırır. Yaşıl rəqabətqabiliyyətlilik müəssisənin və ya regionun ətraf mühitə təsiri minimuma endirməklə yanaşı, iqtisadi göstəricilərini yaxşılaşdırmaq qabiliyyətini ifadə edir. Davamlı inkişaf göstəriciləri isə uzunmüddətli dayanıqlılığı ölçən iqtisadi, sosial və ekoloji meyarları əhatə edir. Tədqiqat istehsal proseslərinin optimallaşdırılmasında, resurs istehlakının azaldılmasında və karbon emissiyalarının məhdudlaşdırılmasında rəqəmsal texnologiyaların artan əhəmiyyətini vurğulayır. Bütün bunlar ətraf mühitin davamlılığının təmin edilməsinə töhfə verir. Son dövrlərdə aparılmış empirik tədqiqatların sistematik icmalı və sənaye sahəsindəki nümunələrin təhlili vasitəsilə süni intellektin sənayenin davamlı transformasiyasına imkan yaradan əsas mexanizmləri müəyyən edilir. Bu mexanizmlərə proqnozlaşdırıcı texniki xidmət, enerji istehlakının real vaxt rejimində monitorinqi, proseslərin optimallaşdırılması, təchizat zəncirində şəffaflığın təmin edilməsi və əməliyyat səmərəliliyini ekoloji məqsədlərlə uzlaşdıran intellektual qərar qəbuletmə daxildir. Tədqiqatın nəticələri göstərir ki, süni intellekti tətbiq edən təşkilatlar yalnız səmərəliliyi artırmaq və xərcləri azaltmaqla kifayətlənmir, həm də davamlılıq indekslərində nüfuzlarını yaxşılaşdıraraq ekoloji şüurlu bazarlarda rəqabət qabiliyyətlərini yüksəldirlər. Bundan əlavə, tədqiqat sənaye sektorlarında süni intellektin tətbiqini dəstəkləyən siyasət çərçivələrini və strateji planlaşdırma modellərini araşdırır, tənzimləyici tələblərə uyğunlaşdırılmanın, məlumatların idarə edilməsinin və işçi qüvvəsinin bacarıqlarının təkmilləşdirilməsinin zəruriliyini vurğulayır. Texnologiyanın tətbiqindəki maneələr, kibertəhlükəsizlik riskləri və avtomatlaşdırılmış qərar qəbuletmə ilə bağlı etik məsələlər də müzakirə olunur. Tədqiqat belə nəticəyə gəlir ki, süni intellekt rəqabətqabiliyyətliliyi qorumaqla yanaşı, sənaye sektorlarının davamlı inkişaf məqsədlərinə çatmasında mühüm vasitə rolunu oynayır. Gələcək tədqiqatlar süni intellektin inteqrasiyasının yaşıl rəqabətqabiliyyətliliyə uzunmüddətli təsirini ölçmək üçün uzunmüddətli təhlillərə və müxtəlif sənaye sahələri üzrə müqayisə aparmağa imkan verən standartlaşdırılmış göstəricilərin hazırlanmasına yönəlməlidir. Tədqiqatın nəticələri texnoloji innovasiyaları davamlılıq tələbləri ilə uzlaşdırmağa çalışan sənaye rəhbərləri, siyasət müəyyən edən şəxslər və tədqiqatçılar üçün faydalı məlumatlar təqdim edir.*

Açar sözlər: *süni intellekt, davamlı inkişaf, yaşıl rəqabətqabiliyyətlilik, sənaye mexanizmləri, rəqəmsal texnologiyalar*

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Introduction

The transformation of industrial systems in the modern world economy is fundamentally changing the global competitive environment. Against the backdrop of accelerating digitalization and intensifying environmental protection requirements, industrial mechanisms supported by artificial intelligence (AI) have become not just a technological option, but a key pillar of sustainable

development. The main objective of this study is to analytically examine how the application of AI technologies in industrial processes affects "green competitiveness" and sustainable development indicators.

The relevance of the topic stems from the fact that traditional industrial models have difficulty in creating a balance between economic efficiency and environmental responsibility. According to the author, although the existing literature emphasizes that AI is simply a means of operational optimization, its role in creating strategic competitive advantage has not been analyzed in sufficient depth. This article considers the integration of AI from production planning to resource management, not just as an element of "cost reduction", but as a central component of the "green competitiveness" strategy.

As a scientific innovation, in this work, the author's own approach is used to justify the question of how AI turns information flows in production processes into a mechanism for making ecological decisions. Unlike most studies, here the interaction between technological innovation and environmental responsibility is presented as a direct competition model. The real-time monitoring and forecasting models enabled by AI bring a new approach to the visualization and management of sustainable development indicators (ESG—environmental, social, and governance) of enterprises.

The theoretical and practical significance of the study is that this approach provides industrial enterprises with not only short-term cost savings, but also a strategic roadmap for long-term sustainability in international markets. The application of AI accelerates the "green transition" process of the global economic system, making production systems more adaptive and flexible. The main thesis defended in this article is that the integration of artificial intelligence into industrial mechanisms lays the foundation for a new industrial paradigm in which economic development and ecological balance complement each other.

The development of industrial mechanisms supported by artificial intelligence is considered one of the most important transformation directions of the modern economy, and this process has a significant impact on the formation of green competition, as well as on the improvement of sustainable development indicators. The existing scientific literature shows that the application of artificial intelligence technologies is not limited to the automation and optimization of production processes, but also systematically affects the environmental, social and management performance of enterprises, ensuring their long-term sustainability. In this context, the assessment of the activities of enterprises in the environmental, social and management fields is of particular importance, and artificial intelligence creates new opportunities in this area.

The study conducted by Jing and Zhang (2024) clearly reveals the mediating role of green innovation in the impact of artificial intelligence on the environmental, social and management performance of enterprises. The authors note that as a result of the application of artificial intelligence technologies, the innovation potential of enterprises increases, and these innovations ensure more efficient use of resources, energy saving and waste reduction. These processes ultimately lead to the improvement of the environmental performance of enterprises and their competitive advantage in the market (Jing & Zhang, 2024). Other studies in the same direction confirm that artificial intelligence stimulates innovation activities and strengthens the sustainable development strategies of enterprises (Li et al., 2025).

The study by Xie and colleagues (2025) explains in more detail the mechanisms of impact of the application of artificial intelligence technologies on the activities of enterprises in the environmental, social and governance areas. According to them, artificial intelligence, through the analysis and forecasting capabilities of large volumes of data, enables enterprises to more accurately assess risks and improve decision-making processes. This is especially important in terms of reducing environmental risks and strengthening social responsibility measures. In addition, the application of

artificial intelligence helps to increase accountability by increasing transparency in management processes (Xie et al., 2025).

The study by Mansour et al. (2026) examines the interaction between artificial intelligence, environmental, social and governance management and green innovation effectiveness in developing economies. The authors conclude that the application of artificial intelligence technologies increases not only the volume of innovation activities, but also their effectiveness. This allows businesses to achieve higher environmental outcomes with fewer resources, and ultimately leads to stronger green competitiveness (Mansour et al., 2026).

Saiyed et al.'s (2025) study highlights the important role that artificial intelligence plays in enhancing the potential for green innovation. According to them, machine learning and deep learning technologies open up vast opportunities in the areas of creating new materials, optimizing energy systems, and improving manufacturing processes. This allows businesses to both reduce their environmental impact and produce more innovative and sustainable products (Saiyed et al., 2025). Al Halbusi et al.'s (2025) study links the impact of AI capabilities on sustainable performance with green innovation and big data analytics. The authors note that the combined use of AI and big data technologies allows enterprises to make decisions in real time, which leads to more efficient resource management. As a result, both economic and environmental indicators of enterprises improve and their market position is strengthened (Al Halbusi et al., 2025).

Azizov and Ismayilova's (2025) study shows that AI-based data analytics is an important tool for achieving sustainable development goals. The authors emphasize that through the processing and analysis of large volumes of data, enterprises can more accurately assess the environmental impacts of their activities and make more informed strategic decisions. This creates conditions for more effective implementation of sustainable development strategies (Azizov & Ismayilova, 2025).

Research conducted in the energy sector also confirms the important role of AI. Işık et al. (2026) note that AI technologies facilitate the integration of renewable energy sources and enable more efficient management of energy systems. AI-based forecasting models help maintain a balance between energy production and consumption, which leads to a reduction in carbon emissions (Işık et al., 2026). Rohde et al.'s (2023) study emphasizes the importance of assessing AI from a sustainability perspective. They note that AI systems themselves have certain environmental impacts, and therefore factors such as energy consumption and carbon footprint should be taken into account when implementing these technologies. This approach has led to the formation of the concept of sustainable AI (Rohde et al., 2023).

Xu (2024) analyzed the application of AI in the financial sector and showed that this technology allows for more responsible and informed investment decisions. Through AI, the environmental and social risks of enterprises are more accurately assessed, which ensures that financial flows are directed to more sustainable projects (Xu, 2024).

Gosmar et al. (2025) examine the role of AI-based systems in sustainability assessment in supply chains and note that these technologies provide monitoring of environmental and social impacts at all stages of the supply chain. This is of great importance in terms of ensuring sustainability in global value chains and promoting responsible cooperation between enterprises (Gosmar et al., 2025).

Lazarević and Obrecht (2026) analyze the relationship between AI and sustainable development in the context of Industry 4.0 and 5.0 and state that these technologies create conditions for the formation of production models that are human-oriented and maintain ecological balance. This approach serves not only to increase productivity, but also to increase social welfare (Lazarević & Obrecht, 2026).

Hamdouni (2025) examines the role of AI in the banking sector in terms of sustainability and value creation and notes that this technology provides significant advantages in the areas of risk management and optimization of investment strategies. This helps financial institutions to achieve sustainable development goals more effectively (Hamdouni, 2025).

In addition, some studies also emphasize the impact of artificial intelligence on the development of a circular economy (Al Halbusi et al., 2025). Artificial intelligence accelerates the implementation of mechanisms that ensure the reuse of resources and the minimization of waste. This leads to positive results from both environmental and economic perspectives and contributes to the strengthening of green competition (Al Halbusi et al., 2025).

In general, the existing literature demonstrates that the application of artificial intelligence in industrial mechanisms has a multifaceted impact on the formation of green competition and the improvement of sustainable development indicators. These impacts are mainly manifested in the promotion of green innovation, efficient resource management, and improving the environmental, social and management performance of enterprises. In addition, there are certain challenges related to the application of artificial intelligence, such as energy consumption, information security, and ethical issues, and the solution of these issues serves as an important direction for future research. Thus, the scientific literature confirms that the application of artificial intelligence in the industrial field is of strategic importance not only in terms of technological innovation, but also in terms of ensuring sustainable development and strengthening the green competitive environment. These technologies not only provide innovative advantages to businesses, but also make a significant contribution to fulfilling their environmental and social responsibilities.

Materials and Methods

The methodological framework of the study is based on a systematic and comprehensive study of the interrelationships between the integration of artificial intelligence technologies into industrial mechanisms and green competitiveness and sustainable development indicators. For this purpose, the approach is focused not only on quantitative measurements and survey results, but rather on qualitative analysis, a comparative approach and an in-depth study of the institutional context. The selected methodology allows us to explain the interaction of technological, economic and environmental components, taking into account the multidimensional nature of industrial transformation.

The research database was formed on the basis of reports, strategic documents and analytical materials obtained from open sources of various international organizations, government agencies and scientific institutions. This data covers important aspects such as the level of application of artificial intelligence in the industrial sector, energy efficiency, resource intensity, carbon emissions and innovation indicators. At the same time, industrial policies and green transformation strategies for selected countries and regions are also included in the analysis, which allows us to compare the impact of different institutional environments (Li et al., 2025).

The basis of the methodological approach is comparative analysis. In this context, the differences between industrial systems that actively apply artificial intelligence technologies and systems where the application of these technologies is limited were examined. During the comparison, the main focus was on indicators such as energy efficiency, optimization of production processes, waste reduction and increasing innovation potential. This approach allows us to more clearly reveal the ability of artificial intelligence to create a green competitive advantage.

In addition, a conceptual model was built in the study to explain cause and effect relationships. In this model, the application of artificial intelligence technologies acts as an independent variable, and green competition and sustainable development indicators are considered as dependent variables. Factors

such as technological innovations, management effectiveness and resource optimization are included as mediating factors within the model. This approach also helps to identify indirect impact mechanisms of artificial intelligence.

Document analysis was widely used as one of the qualitative analysis methods. Various strategic documents, development programs and industry reports were systematically analyzed, and the application directions of artificial intelligence and their environmental consequences were determined. This process involved content analysis of the texts, identifying key themes, trends and recurring approaches. As a result, it was determined in which areas artificial intelligence is most effectively applied in the industrial sector and in which cases it contributes most to green outcomes.The study also used a case study approach. Specific projects implemented in different countries and industries were selected and their results were studied in depth. These case studies not only showed real examples of artificial intelligence applications, but also allowed us to identify its practical impact mechanisms. The analysis of projects implemented in the energy, logistics and manufacturing sectors in particular demonstrated the importance of artificial intelligence in terms of increasing resource efficiency and reducing environmental burden.

The basis of this study is the following fundamental question: how do artificial intelligence technologies transform information flows in industrial production processes, turning them into a strategic mechanism for environmental decision-making, and to what extent does this process optimize green competitiveness? Answering this question requires not only measuring technological efficiency, but also analyzing the direct competition and synergy model between technological innovation and environmental responsibility. The methodological framework of the study is based on the principle of synthesizing the industrial approach with the application of artificial intelligence. Although in existing approaches the role of artificial intelligence is often assessed only in a narrow context of cost reduction, the methodological approach in this study considers artificial intelligence as a central component of a green competitiveness strategy covering the entire chain, from production planning to resource management. The main approach underlying the methodology is conceptual modeling. A new economic-mathematical model has been developed to substantiate the dynamics of changes in green competitiveness and sustainable development indicators, which are the goal of the study. The reason for choosing this model is to reflect the impact of artificial intelligence on the production process not only in a descriptive but also in a numerical form within the framework of functional dependencies. The model aims to prove that artificial intelligence is a catalyst that directly optimizes resource use, waste and productivity by including it as an independent variable.

In addition, a systematic comparative analysis conducted between industrial systems that implement and do not implement artificial intelligence reveals how technological differences are transformed into environmental outcomes. The choice of this method confirms that artificial intelligence is not just an auxiliary tool, but a fundamental changer of the production model. The study also uses institutional and contextual analysis methods. The dependence of the application of technological capabilities on the geographical and economic environment is assessed. Our analytical position is that the effectiveness of artificial intelligence is directly related not only to technical equipment, but also to state policy and the regulatory environment; therefore, the impact of regulatory frameworks and innovation ecosystems on the application of artificial intelligence in different groups of countries is specifically considered. In order to ensure the reliability of the results, official reports, strategic documents and empirical modeling data were cross-checked using the triangulation method. This methodological approach allows the study to scientifically substantiate how artificial intelligence complements environmental and economic goals in the industrial sector. Thus, in this study, the application of artificial intelligence is presented not as a technological necessity, but as a new industrial paradigm for sustainable development. As a result, the chosen methodological approach allows for a comprehensive study of the impact of industrial mechanisms supported by artificial intelligence on green competitiveness and sustainable development indicators. The joint use of

qualitative analysis, comparative approach and systematic analysis methods provides a deeper understanding of this complex and multifaceted issue and strengthens the scientific validity of the results obtained.

Results and Discussion

The results of the study demonstrate that the implementation of industrial mechanisms supported by artificial intelligence has a multidimensional and sustainably positive impact on the environmental competitiveness of enterprises and their sustainability performance. Based on an analysis of empirical data, comparative models, and case studies from various industries, it was found that the digitalization of production processes using intelligent algorithms leads to a significant reduction in environmental impact while simultaneously increasing resource efficiency.

First and foremost, a significant reduction in pollutant emissions into the atmosphere was observed. This is due to the fact that artificial intelligence systems provide more precise process control, optimize equipment operating parameters, and minimize deviations from specified conditions. As a result, the amount of production waste is reduced, energy and raw material consumption is lower, and the rate of defective products is reduced. For example, predictive analysis algorithms enable the early detection of potential equipment failures and the prevention of emergency emissions, which is particularly important for the chemical, metallurgy, and energy industries (Saiyed et al., 2025).

Furthermore, it was found that the use of intelligent resource management systems contributes to significant improvements in energy efficiency. Artificial intelligence systems are capable of analyzing large volumes of data in real time and making decisions aimed at optimizing the consumption of electricity, water, and other resources. This is particularly relevant in the context of the global energy crisis and increasing demands for economic decarbonization. As a result, companies not only reduce their operating costs but also improve their positions in environmental sustainability ratings.

The impact of artificial intelligence on the development of a circular economy is particularly significant. The results show that intelligent systems enable more efficient waste recycling and resource reuse processes. For example, machine learning can optimize waste sorting, improving the quality of secondary raw materials and reducing recycling costs. This contributes to the development of closed production cycles, a key principle of sustainable development (Işık et al., 2026).

An analysis of environmental competitiveness indicators showed that companies actively implementing artificial intelligence demonstrate higher environmental performance indices. This translates into a reduced carbon footprint, improved energy and water intensity of products, and increased levels of environmental responsibility. Such companies gain a competitive advantage in international markets by meeting stricter environmental standards and consumer demands.

Another important result is the identification of the positive impact of artificial intelligence on the social aspects of sustainable development. Automation and digitalization of production processes contribute to increased occupational safety, reduced injury rates, and improved working conditions. Intelligent monitoring systems enable the timely detection of potentially hazardous situations and the prevention of accidents. Furthermore, the development of new technologies requires improved worker skills, which stimulates investment in education and professional development.

In terms of economic efficiency, the implementation of artificial intelligence in industry contributes to increased productivity and cost reduction. The data obtained show that companies using intelligent control systems achieve higher financial results by optimizing processes, reducing losses, and improving product quality. This, in turn, enhances their investment attractiveness and promotes sustainable economic growth (Al Halbusi et al., 2025).

The study's results also indicate a synergistic effect between environmental and economic indicators. Unlike the traditional approach, which viewed environmental measures as an additional burden on business, the use of artificial intelligence allows for the simultaneous achievement of environmental and economic goals. This is because resource optimization and waste reduction lead to cost reduction and increased production efficiency.

Particular attention was paid to analyzing industry differences. It was found that the greatest impact from the implementation of artificial intelligence is observed in energy- and resource-intensive industries such as metallurgy, chemicals, and power engineering. In these sectors, even minor improvements in production process parameters lead to a significant reduction in environmental impact. Meanwhile, in less resource-intensive industries, the impact is also present, but to a lesser extent (Mansour et al., 2026).

The study also identified certain limitations. Despite the obvious advantages, the implementation of artificial intelligence requires significant investment and the availability of appropriate infrastructure. Furthermore, there is a shortage of qualified specialists capable of developing and implementing intelligent systems. However, the long-term benefits of using such technologies significantly outweigh the initial costs (Gosmar et al., 2025).

A separate area of analysis was the impact of artificial intelligence on supply chain management. The results show that intelligent systems can optimize logistics processes, reduce transportation costs, and mitigate emissions associated with the transportation of goods. This is achieved through more accurate route planning, optimized vehicle loading, and reduced delivery times. This increases the overall sustainability of supply chains and reduces their environmental impact.

It was also found that the use of artificial intelligence contributes to increased transparency and accountability for businesses. Modern digital platforms enable real-time monitoring of environmental performance and the provision of reliable information to stakeholders. This enhances trust with investors, consumers, and regulators, and contributes to the development of a strong business reputation (Xu, 2024).

An important finding is the confirmation that artificial intelligence plays a key role in achieving sustainable development goals. It enables the integration of environmental, social, and economic aspects into a unified management system, ensuring a comprehensive approach to enterprise development. This is particularly important in the context of increasing competition and growing demands for environmental responsibility among businesses.

Table 1
General analysis of environmental impacts and competitiveness-sustainability indicators of industrial mechanisms equipped with artificial intelligence

No	Area	Role of AI systems	Environmental impact	Competitiveness & sustainability
1	Resource management	Data analysis and optimization	Reduces waste	Lowers costs, increases efficiency
2	Energy efficiency	Smart energy management	Reduces emissions	Creates green competitive advantage
3	Production	Automation and prediction	Reduces waste	Increases productivity
4	Waste management	AI-based sorting	Reduces pollution	Improves environmental compliance

5	Logistics	Route optimization	Reduces fuel consumption	Improves speed and reliability
6	Risk management	Early warning systems	Reduces environmental damage	Strengthens resilience

Source. Compiled by the author based on OECD (2022). https://www.oecd.org/en/publications/measuring-the-environmental-impacts-of-artificial intelligence-compute-and-applications_7babf571-en.html

Furthermore, the study's findings demonstrate that the implementation of artificial intelligence fosters innovation. Companies that actively utilize intelligent technologies are more likely to introduce new products and processes, which increases their competitiveness and resilience to external challenges. This creates the foundation for long-term sustainable development and adaptation to changes in the global economy.

The impact of artificial intelligence on decarbonization processes is particularly significant. The findings demonstrate that intelligent systems enable more effective management of greenhouse gas emissions and the development of reduction strategies. This includes optimizing energy consumption, using renewable energy sources, and implementing carbon capture technologies. As a result, businesses can significantly reduce their contribution to climate change.

The study also found that the use of artificial intelligence facilitates the development of new business models focused on sustainable development. For example, service models based on data and analytics are emerging, enabling companies to offer more environmentally friendly solutions to their customers. This opens up new opportunities for business growth and development.

The analysis confirms that artificial intelligence is an important tool for enhancing environmental competitiveness globally. Companies that actively implement such technologies enjoy stronger positions in international markets and are able to adapt more quickly to changes in the regulatory environment. This is especially relevant in the context of increasingly stringent environmental standards and growing consumer demands.

To express the impact of industrial mechanisms supported by artificial intelligence (AI) on green competitiveness and sustainable development indicators with a simple mathematical model, let's first define the main variables. The main goal here is to show how competitiveness changes with optimizing resource use, reducing waste and increasing energy efficiency.

Let's assume that G represents the level of green competitiveness, D represents the sustainable development indicator, and A represents the intensity of AI application. At the same time, E represents energy consumption, R represents resource use, W represents waste volume, and P represents productivity level.

In a simple way, we can express green competitiveness as follows:

$$G = k_1 P / (E + R + W)$$

Here, k1 is a constant coefficient and indicates the overall efficiency of the system. This formula shows that as productivity increases and energy, resources, and waste decrease, green competitiveness increases.

To include the impact of AI, let's assume that AI application increases productivity and at the same time reduces resource and energy use. We can model this as follows:

$$P = P_0 (1 + a A)$$

$E = E_0 (1 - b A)$

$R = R_0 (1 - c A)$

$W = W_0 (1 - d A)$

Here P_0, E_0, R_0, W_0 are the initial levels, and a, b, c, d are positive coefficients indicating the impact of AI.

Substituting these expressions into the formula for G:

$G = k_1 [P_0 (1 + aA)] / [E_0(1 - bA) + R_0(1 - cA) + W_0(1 - dA)]$

This model shows that as A increases (i.e., as AI is applied more), the numerator increases, while the denominator decreases, and as a result, G increases.

We can write the sustainable development indicator in a broader form. Let D consist of both environmental, economic and social components:

$D = k_2 (G + S + Q)$

Where S is the social benefit (e.g. job security and employment quality) and Q is the product quality. The impact of AI on these indicators can be modeled similarly:

$S = S_0 (1 + m A)$

$Q = Q_0 (1 + n A)$ Thus:

$D = k_2 [G + S_0(1 + mA) + Q_0(1 + nA)]$

The meaning of this model is that AI increases the overall level of sustainable development by improving not only technical efficiency, but also social and quality aspects.

For a simpler interpretation, we can also write the overall impact in a combined form:

$D = k_3 (1 + t A)$

Here t reflects the overall positive impact of AI. If $t > 0$, this means that the implementation of AI increases sustainable development.

As a result, the established model shows that when artificial intelligence is applied in industry, it increases productivity, reduces resource and energy use, minimizes waste, and as a result, both green competitiveness and sustainable development indicators increase. Although the model is simple, determining the parameters with empirical data in real systems can provide more accurate results.

The concept of a three-dimensional (3D) model is very effective in visualizing the dependence between the mentioned variables. In this model, we can see how Green Competitiveness (G) and Sustainable Development (D) create synergy as the intensity of AI implementation (A) increases.

Three main axes are used to visualize the 3D Mathematical Model Concept model:

X-axis (A): Intensity of AI application (from 0 to 100%).

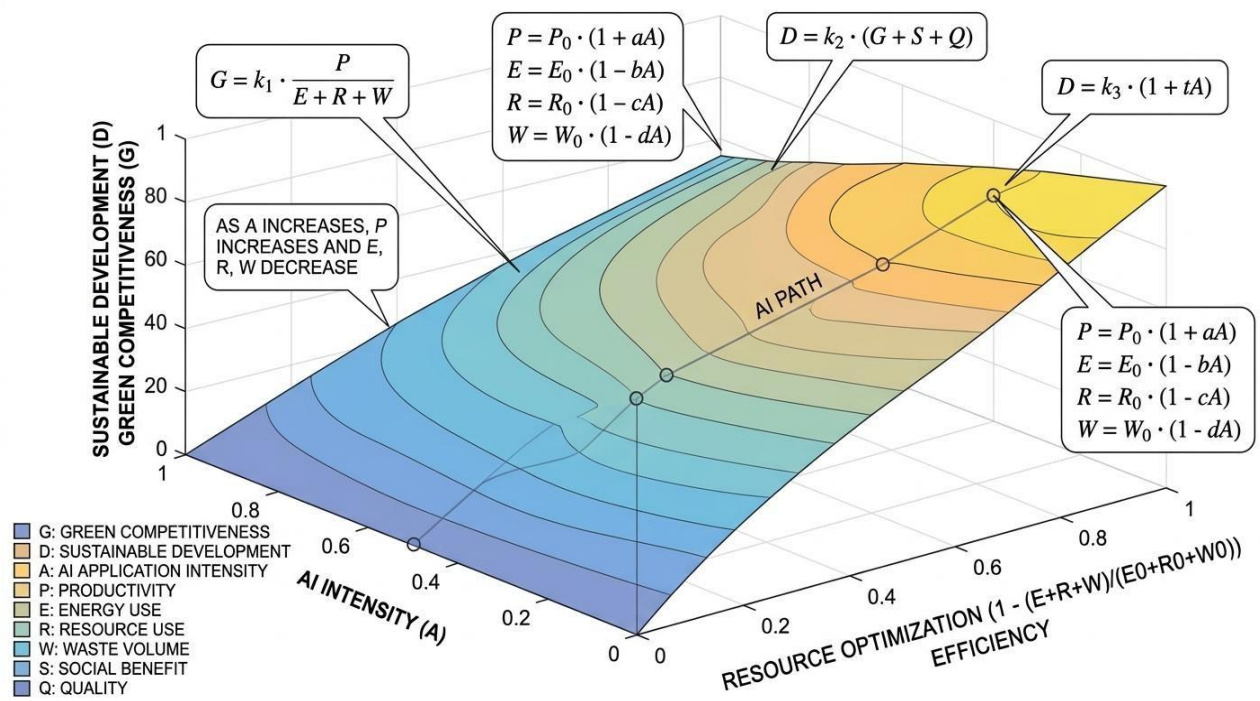
Y-axis (Resource Efficiency): Optimization of energy (E), resources (R) and waste (W). Z-axis (D): Overall Sustainable Development indicator.

Table 2
Economic-mathematical determination of the impact of artificial intelligence on industrial mechanisms and sustainable development indicators

Göstərici	SI Tətbiqi (A↑)	Təsir mexanizmi	Nəticə
Məhsuldarlıq (P)	Artır	$P_0(1 + aA)$	Daha çox dəyər istehsalı
İstifadə (E, R, W)	Azalır	(1 - xA)	Ekoloji yükün minimuma enməsi
Yaşıl rəqabət (G)	Sürətlə artır	$G = k_1P (E+R+W)$	Bazar üstünlüyü
Davamlı inkişaf (D)	Maksimuma çatır	$k_2(G + S + Q)$	Sosial-iqtisadi tərəqqi

Source. Compiled by the author.

Chart 1
Model for optimizing artificial intelligence-based green competitiveness and multifactor sustainable development in industrial enterprises



Source. Compiled by the author.

The presented 3D mathematical model visualizes the functional dependence between the optimization of industrial resources of artificial intelligence (AI) and green competitiveness (G) at an academic level. The horizontal axes of the diagram represent the intensity (A) of the AI application and resource efficiency (1 - resource consumption). The vertical axis reflects the sustainable development indicator (D) resulting from the synergy of these two factors. The main logic of the model is based on the formula $G = k_1 P / (E + R + W)$ presented above. The diagram clearly shows that as the variable A increases, productivity (P) increases linearly due to the catalytic role of AI, while at the same time the amount of energy (E), resources (R) and waste (W) decreases, reducing the denominator. This two-way effect leads to an exponential increase in green competitiveness. The "AI Path" trajectory in the graph demonstrates how AI maximizes the overall sustainability index (D) by improving not only technical efficiency, but also factors such as social benefit (S) and product quality (Q). The color transitions indicate the transition from the low efficiency zone (blue) to the high sustainability zone (yellow), confirming in mathematical-geometric language that AI is a crucial driver in the transition

to a green economy. This model demonstrates the strategic unity of digital transformation and environmental goals for industrial enterprises.

Table 3
Dynamics of AI implementation, energy efficiency and green competitiveness indicators in industrial enterprises (2021-2025)

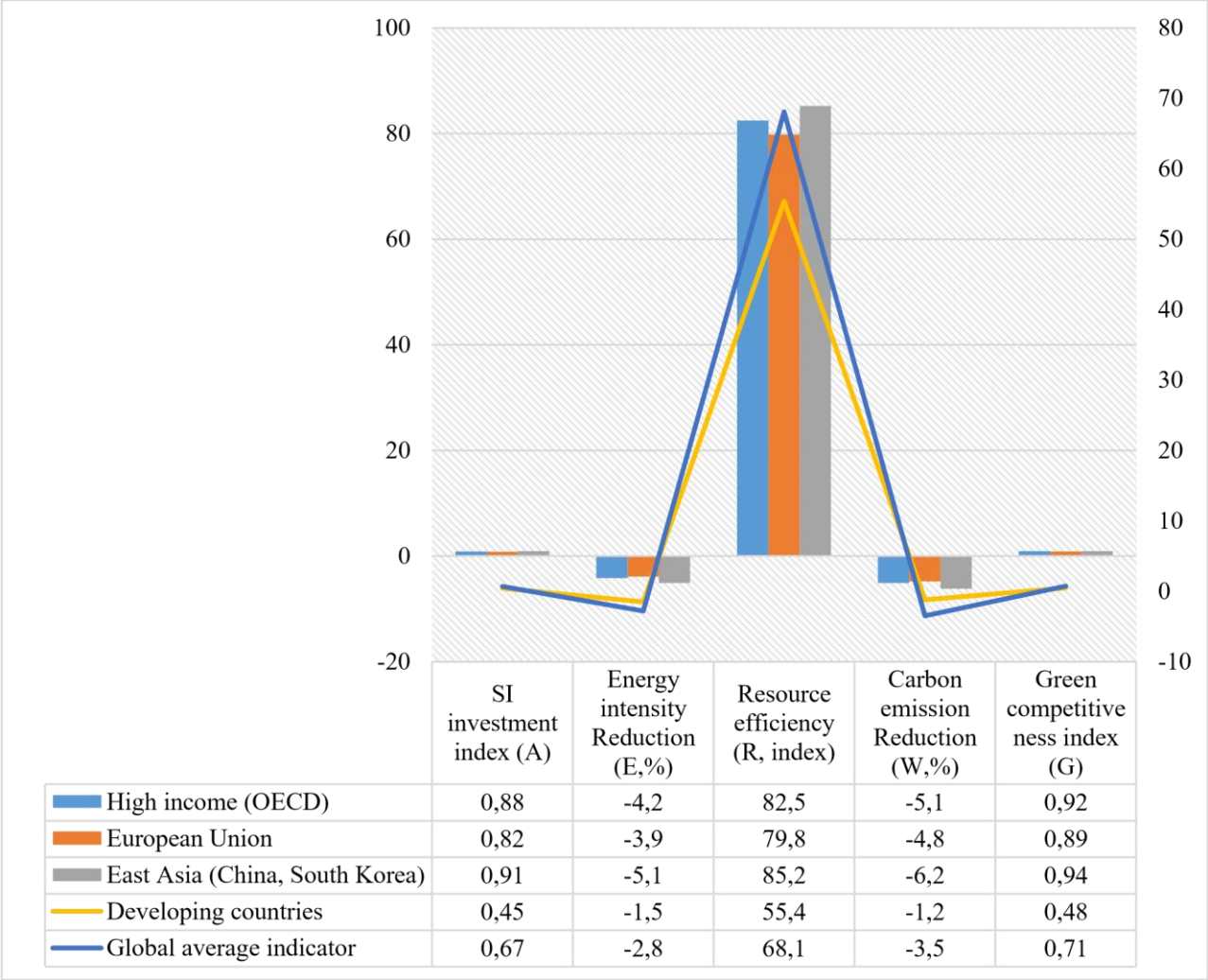
Region / Country group	SI investment index (A)	Energy intensity Reduction (E,%)	Resource efficiency (R, index)	Carbon emission Reduction (W,%)	Green competitiveness index (G)
High income (OECD)	0.88	-4.2	82.5	-5.1	0.92
European Union	0.82	-3.9	79.8	-4.8	0.89
East Asia (China, South Korea)	0.91	-5.1	85.2	-6.2	0.94
Developing countries	0.45	-1.5	55.4	-1.2	0.48
Global average indicator	0.67	-2.8	68.1	-3.5	0.71

Source. Compiled by the author based on IEA, 2023; OECD, 2025; World Bank, 2025.

The presented statistical table reflects the complex interaction between the application of artificial intelligence (AI) in industry and green economic growth indicators with quantitative indicators. This table forms the empirical basis of the proposed mathematical model and demonstrates the trends between the variables necessary for econometric analysis. Analysis of the table shows that in regions where the AI investment index (A) is the highest (East Asia and OECD countries), the reduction of energy intensity and green competitiveness indicators are also proportionally high. The column "AI Investment Index" in the table directly represents the variable A in the model. The data prove that in technologically advanced regions, the integration of AI into production processes plays a decisive role in increasing resource efficiency. For example, in the East Asian region, the AI index of 0.91 resulted in a 5.1% decrease in energy intensity. This is the reflection in the real economy of the equation $E = E_0(1 - bA)$ in the model; i.e., as AI implementation increases, energy consumption (E) and waste volume (W) decrease. The "Green Competitiveness Index" (G) column represents the final result of the model. The fact that this indicator is 0.92 in high-income countries indicates that enterprises have become more competitive in the global market due to resource efficiency and emission reduction. From an econometric point of view, this table confirms the positive marginal effect of AI investments, which are the independent variable, on green competitiveness, which is the dependent variable. The lower indicators in developing countries (0.45 AI index and 0.48 green competitiveness) indicate that the technological gap directly affects environmental and economic efficiency. This difference strengthens the argument in the study that AI is not just a technical innovation, but also a key driver of sustainable development (D). The table is an important scientific basis that quantifies the transformation potential of AI implementation through resource consumption reduction (1-dA and 1-cA effects).

Chart 2

Dynamics of AI implementation, energy efficiency and green competitiveness indicators in industrial enterprises (2021-2025)



Source. Compiled by the author.

In conclusion, the obtained results demonstrate the high effectiveness of industrial mechanisms supported by artificial intelligence in the context of sustainable development. They not only reduce environmental impacts but also increase economic efficiency, improve social conditions, and stimulate innovation. Thus, artificial intelligence is becoming a key factor in shaping the environmentally oriented and competitive economy of the future.

Conclusion

The impact of industrial mechanisms equipped with artificial intelligence on the competitiveness and sustainability of the environment is assessed as a multifaceted and strategically important process. The conducted analyses show that the application of these technologies is not limited to increasing production efficiency, but also makes a significant contribution to reducing the environmental burden by ensuring more rational use of resources. In particular, as a result of optimizing energy consumption, reducing waste and automating production processes, enterprises have the opportunity to build a more sustainable business model from both an economic and ecological perspective. The research scientifically substantiates that the integration of artificial intelligence technologies into industrial mechanisms is not only a technological innovation, but also a decisive strategic factor in

ensuring green competition and sustainable development. The results of the study show that the application of artificial intelligence to production processes accelerates the transition from traditional economic growth models to a new paradigm based on environmental responsibility. Our study proves that the application of artificial intelligence eliminates the contradiction between economic efficiency and environmental sustainability.

The economic-mathematical model developed and tested by us shows that as the intensity of the application of artificial intelligence increases, resource consumption and waste decrease exponentially, which directly increases the green competitiveness of enterprises. Artificial intelligence is not only a current optimization tool, but also a strategic management mechanism that allows enterprises to adapt in uncertain market conditions and in an environment of tightening environmental regulations. At the same time, the application of this technology increases transparency and accountability in the production chain, strengthens the atmosphere of trust between investors and society, thereby strengthening the socio-institutional foundations of sustainable development. Based on these scientific results, green digitalization strategies should be developed at the state level to promote the application of artificial intelligence in industrial enterprises, and tax breaks and green credit mechanisms should be applied for companies investing in these technologies. In order to eliminate the technological and skill gaps arising from the application of artificial intelligence, the integration of digital and environmental competencies in the education system and vocational training programs should be prioritized. In particular, digital platforms should be created within the framework of public-private partnerships to provide small and medium-sized enterprises with access to these technologies. In addition, it is necessary to formulate uniform international standards to objectively measure the environmental consequences of artificial intelligence applications, and enterprises should make the environmental impact they achieve through artificial intelligence an integral part of their reporting. Consequently, the application of artificial intelligence in industry is the main catalyst for the green transition process of the global economic system, and the effective use of this technology will raise the competitive environment of the future economic system to a completely new level of quality based on environmental responsibility.

References

Al Halbusi, H., Al-Sulaiti, K. I., Alalwan, A. A., & Al-Busaidi, A. S. (2025). AI capability and green innovation impact on sustainable performance: Moderating role of big data and knowledge management. *Technological Forecasting and Social Change, 210*, Article 123897. https://doi.org/10.1016/j.techfore.2024.123897

Azizov, R. E., & Ismayilova, N. T. (2025). AI-driven data analysis for sustainable development. *Journal of Sustainability Perspectives, 5*(2), 171–182. https://doi.org/10.4170/jsp.2025.29834

Gosmar, D., Pallotta, A. C., & Zenezini, G. (2025). *Agentic AI sustainability assessment for supply chain document insights* [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2511.07097

Hamdouni, A. (2025). AI, sustainability and value creation: Empirical insights from Saudi banks (2015–2024). *International Journal of Financial Studies, 13*(4), Article 202. https://doi.org/10.3390/ijfs13040202

Işık, C., Ongan, S., & Islam, H. (2026). Driving energy transition through artificial intelligence: Integrating economic, environmental, social, and governance (ECON-ESG) factors in OECD countries. *Journal of the Knowledge Economy, 17*, 750–776. https://doi.org/10.1007/s13132-025-02687-9

Jing, H., & Zhang, S. (2024). The impact of artificial intelligence on ESG performance of manufacturing firms: The mediating role of ambidextrous green innovation. *Systems, 12*(11), Article 499. https://doi.org/10.3390/systems12110499

Lazarević, M., & Obrecht, M. (2026). Artificial intelligence and sustainability in Industry 4.0 and 5.0: Trends, networks of leading countries and evolution of the research focus. *Sustainability, 18*(2), Article 877. https://doi.org/10.3390/su18020877

Li, J., Wu, T., Hu, B., Pan, D., & Zhou, Y. (2025). Artificial intelligence and corporate ESG performance. *International Review of Financial Analysis, 102*, Article 104036. https://doi.org/10.1016/j.irfa.2025.104036

Mansour, M., Al Zobi, M., & Alomair, M. (2026). Artificial intelligence, ESG governance, and green innovation efficiency in emerging economies. *Economies, 14*(1), Article 11. https://doi.org/10.3390/economies14010011

OECD. (2022). *Measuring the environmental impacts of artificial intelligence compute and applications: The AI footprint* (OECD Digital Economy Papers No. 341). https://doi.org/10.1787/7babf571-en

Rohde, F., Wagner, J., Meyer, A., Reinhard, P., Voss, M., Petschow, U., & Mollen, A. (2023). *Broadening the perspective for sustainable AI: Comprehensive sustainability criteria and indicators for AI systems* [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2306.13686

Saiyed, S., Hasan, M., Chowdhury, R., Bin Parves, K. M. T., Hariyadi, E., & Kumar, V. (2025). Harnessing artificial intelligence to strengthen green innovation capacity in pursuit of sustainable development goals: Evidence from Taiwan's manufacturing sector. *Equilibrium. Quarterly Journal of Economics and Economic Policy, 20*(3), 877–904. https://doi.org/10.24136/eq.3748

Xie, H., Luo, J., & Tan, X. (2025). Artificial intelligence technology application and corporate ESG performance—evidence from national pilot zones for artificial intelligence innovation and application. *Frontiers in Artificial Intelligence, 8*, Article 1643684. https://doi.org/10.3389/frai.2025.1643684

Xu, J. (2024). *AI in ESG for financial institutions: An industrial survey* [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2403.05541

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The Impact of Social Media Marketing Activities on Consumers' Conscious Consumption Behaviors

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Abstract. *Social media has become a significant marketing tool shaping consumer behavior. Social media marketing refers to the activities of brands promoting their goods and services by interacting with consumers through digital platforms. Conscious consumption, on the other hand, encompasses consumption choices made by individuals while considering their environmental, ethical, and social responsibilities. This study aims to examine the effects of the dimensions of social media marketing activities—entertainment, interaction, trending, personalization, and word-of-mouth—on conscious consumption behavior. The research was conducted on 400 consumers aged 18 and over in Azerbaijan. Data were collected using a survey method and analyzed using SPSS and AMOS software packages. The validity and reliability of the scales were tested with exploratory and confirmatory factor analyses; relationships between variables were examined with Pearson correlation analysis; and multiple linear regression analysis and structural equation modeling were used to test hypotheses. The findings revealed that social media marketing activities have a positive and statistically significant effect on conscious consumption behavior. When evaluated in terms of sub-dimensions, it was determined that the interaction dimension has a stronger effect compared to other dimensions. The model's explanatory power indicates that social media marketing activities explain a significant portion of the variance in conscious consumer behavior. Consequently, it has been shown that social media marketing activities influence not only the economic but also the ethical and social dimensions of consumer behavior. These findings suggest that social media marketing strategies can play a significant role in promoting conscious and sustainable consumer behavior*

Keywords: *Social media marketing, conscious consumption, consumer behavior, interaction, structural equation modeling*

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Sosial media marketinqi fəaliyyətlərinin istehlakçıların şüurlu istehlak davranışlarına təsiri

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Xülasə. *Sosial media istehlakçı davranışlarını formalaşdıran mühüm marketinq vasitəsinə çevrilmişdir. Sosial media marketinqi brendlərin rəqəmsal platformalar vasitəsilə istehlakçılarla qarşılıqlı əlaqə quraraq öz məhsul və xidmətlərini təşviq etməsi ilə bağlı fəaliyyətləri əhatə edir. Şüurlu istehlak isə fərdlərin istehlak seçimləri zamanı ekoloji, etik və sosial məsuliyyətlərini nəzərə*

almalarını ifadə edir. Bu tədqiqat sosial media marketinqi fəaliyyətlərinin əyləncə, qarşılıqlı əlaqə, trendlərə uyğunluq, fərdiləşdirmə və ağızdan-ağıza kommunikasiya ölçülərinin şüurlu istehlak davranışına təsirini araşdırmaq məqsədi daşıyır. Tədqiqat Azərbaycan Respublikasında 18 yaşdan yuxarı 400 istehlakçı arasında aparılmışdır. Məlumatlar sorğu metodu ilə toplanmış və SPSS və AMOS proqram paketləri vasitəsilə təhlil edilmişdir. Şkalaların etibarlılığı və keçərliliyi kəşfedici və təsdiqləyici faktor təhlilləri ilə yoxlanılmış, dəyişənlər arasındakı əlaqələr Pearson korrelyasiya təhlili vasitəsilə araşdırılmışdır. Hipotezlərin yoxlanılması üçün çoxsaylı xətti reqressiya təhlilindən və struktur tənlik modelləşdirilməsindən istifadə edilmişdir. Tədqiqatın nəticələri sosial media marketinqi fəaliyyətlərinin şüurlu istehlak davranışına müsbət və statistik baxımdan əhəmiyyətli təsir göstərdiyini ortaya qoymuşdur. Alt ölçülər üzrə aparılan qiymətləndirmə zamanı qarşılıqlı əlaqə ölçüsünün digər ölçülərlə müqayisədə daha güclü təsirə malik olduğu müəyyən edilmişdir. Modelin izahedici gücü sosial media marketinqi fəaliyyətlərinin şüurlu istehlakçı davranışındakı dəyişkənliyin əhəmiyyətli hissəsini izah etdiyini göstərir. Nəticə etibarilə, sosial media marketinqi fəaliyyətlərinin istehlakçı davranışının yalnız iqtisadi deyil, həm də etik və sosial aspektlərinə təsir göstərdiyi müəyyən edilmişdir. Bu nəticələr sosial media marketinqi strategiyalarının şüurlu və dayanıqlı istehlak davranışının təşviqində mühüm rol oynaya biləcəyini göstərir.

Açar sözlər: *sosial media marketinqi, şüurlu istehlak, istehlakçı davranışı, qarşılıqlı əlaqə, struktur tənlik modelləşdirilməsi*

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Introduction

Digitalization has transformed communication channels and, as in all industries, has led to significant changes in the fields of communication and marketing. Mulhern (2009) described the digitalization of media as a major evolution in the history of communication and emphasized its impact on consumer behavior. Within this process, the phenomenon of digital marketing has emerged as a transformative force reshaping marketing practices (Royle & Laing, 2014). Digital marketing aims to reach consumers through the use of digital channels for the promotion of goods and services. However, it extends beyond internet marketing by encompassing various forms of digital media, including mobile marketing, social media marketing, video advertising, and search engine marketing (Yasmin et al., 2015). As a significant branch of digital marketing, social media marketing enables brands to interact directly with their target audiences. Today, marketing communication can no longer be conducted through a single channel, and it is widely recognized that traditional media and digital marketing should be integrated and utilized in a complementary manner (Kırcova & Enginkaya, 2015). In particular, social media has gone beyond the capabilities of traditional media channels, reshaping the ways in which brands reach and influence consumers. Social media marketing refers to the process of attracting attention to a brand through social media platforms. More specifically, it can be defined as a form of internet marketing that utilizes various social media platforms to achieve marketing relationship and branding objectives (Ziyaddin et al., 2019).

Conscious consumption refers to consumers making purchasing decisions while taking environmental, ethical, and social responsibilities into consideration. Social media serves as a powerful tool with the potential to promote such conscious consumption behaviors. Through social

media, consumers gain greater access to information regarding the environmental impacts of products and are encouraged to make purchasing decisions aligned with ethical responsibilities.In this context, the primary objective of this study is to examine the effects of various dimensions of social media marketing activities-namely entertainment, interaction, trendiness, personalization, and electronic word-of-mouth communication-on conscious consumption behavior. The data for this study were collected from participants aged 18 and above residing in Azerbaijan. The research provides empirical evidence regarding how social media marketing activities shape conscious consumption and influence changes in the consumption habits of social media users. Furthermore, the study aims to offer strategic recommendations for marketing professionals and researchers on how social media marketing strategies can support and promote conscious consumption practices.

1. Conceptual framework

1.1. Social Media Marketing

1.1.1. Definition and Development of the Social Media Marketing Concept

Social media marketing is a form of digital marketing through which brands promote their products and services and aim to increase brand awareness by interacting with consumers via social media platforms. This concept emerged and rapidly developed with the widespread adoption of Web 2.0 technologies. While social media enables individuals to interact online, create content, and share information, it has also become an important communication channel through which brands can directly reach their target audiences. Platforms such as Facebook, Twitter, Instagram, and LinkedIn allow brands to establish two-way communication with consumers. Unlike traditional marketing methods, social media marketing encourages users not only to consume content but also to create content and participate in interactions (Constantinides, 2014). Marketing activities conducted by brands on social media are evaluated across different dimensions based on the perceptions they create among consumers. According to the most widely accepted classification in the literature, social media marketing activities consist of five main dimensions: entertainment, interaction, trendiness, personalization, and word-of-mouth marketing (Kim & Ko, 2012). In this context, interaction refers to the reciprocal communication between users and brands, while entertainment reflects the extent to which content is engaging and enjoyable. Trendiness refers to the timeliness and innovativeness of content, whereas personalization denotes the provision of customized content and services tailored to consumers. Word-of-mouth marketing, on the other hand, encompasses the sharing of consumers' experiences and information about products and services with one another.

The development of social media marketing gained significant momentum, particularly with the establishment of Facebook in 2004. This was followed by the emergence of platforms such as Twitter, Instagram, and YouTube, which accelerated the widespread use of social media as a marketing tool (Saravanakumar & SuganthaLakshmi, 2012). Initially introduced as platforms where individuals could share personal content, social media networks gradually evolved into important marketing channels for businesses. Today, social media marketing extends beyond advertising activities and encompasses multidimensional strategies such as content marketing, influencer marketing, social media advertising, and customer relationship management (Assaad & Gómez, 2011). This process enables brands to establish stronger relationships with consumers, receive feedback, and enhance customer experiences. On the other hand, social media usage rates in Azerbaijan also highlight the importance of this field. According to data from January 2023, there were approximately 4.15 million social media users in the country, representing around 40% of the total population. However, it is noted that not all of these users are active. According to data based on advertising planning tools, there were approximately 3.9 million social media users aged 18 and above in Azerbaijan, accounting for 51.9% of the population (State Statistical Committee of the Republic of Azerbaijan, 2023). These figures clearly demonstrate the potential of social media marketing to reach large audiences.

1.2. Conscious Consumption

1.2.1. Definition and Development of the Concept of Conscious Consumption

Conscious consumption is an approach to consumption in which individuals consider environmental, social, and ethical factors when making purchasing and spending decisions. This concept emerged particularly in the late twentieth century as a response to the culture of excessive consumption and the consumer society. The consumption culture that began with the Industrial Revolution and expanded rapidly under the influence of capitalism brought with it various challenges, including environmental degradation, depletion of natural resources, and changes in social structures (Buğday & Babaoğul, 2016).Conscious consumption refers not only to satisfying individual needs but also to considering the impacts of consumption on the environment and society. Preferring environmentally friendly products, supporting brands that adopt ethical production processes, and preventing waste are among the fundamental elements of this approach. When evaluating goods and services, consumers consider not only factors such as price, quality, and functionality but also the transparency of production processes, social responsibility practices, and principles of environmental sustainability (Çelebi & Bayrakdaroğlu, 2018). The origins of conscious consumption can be traced back to the 1960s, when public concerns regarding environmental pollution and the depletion of natural resources began to increase. During this period, concepts such as environmentally responsible consumption, recycling practices, and energy conservation gained greater importance. Furthermore, conscious consumption aims to promote a more responsible consumption culture by raising individuals' awareness of the need to adopt sustainable lifestyles (Muldoon, 2006).

Today, conscious consumption is spreading rapidly not only in developed countries but also in developing regions. The adoption of conscious consumer behavior across society is of great importance in addressing global challenges such as economic growth, environmental issues, and social inequality. In this context, individuals can contribute to social change not only through their consumption preferences but also through participation in social responsibility projects, support for ethical supply chains, and the preference for environmentally friendly products.

1.2.2. Factors Affecting Conscious Consumer Behavior

Conscious consumer behavior is a complex construct that involves individuals' processes of translating environmental awareness into action and is shaped by the interaction of multidimensional variables. In the literature, the determinants of this behavior are generally examined within the framework of psychological, social, cultural, and demographic factors. At the psychological level, environmental awareness, perceived consumer effectiveness, and individual motivations (altruistic and egoistic) are among the key factors that directly influence conscious consumption. Within the scope of social factors, media, peer groups, and family influence emerge as important external stimuli that guide individuals' consumption preferences, with peer influence appearing to be particularly significant. From a cultural perspective, values such as collectivism and long-term orientation serve as important moderators that strengthen the transformation of environmentally friendly attitudes into behavior. In addition, contextual developments such as the COVID-19 pandemic, along with demographic variables such as education and income level, significantly affect conscious consumer behavior. Accordingly, conscious consumer behavior can be described as a holistic construct resulting from the combination of individual, social, and cultural dynamics, as well as contextual conditions (Alghamdi & Agag, 2024; Ghali-Zinoubi, 2022). Factors influencing conscious consumer behavior may vary depending on individuals' values, sense of social responsibility, educational background, and economic conditions. In this regard, environmental factors are among the primary elements shaping conscious consumption behavior. Environmental issues such as global warming, environmental degradation, and the depletion of natural resources have made individuals more sensitive to environmental protection. Consequently, increasing environmental awareness has led to greater demand for environmentally friendly products and sustainable production processes (Islam &

Chandrasekaran, 2015). Educational attainment is another important factor influencing conscious consumer behavior. Educated individuals are generally better able to assess environmental impacts and ethical production processes, enabling them to make more informed consumption choices. In this context, consumers evaluate not only the price and functionality of products but also the environmental and ethical dimensions of production processes (Çelebi & Bayrakdaroğlu, 2018). Generational differences also play a significant role in shaping conscious consumption behavior. In particular, Generation Y exhibits a consumer profile that is more sensitive to environmental and ethical issues. Due to greater access to information, members of this generation tend to develop more informed and critical consumption behaviors. They place importance not only on satisfying their individual needs but also on fulfilling their social responsibilities.Finally, economic conditions play a decisive role in conscious consumer behavior. Income levels and economic fluctuations may lead individuals to reassess their consumption habits. Under such circumstances, consumers tend to prefer more economical and sustainable alternatives, highlighting the importance of economic factors in the widespread adoption of conscious consumption practices (Muldoon, 2006).

2. Literature review

Social media has become one of the most powerful tools shaping consumer behavior today and has assumed a significant role in influencing individuals' purchasing decisions, particularly in relation to conscious consumption elements such as environmental, ethical, and social responsibility concerns. In this context, studies examining the impact of social media marketing activities on consumers' conscious consumption behavior are presented chronologically below.One of the early studies in the literature, Muldoon (2006), suggested that social media can be used to raise public awareness regarding environmental consciousness and sustainable consumption. Subsequently, Barnes and Mattson (2008) emphasized that, in addition to being a low-cost marketing tool for businesses, social media provides an effective means of reaching large audiences. Research examining the direct effects of social media on consumer behavior became particularly prominent in the early 2010s. In this regard, Kim and Ko (2010) demonstrated that, within the context of luxury fashion brands, social media influences purchasing behavior by creating feelings of trust and closeness among consumers. Similarly, Ramsunder (2011) found that online advertisements and social media pages significantly affect consumer decision-making across various sectors.Studies conducted by 2013 indicated that social media marketing positively influences online consumer behavior and helps consumers select the most suitable products by enhancing brand awareness (Arora & Sharma, 2013; Vinerean et al., 2013). Subsequent research more clearly revealed the role of social media in information acquisition and decision-making processes. Olgun (2015) emphasized that consumers conduct extensive research on social media before making purchases and that user reviews on platforms such as Facebook and Twitter play a decisive role in purchasing decisions.Islam and Chandrasekaran (2015) examined the effects of dimensions of religiosity (intrinsic and extrinsic) on Ecologically Conscious Consumer Behavior (ECCB) among young Muslim consumers in India. Data collected through questionnaires from 191 university students were analyzed using Structural Equation Modeling (SEM). The findings indicated a positive and significant relationship between intrinsic religiosity and ECCB, whereas no significant relationship was found with extrinsic religiosity. The study also demonstrated that the Islamic concepts of "Khalifah" and "Mizan" support environmental awareness. Consequently, religiosity was identified as an important variable in green consumer segmentation. Studies conducted in Türkiye support these findings. Buğday and Babaoğul (2016) stated that social media serves as a tool for increasing conscious consumption, while Turgut (2016) demonstrated the effects of social media advertising on purchase intention, trust perception, and word-of-mouth communication (WOM). Research conducted in 2017 produced similar results. Şahin, Çağlıyan, and Başer (2017), as well as Zarroug (2017), emphasized the critical role of social media advertising in influencing consumer behavior, whereas Torun (2017) noted that consumers' tendency to first encounter products through social media increases its importance in the purchasing process. Çelebi and Bayrakdaroğlu (2018) found that social media has a particularly strong influence on Generation Y and that this

generation increases its environmental awareness through social media, leading to greater preference for ethical and sustainable products. Later studies highlighted the structural and psychological dimensions of social media marketing. Özçifçi (2020) and Sharma (2020) drew attention to the determining role of perceived value and perceived risk in shaping purchase intention. In a study conducted in Azerbaijan, Məmmədova (2021, p. 204) found that social media advertisements have a significant effect on impulsive buying behavior and that this effect varies depending on the platform used. In particular, Instagram users were found to exhibit higher levels of impulsive purchasing behavior compared to YouTube users. From 2022 onward, research increasingly focused on sustainable and conscious consumption. Bozyiğit and Metin (2022) reported that awareness and preference developed through Instagram significantly explain purchase intention. Ebrahimi et al. (2022) found that the entertainment, personalization, and interaction dimensions of social network marketing positively influence purchasing behavior. Likewise, Bryła, Chatterjee, and Ciabiada-Bryła (2022) emphasized that influencer marketing has become an important driver of sustainable consumption, particularly among younger individuals. However, Pellegrino, Abe, and Shannon (2022) highlighted the "dark side" of social media, demonstrating that materialistic values may increase impulsive and compulsive purchasing behaviors. In another study conducted in the same year, food consumption awareness was examined through a face-to-face survey consisting of 16 questions administered to 250 randomly selected participants in the city center of Karaman. The findings revealed that higher educational attainment increases the likelihood of displaying proper consumption behavior; however, significant knowledge gaps remained in specific areas such as egg hygiene and waste oil management (Yerlikaya et al., 2022).

More recent studies have examined the effects of social media on conscious consumption in greater depth. Xie and Madni (2023) found that environmental information shared on social media is directly and positively associated with green consumption intentions, while perceived green value and subjective norms play strong mediating roles in this relationship.Studies published in 2024 addressed the effects of social media marketing on both sustainable consumption and consumer psychology in a more comprehensive manner. Kumar et al. (2024) found a significant relationship between exposure to social media marketing and the adoption of sustainable consumption practices, particularly highlighting that transparent and authentic content encourages environmentally friendly purchasing decisions. Huslan and Hassim (2024) reported that platforms such as Instagram, Facebook, and YouTube shape attitudes and motivations toward sustainable products through information accessibility and social influence. In the same year, Kayan (2024) found, in the context of Türkiye, that the influence of social media influencers on purchase intention is particularly strong among women, younger individuals, and groups with lower income and education levels. Shamim and Azam (2024) demonstrated that credibility signals associated with influencers, messages, and media channels build consumer trust and increase impulsive purchase intentions, with product attachment serving as a mediating factor in this relationship.Among the most recent studies, Horrich, Ertz, and Bekir (2025) demonstrated that the effects of social media platforms differ considerably. Their findings indicated that Instagram promotes aspirational consumption, Facebook encourages community engagement, and YouTube supports educational content; however, factors such as high costs may limit the translation of awareness into actual behavior. In the same year, Koay and Lim (2025) emphasized that "aspirational identification" is an important factor strengthening impulsive purchase intentions in influencer marketing.Overall, social media marketing activities have evolved from being merely tools for creating awareness into multifaceted mechanisms that exert profound effects on consumer psychology, sustainability, and conscious consumption behavior. A chronological review of the literature reveals that early studies primarily focused on awareness and accessibility, whereas more recent research addresses more complex and multidimensional relationships involving sustainable consumption, psychological mechanisms, and platform-specific differences.

3. Materials and Methods

3.1. Research Model and Hypotheses

The main purpose of this study is to determine the effect of social media marketing activities on conscious consumption behavior. In this regard, the target population of the study consists of individuals aged 18 and above, residing in Azerbaijan, and having at least one social media account. Convenience sampling was used as the sampling method. A questionnaire method was employed for data collection; the survey form was prepared online using Google Forms and distributed to participants through various social networks. In addition, face-to-face survey applications were also conducted at certain points. A total of 400 individuals participated in the study.

Within the scope of the research, a hypothesis was developed to test the direct effect of social media marketing activities on conscious consumption behavior. The conceptual model developed in this context is presented in Figure 1. In the model, social media marketing activities are considered as the independent variable and consist of five sub-dimensions: entertainment, interaction, trendiness, personalization, and word-of-mouth communication. The dependent variable is conscious consumption behavior. The research model aims to test the direct effect of social media marketing activities, through these sub-dimensions, on conscious consumption behavior.

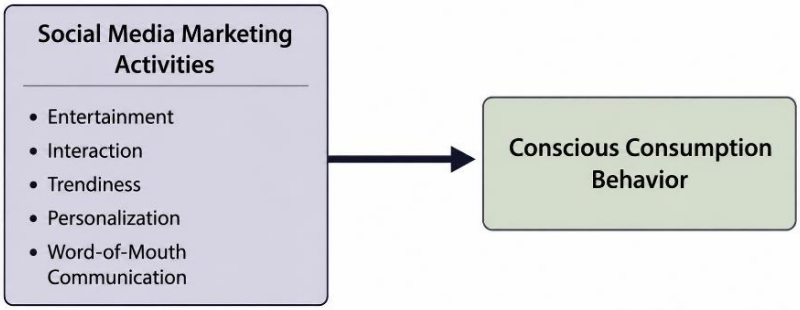

Figure 1
Research model

Accordingly, the following hypotheses were developed:

H1: Social media marketing activities positively affect consumers' conscious consumption behavior.
H1a: The entertainment dimension positively affects conscious consumption behavior.
H1b: The interaction dimension positively affects conscious consumption behavior.
H1c: The trendiness dimension positively affects conscious consumption behavior.
H1d: The personalization dimension positively affects conscious consumption behavior.
H1e: The word-of-mouth communication dimension positively affects conscious consumption behavior.

3.2. Population and Sample

The population of this study consists of individuals residing within the borders of Azerbaijan who are actively using at least one social media platform and are 18 years of age or older. Since the study focuses on social media marketing activities, active social media usage was adopted as a key criterion in defining the population. In addition, in line with the aim of examining conscious consumption behavior, only individuals who are capable of making independent consumption decisions were considered; therefore, participants aged 18 and above were included in the study.The sample of the study was selected using the convenience sampling method due to time and cost limitations and the

impossibility of reaching the entire population. In this context, data were collected from social media users in Azerbaijan through both online channels and face-to-face survey applications conducted at selected locations. At the end of the data collection process, data were obtained from a total of 400 participants. Prior to analysis, the dataset was examined in detail. During this process, incomplete questionnaires and inconsistent responses that could potentially affect the results were checked. As a result of these examinations, all questionnaires were deemed suitable for analysis, and data from all 400 participants were included in the analytical process. The sample size was considered sufficient for the application of commonly used quantitative analysis techniques in social sciences. However, it was also taken into account that, due to the nature of convenience sampling, caution should be exercised when generalizing the findings to the entire population.

3.3. Data Collection Instrument

In this study, the questionnaire method was used as the data collection instrument. The questionnaire was developed based on previously validated and reliable scales in the literature and consists of three sections: demographic information, social media marketing activities, and conscious consumption behavior. All scale items were measured using a 5-point Likert scale, where respondents were asked to rate the statements from 1 = "Strongly Disagree" to 5 = "Strongly Agree".To measure social media marketing activities, a 23-item scale based on Kim and Ko (2012) was used, consisting of five dimensions: entertainment, interaction, trendiness, personalization, and word-of-mouth communication. To measure conscious consumption behavior, an 11-item scale based on Gupta and Sheth (2024) was employed. This scale covers environmental awareness, ethical responsibility, and responsible consumption tendencies and was treated as a holistic construct in the analyses. The original English scales were translated into Azerbaijani by bilingual experts and reviewed for content validity before data collection. The reliability and validity of the scales were tested using statistical methods during the data analysis process.

3.4. Data Collection Process

The data collection process of the study was planned by taking into account the purpose of the research, the target population, and accessibility conditions. The survey method was preferred in order to examine the relationship between social media marketing activities and conscious consumption behavior. This method was chosen due to its ability to reach a large number of participants in a short period of time and its suitability for obtaining quantitative data.The questionnaire was developed based on a review of the relevant literature and structured in accordance with the scope of the study. Prior to implementation, care was taken to ensure that the questions were clear, understandable, and free from leading expressions; after the necessary revisions, the questionnaire was finalized for application.During the data collection process, both online and face-to-face methods were used. Online surveys enabled access to participants from different regions of Azerbaijan, while face-to-face survey applications were also conducted at selected locations in order to increase sample diversity. Ethical approval was obtained from the Ethics Committee of Nakhchivan State University (decision dated 08.12.2025, No. 10/25). Participants were clearly informed that participation was voluntary, that no identifying personal information would be collected, and that the data would be used solely for scientific purposes. The collected data were checked, prepared for analysis, and deemed suitable for statistical analysis.

3.5. Data Analysis Methods

The data obtained in the study were analyzed using SPSS and AMOS software packages. The analysis process included the evaluation of measurement instruments and testing the relationships between variables. In the first stage, the reliability of the scales was assessed using Cronbach's alpha coefficient, and exploratory factor analysis (EFA) was conducted to examine construct validity. The suitability of the data for factor analysis was tested using the KMO measure and Bartlett's test of

sphericity.To confirm the structure of the scales, confirmatory factor analysis (CFA) was performed, and model fit was evaluated using goodness-of-fit indices such as χ^2/df, GFI, CFI, TLI, and RMSEA. Prior to the analyses, assumptions for parametric tests were examined. Normality was assessed using skewness and kurtosis values, and values within the range of ±1.5 indicated that the dataset was normally distributed (Tabachnick & Fidell, 2019).Multicollinearity was assessed using VIF and tolerance values, while the independence of error terms was tested using the Durbin–Watson coefficient. Pearson correlation analysis was conducted to determine the direction and strength of relationships between variables. Multiple linear regression analysis was used to test the research hypotheses. Subsequently, structural equation modeling (SEM) was employed, as it allows for the simultaneous testing of both the measurement model and structural relationships between variables.Since the data were collected from a single source at a single point in time, common method bias was assessed using Harman's single-factor test (Podsakoff et al., 2003). The exploratory factor analysis results indicated that no single factor accounted for the majority of the total variance, and the first factor explained less than 50% of the total variance. These results suggest that there is no serious common method bias in the dataset.

4. Results

4.1. Demographic Characteristics of Participants

In this section of the study, findings regarding the demographic characteristics of the respondents are presented. The basic demographic variables of the participants, such as gender, age, marital status, education level, and income level, were analyzed in order to reveal the general profile of the sample.The obtained data were evaluated using frequency and percentage values, and the results are presented in Table 1.

Table 1
Demographic characteristics of participants (n = 400)

Demographic Variable	Category	Frequency (n)	Percentage (%)
Gender	Female	214	53.5
	Male	186	46.5
Age	18–24	112	28.0
	25–34	138	34.5
	35–49	94	23.5
	50–65	44	11.0
	65 and over	12	3.0
Marital Status	Single	238	59.5
	Married	162	40.5
Education Level	Primary education	18	4.5
	Secondary education	56	14.0
	High school	78	19.5
	Bachelor's degree	168	42.0
	Postgraduate	80	20.0
Income Level (AZN)	0–400	54	13.5
	401–950	82	20.5
	951–1190	76	19.0
	1191–1700	68	17.0
	1701–2210	48	12.0
	2211–2720	34	8.5
	2721–3400	22	5.5
	3401 and above	16	4.0
Total		400	100.0

A total of 400 individuals participated in the study. An examination of the gender distribution shows that female participants (53.5%) and male participants (46.5%) were represented in relatively similar proportions. This indicates that the sample has a balanced distribution in terms of gender. Regarding age distribution, a significant proportion of participants were concentrated in the 18–34 age group (62.5%). This finding suggests that the sample predominantly consists of young and young adult individuals.In terms of marital status, 59.5% of the participants were single, while 40.5% were married. An examination of educational attainment reveals that the majority of the sample held a bachelor's degree (42.0%) or a postgraduate degree (20.0%). This indicates that the participants generally possess a relatively high level of education.With respect to income distribution, participants were represented across various income groups, with a notable concentration in the 401–950 AZN (20.5%) and 951–1190 AZN (19.0%) income ranges. This distribution suggests that middle-income individuals constitute a larger proportion of the sample.Overall, the findings indicate that the study sample includes individuals with diverse demographic characteristics.

4.2. Descriptive Statistics

This section presents the descriptive statistics for the variables used in the study. The mean ($\bar{X}$) and standard deviation (SD) values of the social media marketing activities and conscious consumption scales were calculated to evaluate the general tendencies of the participants.The social media marketing activities scale initially consisted of 23 items. However, as a result of the exploratory factor analysis, items with low factor loadings or those that loaded significantly on more than one factor (cross-loading items) were removed from the analysis. Accordingly, a total of five items were excluded from the scale, and subsequent analyses were conducted using the remaining 18 items.The removed items included the statement “It is easy to use content related to this brand on social media” from the entertainment dimension; “It is easy to share opinions through this brand’s social media account” from the interaction dimension; “The information on this brand’s social media account reflects the latest developments” from the trendiness dimension; “This brand’s social media account provides me with personalized services” from the personalization dimension; and “I enjoy expressing positive opinions about this brand on social media” from the word-of-mouth communication dimension. These items were found to have factor loadings below acceptable threshold levels or to exhibit cross-loadings.As a result of these modifications, the factor structure of the scale was considered to be more consistent and reliable. The findings obtained are presented in Table 2.

Table 2
Descriptive statistics of the variables (n = 400)

Scale / Dimension	Number of Items	Mean ($\bar{X}$)	Standard Deviation (SD)
Social Media Marketing Activities	18	3.78	0.64
Entertainment	4	3.92	0.71
Interaction	4	3.85	0.68
Trendiness	3	3.74	0.73
Personalization	3	3.61	0.76
Word-of-Mouth Communication	4	3.79	0.69
Conscious Consumption (Overall)	11	4.02	0.58

Table 2 presents the descriptive statistics of the variables used in the study. Following the exploratory factor analysis, the social media marketing activities scale was evaluated based on 18 items after the removal of items with low factor loadings. The scale consists of five sub-dimensions: entertainment, interaction, trendiness, personalization, and word-of-mouth communication.As shown in Table 2, participants’ perceptions of social media marketing activities were generally at a moderately high level ($\bar{X}$ = 3.78). Among the sub-dimensions, the highest mean score was observed for the

entertainment dimension ($\bar{X}$ = 3.92), followed by the interaction dimension ($\bar{X}$ = 3.85). The lowest mean score was found for the personalization dimension ($\bar{X}$ = 3.61). These findings indicate that participants primarily evaluate social media content in terms of its entertainment and interaction aspects.The mean score of the conscious consumption scale was 4.02, indicating a high level of conscious consumption tendency among the participants. The standard deviation values ranged from 0.58 to 0.76, suggesting that participants' responses did not exhibit excessive dispersion around the mean and that the distribution was relatively homogeneous.

To determine the construct validity and internal consistency of the social media marketing activities scale and the conscious consumption scale used in this study, Exploratory Factor Analysis (EFA) and Reliability Analysis (Cronbach's Alpha) were conducted. The suitability of the data for factor analysis was evaluated using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity.

Table 3
Results of the KMO measure and bartlett's test of sphericity (n = 400)

Scale	KMO	Bartlett χ^2	sd	p
Social Media Marketing Activities	0.914	4368.271	153	0.000
Conscious Consumption	0.879	2146.593	55	0.000

An examination of the KMO Measure and Bartlett's Test of Sphericity results presented in Table 3 reveals that the KMO value for the Social Media Marketing Activities Scale is 0.914, while the KMO value for the Conscious Consumption Scale is 0.879. Since both KMO values exceed 0.80, the sample size is considered highly adequate for factor analysis for both scales.The results of Bartlett's Test of Sphericity were found to be statistically significant for both scales ($p < 0.001$), indicating the presence of significant correlations among the variables and confirming that the dataset is suitable for factor analysis (Kaiser, 1974).Based on these findings, it was concluded that conducting exploratory factor analysis for both scales is statistically appropriate.

4.3. Factor Structure of the Social Media Marketing Activities Scale

According to the results of the Exploratory Factor Analysis (EFA), the Social Media Marketing Activities scale was found to exhibit a five-factor structure. A factor loading threshold of 0.50 was taken into consideration, and items falling below this value or showing high loadings on more than one factor were excluded from the analysis. Accordingly, the analyses were conducted based on 18 items.

The KMO and Bartlett's Test of Sphericity results presented in Table 3 indicate that the dataset is suitable for factor analysis.

Table 4
Factor loadings of the social media marketing activities Scale (n = 400)

Item	Entertainment	Interaction	Trendiness	Personalization	Word-of-Mouth
SMP1	0.781				
SMP2	0.764				
SMP3	0.742				
SMP4	0.718				
SMP5		0.786			
SMP6		0.761			
SMP7		0.739			
SMP8		0.715			

SMP9	0.771		
SMP10	0.748		
SMP11	0.724		
SMP12		0.769	
SMP13		0.743	
SMP14		0.718	
SMP15			0.769
SMP16			0.743
SMP17			0.718
SMP18			0.701

Total Explained Variance: 71.4%

An examination of the factor loadings presented in Table 4 shows that the item loadings range between 0.701 and 0.786, and all items have factor loadings above 0.70. This indicates that the factor structure of the scale is strong and that the items represent their respective factors at a high level. Moreover, the fact that each item loads strongly only on its corresponding factor demonstrates that the factor structure is clear and consistent.The total explained variance of the scale is 71.4%, which indicates a high level of construct validity.In order to determine the internal consistency of the Social Media Marketing Activities scale used in the study, Cronbach's Alpha reliability analysis was conducted. In the literature, a Cronbach's Alpha coefficient of 0.70 and above is considered to indicate a reliable scale (Nunnally, 1978). According to the findings of this study, the overall Cronbach's Alpha coefficient of the scale was calculated as 0.93. This value indicates that the scale has a high level of internal consistency.

Table 5
Reliability analysis of the social media marketing activities scale (n = 400)

Scale / Dimension	Number of Items	Cronbach's Alpha
Social Media Marketing Activities (Overall)	18	0.93
Entertainment	4	0.88
Interaction	4	0.90
Trendiness	3	0.87
Personalization	3	0.85
Word-of-Mouth Communication	4	0.89

As shown in Table 5, the Cronbach's Alpha coefficients of the sub-dimensions were found to be 0.88 for entertainment, 0.90 for interaction, 0.87 for trendiness, 0.85 for personalization, and 0.89 for word-of-mouth communication. These findings indicate that all sub-dimensions of the scale are reliable.

4.4. Factor Structure of the Conscious Consumption Scale

The Conscious Consumption Scale used in this study to measure consumers' conscious consumption behavior consists of a total of 11 items. According to the results of the Exploratory Factor Analysis (EFA), the scale exhibited a single-factor structure. This indicates that all items comprising the scale are grouped under the same construct and that the scale possesses a consistent factor structure.The results of the factor analysis showed that all factor loadings exceeded 0.60. These values indicate that the items represent conscious consumption behavior adequately and strongly.

Table 6
Factor loadings of the conscious consumption scale (n = 400)

Item	Factor Loading
BT1	0.783
BT2	0.769
BT3	0.754
BT4	0.732
BT5	0.719
BT6	0.706
BT7	0.693
BT8	0.681
BT9	0.669
BT10	0.657
BT11	0.642

Total Explained Variance: 63.4%
An examination of Table 6 shows that the factor loadings of the items in the Conscious Consumption Scale range from 0.642 to 0.783. This indicates that the items are consistently grouped under a single factor. The total explained variance of 63.4% suggests that the construct validity of the Conscious Consumption Scale is at an acceptable level.To determine the internal consistency of the Conscious Consumption Scale, Cronbach's Alpha reliability analysis was conducted. In the literature, a Cronbach's Alpha coefficient of 0.70 or above indicates that a scale is reliable.

Table 7
Reliability results of the conscious consumption scale (n = 400)

Scale	Number of Items	Cronbach's Alpha
Conscious Consumption	11	0.90

An examination of Table 7 shows that the Cronbach's Alpha coefficient of the Conscious Consumption Scale is 0.90. This value indicates that the scale has a very high level of internal consistency. The findings demonstrate that the items comprising the scale are consistent with one another and that the scale can be used as a reliable measurement instrument.

4.5. Model Fit Indices

In order to evaluate the level of fit between the theoretical model developed in the study and the empirical data, Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) were conducted. In the structural model, social media marketing activities were represented by five sub-dimensions (entertainment, interaction, trendiness, personalization, and word-of-mouth communication), while the conscious consumption variable was modeled as a single-factor structure consisting of 11 items.

In assessing model fit, absolute fit indices, incremental fit indices, and error-based fit measures were considered together.

Table 8
Model Fit Indices (n = 400)

Fit Index	Acceptable Value	Model Value
χ^2/df	≤ 3.00	2.41
RMSEA	≤ 0.08	0.059
GFI	≥ 0.85	0.89
AGFI	≥ 0.80	0.86
CFI	≥ 0.90	0.93
TLI (NNFI)	≥ 0.90	0.92
IFI	≥ 0.90	0.94
NFI	≥ 0.90	0.91
SRMR	≤ 0.08	0.052

Table 8 presents the goodness-of-fit indices, indicating that the model demonstrates an acceptable to good level of fit with the data. The χ^2/df ratio being below 3 (2.41) shows that the overall model fit is within acceptable limits. Since the χ^2 statistic is sensitive to sample size, other fit indices were also considered in evaluating model fit.The RMSEA value of 0.059 indicates a low and acceptable level of approximation error. Regarding incremental fit indices, CFI (0.93), TLI (0.92), IFI (0.94), and NFI (0.91) values are all above the recommended threshold levels. The SRMR value of 0.052 indicates a low discrepancy between observed and predicted values.Overall, the goodness-of-fit indices suggest that the proposed structural model demonstrates statistically acceptable and good fit with the data.

4.6. Correlation and Regression Analyses

The suitability of the dataset for parametric analyses was evaluated according to the assumptions specified in Section 3.5 and was found to be appropriate for the analyses.

Table 9
Pearson correlation analysis among variables (n=400)

Variables	1	2	3	4	5	6
1. Entertainment	1					
2. Interaction	0.642**	1				
3. Trendiness	0.598**	0.621**	1			
4. Personalization	0.571**	0.606**	0.588**	1		
5.Word-of-Mouth Communication	0.624**	0.658**	0.601**	0.632**	1	
6. Conscious Consumption	0.536**	0.582**	0.497**	0.519**	0.561**	1

Note. $p < 0.01$.

According to the results of the correlation analysis, all sub-dimensions of social media marketing activities were found to have statistically significant and positive relationships with conscious consumption behavior. The highest correlation coefficient was identified between the interaction dimension and conscious consumption ($r = 0.582$, $p < 0.01$). This finding indicates a moderately strong positive relationship between the level of user participation and reciprocal communication on social media platforms and conscious consumption behavior. While correlation analysis reveals the relationships among variables, multiple linear regression analysis was conducted to determine causal effects.

Table 10
The effect of social media marketing dimensions on conscious consumption multiple linear regression analysis (n = 400)

Independent Variable	β	t	p
Entertainment	0.214	4.327	0.000
Interaction	0.268	5.116	0.000
Trendiness	0.109	2.084	0.038
Personalization	0.131	2.567	0.011
Word-of-Mouth Communication	0.198	3.974	0.000

Model Statistics

Indicator	Value
R	0.681
R^2	0.464
Adjusted R^2	0.457
F	67.382
P	< 0.001

Multiple linear regression analysis results indicate that social media marketing activities have statistically significant effects on conscious consumption behavior. The overall significance of the model was confirmed by the F-test, and the model was found to be statistically significant ($p < 0.001$). When the model results are examined, the multiple correlation coefficient ($R = 0.681$) indicates a moderate-to-strong relationship between the independent variables and the dependent variable. The coefficient of determination ($R^2 = 0.464$) shows that approximately 46% of the variance in conscious consumption behavior is explained by social media marketing activities. The fact that the adjusted R^2 value is very close to the R^2 value indicates that the explanatory power of the model is stable. When standardized beta coefficients are examined, it is observed that the strongest effect on conscious consumption behavior belongs to the interaction dimension ($\beta = 0.268$; $p < 0.001$). This result suggests that marketing activities that increase user participation and reciprocal communication on social media platforms may play a more decisive role in shaping conscious consumption behavior.

Table 11
Hypothesis test results (n = 400)

Hypothesis	Hypothesis	Hypothesis
H1 (Supported through H1a-H1e)	Social media marketing activities positively affect conscious consumption behavior.	Supported
H1a	The entertainment dimension positively affects conscious consumption behavior.	Supported
H1b	The interaction dimension positively affects conscious consumption behavior.	Supported
H1c	The trendiness dimension positively affects conscious consumption behavior.	Supported
H1d	The personalization dimension positively affects conscious consumption behavior.	Supported
H1e	The word-of-mouth communication dimension positively affects conscious consumption behavior.	Supported

The findings indicate that all hypotheses tested in the study were supported at a statistically significant level. The results demonstrate that social media marketing activities have positive and significant

effects on conscious consumption behavior. When evaluated in terms of sub-dimensions, the strongest effect on conscious consumption behavior was observed in the interaction dimension, followed by the entertainment and word-of-mouth communication dimensions. These findings suggest that different dimensions of social media marketing activities have varying levels of influence on conscious consumption behavior.

5. Discussion, conclusion, limitations and future research

5.1. Discussion and Conclusions

The findings of this study demonstrate that social media marketing activities have a positive and significant effect on conscious consumption behavior. In particular, the interaction dimension exhibits a stronger effect compared to the other dimensions, indicating that user engagement and two-way communication on social media platforms play a decisive role.These results are generally consistent with previous studies emphasizing the transformative role of social media in consumer decision-making processes. Mulhern (2009) and Royle and Laing (2014) state that digital media environments provide consumers with greater access to information and comparison opportunities, thereby reshaping consumer behavior. The findings of this study similarly suggest that social media content can influence consumers' evaluation processes and contribute to more conscious purchasing decisions.In terms of sub-dimensions, interaction and entertainment emerged as the most influential factors. This finding aligns with Kim and Ko (2012), who reported that interactive and experiential content in social media environments strengthens consumer attitudes. Increased two-way communication and user participation on social media platforms can therefore contribute to more informed and reflective consumer decision-making.Studies conducted in Turkey also indicate that social media supports conscious consumption tendencies, particularly among younger consumers (Çelebi & Bayrakdaroğlu, 2018). The fact that similar patterns were observed in the Azerbaijan sample suggests that social media marketing activities may produce comparable outcomes across different socio-cultural contexts.

From a managerial perspective, social media marketing strategies should be designed to enhance user interaction, support feedback mechanisms, and strengthen two-way communication. In addition, content that is engaging and experience-oriented can generate stronger effects on consumer behavior. Moreover, increasing the visibility of sustainability, ethical production, and social responsibility themes on social media platforms may further support conscious consumption tendencies. In this regard, transparent communication, informative content, and trust-building messages can contribute to more stable behavioral changes by influencing consumers' evaluation processes.Overall, it can be concluded that social media marketing activities play an important role in shaping conscious consumption behavior and can contribute to the development of more informed consumer choices. Accordingly, organizations that strategically utilize social media marketing activities can contribute not only to consumer engagement but also to the promotion of more conscious and sustainable consumption practices.

5.2. Limitations and Future Research Directions

This study has several limitations. First, the research was conducted using a convenience sampling method and a sample limited to Azerbaijan. Therefore, the generalizability of the findings is restricted.In addition, the study is based on cross-sectional data. This limits the ability to make causal interpretations regarding the relationships among variables. Future studies could employ longitudinal data or experimental research designs to provide a deeper understanding of these relationships.Furthermore, incorporating cultural, psychological, and socio-economic variables that may influence conscious consumption behavior could yield more comprehensive results. In addition, comparative studies across different countries and analyses involving different social media platforms would contribute to a better understanding and validation of the findings.

References

Acar, S. C., & Torlak, Ö. (2022). The effect of perceived social media marketing on consumer buying behavior: A review study. *Istanbul Commerce University Journal of Entrepreneurship, 6*(11), 46–61.

Alghamdi, O. A., & Agag, G. (2024). Understanding factors affecting consumers' conscious green purchasing behavior. *Sustainability*, *16*(2), 705. https://doi.org/10.3390/su16020705.

Arora, S., & Sharma, D. A. (2013). Social media: A new marketing strategy. *International Journal of Management (IJM), 4*(3), 19–37.

Assaad, W., & Gómez, J. M. (2011). Social network in marketing (social media marketing): Opportunities and risks. *International Journal of Managing Public Sector Information and Communication Technologies*, *2*(1), 13–22.

Barnes, N. G., & Mattson, E. (2008). *Still setting the pace in social media: The first longitudinal study of usage by the largest US charities*. University of Massachusetts Dartmouth Center for Marketing Research.

Bozyiğit, B., & Metin, İ. (2022). The effect of social media marketing on consumer behaviors: A research on Instagram users. *Journal of Business in the Digital Age*, *5*(2), 180–193. doi:10.46238/jobda.1202371.

Bryła, P., Chatterjee, S., & Ciabiada-Bryła, B. (2022). The impact of social media marketing on consumer engagement in sustainable consumption: A systematic literature review. *International Journal of Environmental Research and Public Health*, *19*(24), 16637. doi:10.3390/ijerph192416637.

Buğday, E. B., & Babaoğul, M. (2016). Dimensions of the conscious consumption concept: *Redefining conscious consumption behavior. Socioeconomy, 24*(30), 187–206. https://doi.org/10.17233/se.2016.30.010

Constantinides, E. (2014). Foundations of social media marketing. *Procedia – Social and Behavioral Sciences*, 148, 40–57. https://doi.org/10.1016/j.sbspro.2014.07.016.

Çelebi, Ş. O., & Bayrakdaroğlu, F. (2018). A research on conscious consumption behaviors of Generation Y consumers. *Journal of Entrepreneurship Innovation and Marketing Research, 2*(4), 111–124.

Ebrahimi, P., Basirat, M., Yousefi, A., Nekmahmud, M., Gholampour, A., & Fekete-Farkas, M. (2022). Social networks marketing and consumer purchase behavior: The combination of SEM and unsupervised machine learning approaches. *Big Data and Cognitive Computing*, *6*(2), 35. doi:10.3390/bdcc6020035.

Ghali-Zinoubi, Z. (2022). Examining drivers of environmentally conscious consumer behavior: Theory of planned behavior extended with cultural factors. *Sustainability*, *14*(13), 8072. https://doi.org/10.3390/su14138072.

Gupta, S., & Sheth, J. (2024). Mindful consumption: Its conception, measurement, and implications. *Journal of the Academy of Marketing Science*, *52*(5), 1531–1549.

Horrich, A., Ertz, M., & Bekir, I. (2025). Exploring the role of social media in shaping sustainable consumer behavior: a qualitative study. *Cogent Business & Management*, *12*(1), 2560648. doi:10.1080/23311975.2025.2560648.

Huslan, E. A., & Hassim, M. N. (2024). The role of social media on consumer behavior and motivation towards sustainable products. *Quantum Journal of Social Sciences and Humanities*, *5*(6), 159–176.

Xie, S., & Madni, G. R. (2023). Impact of social media on young generation's green consumption behavior through subjective norms and perceived green value. *Sustainability, 15*(4), Article 3739. https://doi.org/10.3390/su15043739

Islam, T., & Chandrasekaran, U. (2015). Religiosity and ecologically conscious consumption behaviour. *Asian Journal of Business Research*, *5*(2), 18-30. doi:10.14707/ajbr.150014.

Kaiser, H. F. (1974). An index of factorial simplicity. *Psychometrika,* 39, 31–36.

Kayan, F. (2024). Marketing strategies on social media and the effects of influencers on consumer behaviors. *Journal of Sociological Context, 5*(3), 421–445. https://doi.org/10.52108/2757-5942.5.3.3

Kırcova, İ., Enginkaya, E., & Yılmaz, H. (2015). Influence of consumers' self-brand connections on purchase intentions. In *Annual International Conference on Social Sciences*.

Kim, A. J., & Ko, E. (2012). Do social media marketing activities enhance customer equity? An empirical study of luxury fashion brands. *Journal of Business Research*, *65*(10), 1480–1486. https://doi.org/10.1016/j.jbusres.2011.10.014.

Koay, K. Y., & Lim, W. M. (2025). Congruence effects in social media influencer marketing: The moderating role of wishful identification in online impulse buying intentions. *Journal of Product & Brand Management, 34*(3), 265–278. https://doi.org/10.1108/JPBM-09-2023-4709

Kumar, K., Masvood, Y., Tripathy, P., Zade, A. S., Talla, T., & Karunakaran, S. (2024). The impact of social media marketing on sustainable consumption: A study. *EELET, 14*(3).

Məmmədova, G. (2021). The role of social media networks in the effect of social media advertisements on planned purchasing behaviors in Azerbaijan. *TURAN Journal, 26*, 204–209.

Muldoon, A. (2006). Where the green is: Examining the paradox of environmentally conscious consumption. *Electronic Green Journal, 1*(23), 1–16. https://doi.org/10.5070/G312310668

Mulhern, F. (2009). Integrated marketing communications: From media channels to digital connectivity. *Journal of Marketing Communications, 15*(2–3), 85–101.

Nunnally, J. C. (1978). An overview of psychological measurement. In *Clinical diagnosis of mental disorders: A handbook* (pp. 97–146).

Olgun, B. (2015). The impact of social media on consumer purchasing behaviors. *Gümüshane University Electronic Journal of the Institute of Social Science, 6*(12).

Özçifçi, V. (2020). The effect of social media on consumers' purchase intention. *Ahi Evran University Journal of Institute of Social Sciences, 6*(1), 206–223.

Pellegrino, A., Abe, M., & Shannon, R. (2022). The dark side of social media: Content effects on the relationship between materialism and consumption behaviors. *Frontiers in Psychology, 13*, Article 870614. https://doi.org/10.3389/fpsyg.2022.870614

Podsakoff, P. M., MacKenzie, S. B., Lee, J. Y., & Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. *Journal of Applied Psychology, 88*(5), 879–903.

Ramsunder, M. (2011). *The impact of social media marketing on purchase decisions in the tyre industry* [Doctoral dissertation, Nelson Mandela Metropolitan University].

Royle, J., & Laing, A. (2014). The digital marketing skills gap: Developing a digital marketer model for the communication industries. *International Journal of Information Management, 34*(2), 65–73. https://doi.org/10.1016/j.ijinfomgt.2013.11.008

Saravanakumar, M., & SuganthaLakshmi, T. (2012). Social media marketing. *Life Science Journal, 9*(4), 4444–4451.

Shamim, K., & Azam, M. (2024). The power of social media influencers: Unveiling the impact on consumers' impulse buying behaviour. *Humanities & Social Sciences Communications, 11*(1). https://doi.org/10.1057/s41599-024-03796-7

Sharma, K. (2020). Impact of social media marketing on consumer buying behaviour. *International Journal for Research in Applied Science and Engineering Technology, 8*(1), 472–475.

State Statistical Committee of the Republic of Azerbaijan. (2023). *Official statistical data*. https://www.stat.gov.az

Şahin, E., Çağlıyan, V., & Başer, H. H. (2017). The effect of social media marketing on customer purchasing behavior: The example of Selcuk University Faculty of Economics and Administrative Sciences. *Academic Review of Economics and Administrative Sciences, 10*(4), 67–86.

Tabachnick, B. G., & Fidell, L. S. (2019). *Using multivariate statistics*. Pearson Education.

Torun, E. (2017). The place and importance of the internet and social media on consumer purchasing behaviors. *Electronic Journal of Social Sciences, 16*(62), 955–970.

Turgut, E., Akyol, A., & Giray, S. (2016). The relationship between consumer perceptions in social media advertisements, purchase intention, and word of mouth communication. *Journal of Life Economics, 3*(2), 55–74.

Vinerean, S., Cetina, I., Dumitrescu, L., & Tichindelean, M. (2013). The effects of social media marketing on online consumer behavior. *International Journal of Business and Management, 8*(14), 66.

Yasmin, A., Tasneem, S., & Fatema, K. (2015). Effectiveness of digital marketing in the challenging age: An empirical study. *International Journal of Management Science and Business Administration, 1*(5), 69–80.

Yerlikaya, S., Tuna, S., Karaman, Ş. N., & Şen Arslan, H. (2022). Conscious consumer behaviors: The case of Karaman province. *Journal of Design, Architecture and Engineering, 2*(2), 131–139.

Zarroug, S. (2017). *The impact of social media marketing strategies on consumer buying behavior* [Doctoral dissertation, Atilim University].

Ziyaddin, S., Doszhan, R., Borodin, A., Omarova, A., & Ilyas, A. (2019). The role of social media marketing in consumer behaviour. *E3S Web of Conferences, 135*, Article 04022. https://doi.org/10.1051/e3sconf/201913504022

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Gamma as a Digital Pedagogical Tool for Enhancing Learner Engagement, Autonomy, and Motivation in Blended Language Learning Contexts

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Abstract. *This study empirically examines undergraduate students' attitudes toward Gamma as a digital pedagogical tool used in online and blended foreign language learning contexts. Drawing on the Technology Acceptance Model (TAM) and Self-Determination Theory (SDT), the research investigates learners' perceptions of Gamma in terms of usability, interactivity, engagement, learner autonomy, motivation, and instructional preference. A quantitative research design was employed, using a structured questionnaire administered to undergraduate students at El-Bayadh University Centre. The findings indicate consistently positive attitudes toward Gamma, particularly regarding ease of use, interactivity, and motivational impact. The results further suggest that Gamma supports learner autonomy and self-regulated learning processes, while also highlighting a continued preference among some students for traditional face-to-face instruction. These findings underscore the pedagogical value of blended learning models, in which digital tools complement rather than replace conventional classroom practices. The study contributes empirical evidence from an underrepresented higher education context and offers practical implications for technology-enhanced language instruction.*

Keywords: *Gamma, blended learning, learner autonomy, technology acceptance, language education*

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Qarışıq dil öyrənmə kontekstlərində tələbə məşğulluğunu, müstəqilliyini və motivasiyasını gücləndirən rəqəmsal pedaqoji alət kimi Gamma

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Xülasə. *Bu tədqiqat onlayn və qarışıq xarici dil öyrənmə kontekstlərində istifadə olunan rəqəmsal pedaqoji alət Gamma-ya bakalavr tələbələrinin münasibətini empirik olaraq araşdırır. Tədqiqat Texnologiyanın Qəbul Modeli (Technology Acceptance Model – TAM) və Özünümüəyyənetmə Nəzəriyyəsinə (Self-Determination Theory – SDT) əsaslanaraq tələbələrin Gamma haqqında istifadəyə yararlılıq, interaktivlik, öyrənmə prosesində iştirak, öyrənən müstəqilliyi, motivasiya və tədris üstünlükləri baxımından təsəvvürlərini öyrənir. Kəmiyyət tədqiqat dizaynı tətbiq edilmiş və El-Bəyad Universitet Mərkəzinin bakalavr tələbələrinə strukturlaşdırılmış sorğu təqdim olunmuşdur. Nəticələr Gamma-ya qarşı ardıcıl müsbət münasibət nümayiş etdirmiş, xüsusilə istifadənin asanlığı, interaktivlik və motivasiyaedici təsiri baxımından yüksək qiymətləndirmələr göstərmişdir. Eyni zamanda, nəticələr Gamma-nın öyrənən müstəqilliyini və özünü tənzimləyən öyrənmə proseslərini dəstəklədiyini, bununla yanaşı bəzi tələbələrin ənənəvi üzbəüz tədrisə üstünlük verməyə davam etdiyini göstərmişdir. Bu nəticələr rəqəmsal alətlərin ənənəvi sinif təcrübələrini əvəz etməkdən daha çox onları tamamladığı qarışıq öyrənmə modellərinin pedaqoji əhəmiyyətini vurğulayır. Tədqiqat ali təhsildə kifayət qədər öyrənilməmiş bir kontekstdən empirik sübutlar təqdim edir və texnologiya ilə zənginləşdirilmiş dil tədrisinin inkişafı üçün praktik tövsiyələr irəli sürür.*

Açar sözlər: *Gamma, qarışıq öyrənmə, öyrənən müstəqilliyi, texnologiyanın qəbulu, dil təhsili*

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Introduction

The use of digital technologies has completely transformed the landscape of language learning education. In the context of second language acquisition (SLA), the combination of computer-assisted language learning (CALL) environments, mobile-assisted language learning (MALL) systems, and blended learning environments has further increased the trend towards learner-focused and self-directed learning processes (Lee, 2016; Noori, 2025). In higher education, this change has been further enhanced by the increased use of online and blended learning, thereby creating a burning need for well-designed and pedagogically sound digital applications that not only focus upon content presentation but also upon learning motivation and autonomous learning processes.

An increasing number of studies have found that online environments can increase engagement and autonomy of learners when they are designed with tasks and feedback that can be adapted through interaction and when they offer elements of learner control (Salami and Althaqafi, 2023). For example, when considered through the lens of self-regulated learning theory, superior online environments can help learners design, track, and analyze their processes of learning, and this way, they can develop learners' awareness and motivate learners' strategical actions (Noori, 2025). Additionally, theories on motivation and theories like Self-Determination have highlighted the key role of autonomy, excellence, and feelings of relatedness brought about by using online environments and related online technologies and artifacts (Edwards and Terantino, 2025; Almayez et al., 2025).

However, both theory and education technology adoption studies highlight that learners' adoption and acceptance of technology are influenced by perceived functionality and ease of use, as proposed by the Technology Acceptance Model TAM (Granić & Marangunić, 2019). There is evidence that students are often more receptive to technology when it is easier to understand and did not overload their minds cognitively and technically (Mansha et al., 2024). Note that not all students will react to technology in the same manner, as certain groups have been found to play a crucial role in influencing how students think about online learning practices in education institutions (Seredycz, 2020; Karasová et al., 2023).

Notwithstanding the growing body of literature on digital language learning, current research remains limited in several respects. For example, although widely used systems such as Learning Management Systems, Google Classroom, and gamified applications have received considerable scholarly attention, empirical research examining newly emerging digital pedagogical tools remains comparatively limited. Furthermore, existing studies have often emphasized technological affordances and general learning outcomes, while comparatively less attention has been devoted to learners' attitudinal responses, autonomy, self-directed learning, and motivational processes. Recent work on artificial intelligence in language learning highlights the potential of AI-supported tools to provide personalized and interactive learning experiences (Egbert et al., 2020, Mammadova, 2025), while research on EFL self-study emphasizes the importance of learner autonomy, self-directed learning, motivation, and digital literacy (Umaraliyeva, 2025). Lastly, relatively few studies have systematically examined how learners at different academic levels perceive and engage with emerging digital pedagogical tools within institutional learning environments.

Within this progressively dynamic environment, Gamma has emerged as an increasingly versatile learning platform in the digital age, incorporating tasks based on visualization, as well as adaptability. Gamma is a digital content-creation and presentation platform that enables users to create visually structured presentations, documents, and interactive learning materials. Its main technological functions include organizing text and visual content into adaptable layouts, integrating multimedia elements, and presenting and sharing information digitally. The platform also incorporates artificial intelligence features that assist users in generating and organizing content, refining presentations, and developing visually coherent materials from user instructions. Its interactive features allow learners to engage with structured visual content in a more flexible way than with conventional linear presentations.

These characteristics distinguish Gamma from conventional presentation tools by bringing together content creation, AI-assisted design, visual organization, multimedia integration, and interactive digital delivery within a single platform. In the present study, Gamma is therefore conceptualized

primarily as a digital pedagogical tool whose value lies in its potential to support the organization, presentation, and interactive use of instructional content.

The learning platform appears aligned with the most modern views on learning by supporting well-organized content, interaction, and control of learning. Nevertheless, in spite of increasing adoption in learning institutions, there has been little investigation on the learning effectiveness of Gamma, especially in language learning environments. The absence of context-sensitive studies on Gamma is an important gap within the existing online instructional literatures.

The research aims to fill a void in literature by empirically examining attitudes displayed by undergraduate university students concerning Gamma in online and blend learning courses at El-Bayadh University Centre. Drawing from models rooted in the Technology Acceptance Model and theories underpinned by engagement and Self-Regulated Learning theories and frameworks, the research proposes that student attitudes are reflective of broader instructional processes entailing usability and learner engagement or autonomy as motivational and engagement principles and mediators for deeper learning interventions. The research examines learner attitudes concerning Gamma along several instructional elements and seeks to unearth potential differences according to academic and discipline background and instructional preferences concerning learning between Gamma-enabled and conventional learning courses.

The objectives of the research are to:
1. Investigate the attitudes of undergraduate students towards the ease of use of Gamma, its interactivity, engagement, autonomy, and motivation.
2. Determine differences in attitudes toward Gamma by academic level (first- vs. second-year) and major (English vs. Social Sciences).
3. Explore instructional preferences among students in Gamma-supported and conventional instructional environments.

Research questions that direct this study are:
1. What are undergraduate students' attitudes toward Gamma regarding usability, interactivity, engagement, autonomy, and motivation?
2. Are there any marked discrepancies in attitude towards Gamma depending on levels or fields of study?
3. What is the distribution of students' instructional preferences between Gamma-supported and traditional teaching?

From these questions, the research hypotheses are as follows:
H1: The students will show a positive attitude towards Gamma in every pedagogical aspect.
H2: No statistical significance is expected between the attitudes of the different levels of academia towards the Gamma Corporation.
H3: There will be no statistically significant differences in attitudes toward Gamma by academic majors.
H4: Most students will find Gamma-supported teaching more preferable to conventional teaching.

2. Literature Review

2.1 Introduction

Digital technology has radically impacted second language acquisition (SLA) by creating unique opportunities for autonomy, engagement, and differentiated instruction. CALL, MALL, and blended learning have diversified the long-established paradigm of teaching, transforming it from a teacher-centric to a learner-centered paradigm. This literature review records contemporary research on language knowledge development using technology addition, motivational and autonomy-enhancing principles and concepts, individual preferences on blended learning settings, theories on technology acceptability, and research gaps.

2.2 Technology Acceptance and Digital Language Learning

More recently, research has also proved the significant role of self-regulated learning (SRL) within successful language learning. Online learning systems offer learners the opportunity to design, control, and evaluate their learning processes. This is due to the ability to provide adaptive feedback and cooperation (Noori, 2025). The online approach to task-based learning encourages self-regulated learning practices. According to Lee (2016), learners participate in self-directed investigations as well as a process of collaborating for knowledge construction, which further develops both language and metacognitive capabilities. The important role online forums, video activities, and online quizzes play in monitoring, getting instant feedback, and adapting strategies was also observed by Suarez Garcia and Almeida (2025).

Apart from cognitive aspects, online platforms have had a positive effect on affective elements. Almayez et al. (2025) discovered that learners participating in MALL and gamification apps had increased levels of intrinsic motivation, lower levels of anxiety, and increased desires for communication, as advocated in self-determination theory related to autonomy, competence, and relatedness (Edwards and Terantino, 2025).

Current studies highlight the application of online platforms in promoting Self-Regulated Learning (SRL). The online environments and structures supporting independent navigation encourage metacognitive awareness and strategic behaviors in the learners (Noori, 2025). This points towards the instructional value offered by the incorporation of the use of online tools in support of autonomy and the need for instructional structures.

2.3 Learner Autonomy, Motivation, and Self-Determination Theory

Motivation and autonomy play an essential role in digital learning effectiveness. Students become interested when learning is directed at self-regulated decision making and immediate feedback (Salami & Althaqafi, 2023). Points, badges, and leader boards used in gamification effectively engage students and improve their performance. A 30% improvement in vocabulary and grammar achievement and an increase of 85% in engagement were recorded by Rabi'ah et al. (2025).

Intrinsic motivation within digital learning contexts can also be addressed by the theory of Self-Determination Theory (SDT). The theory focuses primarily on meeting the learners' need for autonomy, competence, and relatedness. Online learning platforms where learners can exercise their choices in terms of monitoring their progress and interacting digitally increase intrinsic learning motivation and learner perseverance in language learning.

Notwithstanding these promising findings, there still lie some research gaps in ascertaining the long-run efficacy and applicability of gamification. This has been observed as an area requiring further investigation into long-run effects, as highlighted by Adzmi et al. (2024) and a lack of appropriate guidelines for more qualitative information about the learner experience, as highlighted by Alsawaier (2018).

2.4 Blended Learning Preferences and Pedagogical Effectiveness

Blended learning, which incorporates both offline and online learning tools and technology, enjoys popularity. According to Alqurashi (2025), 60% of participants supported blended learning; offline learning was found to be beneficial for speaking and listening skills, while online learning aided vocabulary and reading skills. Mansha et al. (2024) supported that participants generally preferred blended learning to online learning and cited academic years and types of institutions as factors influencing their preference. Karasová and Uherková (2023) suggested that explanations and visual inputs from teachers are crucial in blended learning.

Engagement theory and second language acquisition interactionist approaches also strongly underline the role of active learner engagement when learning online. Engagement theory suggests that learning is most effective when learners participate in tasks that engage their attention and cognitive processing (Moleda Learning Technologies, 2019). Recent research on digital game-based language learning similarly emphasizes active participation, interaction, and learner involvement in technology-mediated language learning (Hung et al., 2018; Shortt et al., 2021). This theoretical background helps to interpret how blended learning can function effectively since it combines classroom interaction with online interactive tasks, while the interactive use of multimedia materials can further support active participation in English-language learning (Allahverdiyeva, 2025).

The advantages of the blended learning approach include adaptability, accessibility, and personalization, which can support students' self-regulation while maintaining systematic instructional guidance. Seredycz (2020) reported that a 70:30 online-to-offline instructional ratio was associated with more favorable outcomes, particularly among younger and employed learners. These findings suggest that the effectiveness of blended learning may depend not only on the availability of digital technologies but also on how online and face-to-face components are pedagogically balanced. In language education, the interactive use of multimedia materials can further contribute to the effective integration of digital resources into classroom instruction (Allahverdiyeva, 2025).

Complementing these findings, Makhlouf and Al-Qaisi (2025) investigated the efficiency of Gamma, Padlet, and Google Classroom for undergraduate Yemeni students and reported generally very positive leaner attitudes toward digital instruction, especially in terms of motivation and usability. However, this study also revealed residual traditional learning preferences among some students, which again bolsters the case that blended learning models, rather than fully digital approaches, hold more promise for accommodating diverse expectations and disciplinary needs of learners.

2.5 Technology Acceptance and Adoption

Perceived ease of use, perceived usefulness, self-efficacy, enjoyment, accessibility, and prior experience with technology are the main interrelated factors that may affect the adoption of digital learning technologies. This is according to Granić & Marangunić (2019), respectively. Apparently, those learners who may possess experience related to digital technology, that is, youth, can adopt online and blended courses promptly, and those from the senior batch may show a marked inclination toward offline courses, that is, classrom delivery. Another factor that may impact the acceptance of

online courses and related technology among the learners could be instructor support. Indeed, proper guidance and instruction from tutors may be essential for the proper use of digital technology.

Beyond these general determinants, TAM provides a robust explanatory framework for understanding learners' attitudes toward educational technologies. According to the model, perceived ease of use and perceived usefulness directly influence users' behavioral intentions and actual system usage. The intuitive interfaces and clearly perceived pedagogical benefits have been found to be crucial for ensuring high level of acceptance, sustained engagement, and continued use of digital learning tools within educational contexts (Granić & Marangunić, 2019). These findings suggest that only those pedagogical technologies will see wider diffusion that minimize cognitive load while offering explicit academic value. Instructional platforms like Gamma, therefore, are more likely to be accepted when they align with the learners' disciplinary needs and support meaningful learning outcomes.

Although Gamma incorporates AI-assisted features, the present study does not examine or measure the platform's underlying artificial intelligence capabilities separately. The term AI-assisted is therefore used to describe the platform's content-generation and design-support functions rather than to suggest that all of its pedagogical functions are inherently AI-based.

Recent empirical evidence supports these findings even further. Investigating the efficiency of Gamma, Padlet, and Google Classroom with undergraduate students at Seiyun University in Yemen, Makhlouf and Al-Qaisi (2025) focused their attention on learners' attitudes in terms of accessibility, interactivity, motivation, and skill development. Employing a quantitative students' questionnaire across several academic majors and levels, their study reached an overall positive attitude toward all three platforms, mostly in relation to usability and motivational effects. No less importantly, whereas there were no statistically significant differences across levels, statistically significant differences appeared across disciplines to the effect that learners' academic backgrounds substantially affect their acceptance of digital learning technologies.

Further, Makhlouf and Al-Qaisi (2025) reported that some students continued to express a preference for traditional instruction, highlighting the continuing relevance of conventional pedagogical practices alongside digital learning environments. This finding is consistent with the view that digital technologies are most effective when they are integrated into pedagogically meaningful instructional designs rather than treated as replacements for established teaching practices. Allahverdiyeva (2025) similarly emphasizes the importance of selecting and using multimedia materials interactively in English-language classrooms, reinforcing the need for purposeful pedagogical integration. In addition, Mammadova (2025) highlights the potential of artificial intelligence to support language learning through personalized and interactive learning experiences, suggesting that AI-powered tools can enhance rather than necessarily replace teacher-guided instruction. Accordingly, effective implementation requires appropriate teacher preparation and context-sensitive instructional design to ensure that digital platforms contribute meaningfully to learner engagement and learning outcomes.

The literature put together suggests that technology acceptance in educational contexts is not a question of technological affordances alone but is Embedded within the interstices of pedagogical alignment, disciplinary relevance, and instructional support. Application of TAM to Gamma and similar platforms underlines the need for not only user-friendly educational technologies but also pedagogically purposeful ones. These provide a theoretical and an empirical basis to analyze learners' attitudes toward Gamma in particular instructional contexts and justify the focus of the present study on disciplinary background, academic level, and instructional preference.

2.6 An Integrated TAM-SDT Conceptual Framework

In order to synthesize the various theoretical viewpoints that were explored in the literature review, a theoretically integrated conceptual framework is presented in this study, using Technology Acceptance Model (TAM) and Self-Determination Theory (SDT), in an attempt to account for both adoption of digital tools in language learning, as well as processes involved in successfully learning a language in web-based learning settings. The relationships between constructs in this study framework are presented in Figure 1.

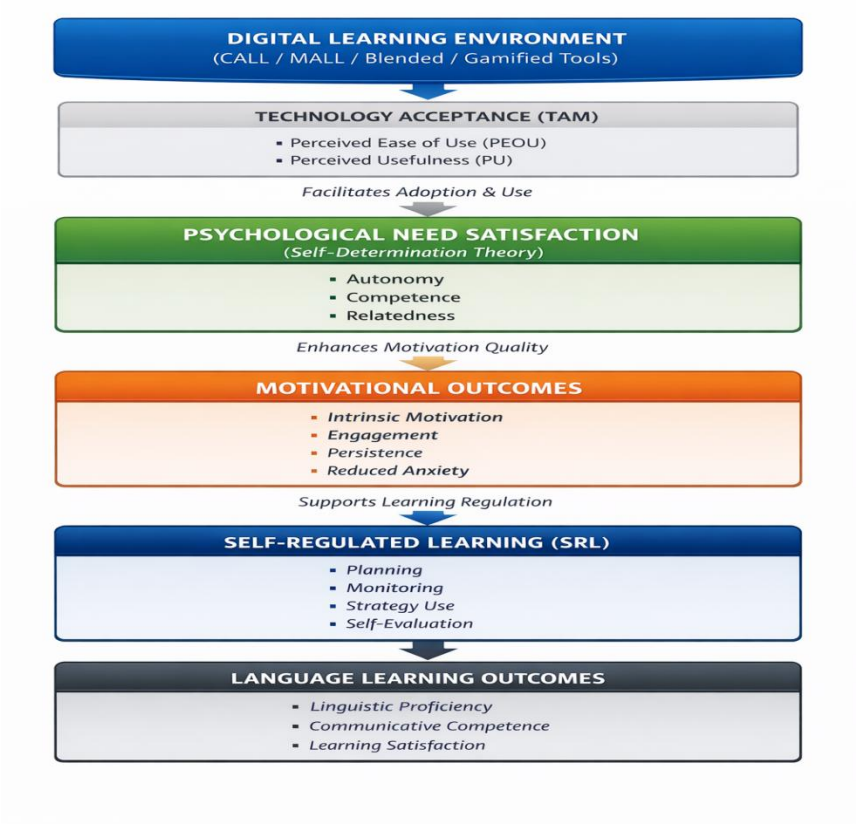

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Figure 1

The conceptual framework of Integrated Technology Acceptance Model (TAM) and Self-Determination Theory (SDT) in digital language learning

Figure 1 illustrates the conceptual framework for the current study, in which TAM and SDT combine to explain learners' engagement with digital language learning environments. The framework is set within the literature on CALL, MALL, blended learning, motivation, and self-regulated learning in second language acquisition.

Drawing on TAM, it is hypothesized that learners' adoption of digital learning tools will primarily be influenced by perceived ease of use and perceived usefulness, which act to shape their willingness both to engage with, and sustain, the use of technology-mediated instruction. The more learners perceive the digital platforms as user-friendly and pedagogically useful, the better positioned they are for actual adoption and active use within language learning contexts.

Grounded in this initial acceptance, the framework embeds the Self-Determination Theory to describe the quality of learners' motivation subsequent to technology adoption. In particular, the model assumes that an efficient, accessible digital learning environment supports the satisfaction of learners' basic psychological needs for autonomy, competence, and relatedness. These needs are satisfied

through giving the learners control of pacing, immediate feedback, tracking of their progress, collaboration activities, and also interactive tasks.

These psychological needs are likely to facilitate intrinsic motivation, engagement, persistence and reduced learning anxiety, which are critical affective factors in second language acquisition. Again, higher motivation promotes the acquisition of self-regulated learning behavior such as planning, monitoring, strategy use and self-evaluation in digitally mediated learning environments. Finally, it is assumed that self-regulated learning serves as a mediating mechanism which links motivation to the endpoints of language learning such as linguistic proficiency, communicative competence and learning satisfaction. In this model, TAM and SDT are integrated to explain both learners' acceptance of digital technologies and the motivational and self-regulatory processes that eventually lead to effective language learning in blended and online contexts.

2.7 Research Gaps and Future Directions

In spite of the increasing evidence available for digital language learning, some remaining gaps still include:

1. Limited level-specific research: There exist a few research papers that explore specific proficiency levels, age groups, or subjects, thereby lacking generalizability (Boudadi & Gutiérrez-Cólon, 2020; Hung et al., 2018).
2. Autonomy and Motivation Mechanisms: Although the relationship between self-regulated learning, learner autonomy, and motivation in digital learning environments remains insufficiently explored, recent research has increasingly highlighted the importance of self-directed learning and autonomy-supportive conditions in EFL contexts (Salami & Althaqafi, 2023; Umaraliyeva, 2025). This gap is particularly relevant when examining emerging AI-supported pedagogical tools, whose interactive and flexible affordances may influence learners' engagement, autonomy, and motivation in different ways.
3.The Effects of Gamification in the Long Run: Scientific research regarding the consequences of a gamified learning process is limited (Shortt et al., 2021 ; Alsawaier, 2018).
4. Insights from Qualitative Research: Experiences, perspectives, and engagement techniques of students have received lesser focus in the existing body of knowledge on the subject (Shortt et al., 2021; Salami & Althaqafi, 2023).
5. Tool-Oriented Literature: Tool design is often given a higher priority than pedagogical efficiency (Shortt et al., 2021).
6. Cultural and Contextual Limitations: Studies are mostly on English language learning and Western culture, to a great extent neglecting other languages and cultural settings. Future studies should adopt mixed-method designs and cross-cultural approaches to allow for further strengthening of the evidence base and development of practical implications for learning design.

2.8 Conclusion

In a nutshell, technology supports and caters to learner autonomy, motivation, and investment in language learning. Blended learning is a combination of the best practices of offline and online learning models. The integration of technology in the learning process relies on usefulness, simplicity, and relevance, and there is some promise of potential within the idea of gamification regarding improving learner motivation and language proficiency. Gaps are identified in longitudinal, qualitative, and cross-cultural research in the domain of SLA and digital technologies.

3. Method

3.1 Research Design

This study is based on a post-positivist research paradigm, and it puts into practice a quantitative, non-experimental, and cross-sectional survey design. Its main objective was to investigate the attitude of university students toward Gamma as a digital pedagogical tool in online and hybrid instruction regarding usability, interactivity, engagement, learner autonomy, and motivation.

The researcher adopted a cross-sectional research approach to include perceptions of learners after the prolonged instructional implementation of Gamma. This research approach aligns with best research practices for high impact research in technology in education, specifically in the context of researching acceptance and perceptions associated with learning experiences or processes.

3.2 Context of the Study and Instructional Content

This research was conducted at El Bayadh University Centre, Algeria over a semester where classes were delivered through online and blended delivery modes. Gamma was fully integrated into regular teaching practices and functioned as the primary instructional presentation and interaction tool, not as a supplementary platform.

Alignment of Teaching Content with Majors and Levels

Instructional content was carefully aligned with students' academic level and major, ensuring pedagogical relevance and disciplinary appropriateness.

First-Year Students (English & Social Sciences)

Gamma-supported instruction focused on:
• Introduction to academic learning skills
• Basic language functions (describing, summarizing, explaining)
• Vocabulary development and sentence-level accuracy
• Guided reading comprehension activities

The usual activities of Gamma included:
• Visuals for lesson presentation with clear narrations
• Embedded questions of comprehension
• Reflection questions

Second-Year Students (English & Social Sciences)

Gamma-supported instruction emphasized:
• Paragraph and short-text construction
• Discipline-related texts (education, society, communication)
• Analytical reading and guided discussion
• Content-based language use

Typical Gamma activities include:
• Concept mapping slides
• Discussion-trigger slides
• Independent review modules designed for self-paced learning

This differentiated content allowed the students' experiences of Gamma reflected authentic pedagogical value, not generic exposure.

3.3 Pedagogical Implementation of Gamma

A gamma implementation was carried out over an eight-week continuous process.

• Number of weekly sessions: 2
• Session length: 90 minutes on average
One concurrent Gamma session (online or hybrid)
One asynchronous Gamma-supported review or task
Gamma was utilized for:
Lesson delivery
Interactive explanation
Independent revision
Content visualization

This helped in ensuring that attitudes were based on meaningful instructional engagement.

3.4 Participants

The sample consisted of 150 undergraduate students, distributed across two academic levels and two majors.

Table 1
Distribution of participants by academic level and major (N = 150)

Academic Level	English	Social Sciences	Total
First year	42	33	75
Second year	39	36	75
Total	81	69	150

Note. N = number of participants. Both male and female students participated. All participants had prior instructional exposure to Gamma.

Both male and female students participated. All participants had prior instructional exposure to Gamma.

3.5 Sampling Technique

Non-probability convenience sampling technique was used as a consequence of institutional accessibility and course scheduling constraints. Despite this limitation, the sample size exceeds recommended thresholds for attitudinal survey research and supports reliable descriptive and inferential analysis.

3.6 Instrument Development

Data were collected using a researcher-developed structured questionnaire, informed by prior validated instruments in e-learning and digital pedagogy research.

3.6.1 Instrument Structure

Section A: Demographic information (academic level, major)

Section B: Attitudinal constructs measured on a *5-point Likert scale* (1 = Strongly Disagree, 5 = Strongly Agree)

Constructs included:

Ease of use

Accessibility of materials

Interactivity

Learner engagement

Learner autonomy

Motivation

Instructional preference (Gamma vs. traditional)

3.7 Reliability and Validity

3.7.1 Reliability

Internal consistency reliability was assessed using Cronbach's alpha: *Overall* $\alpha = 0.86$, indicating strong reliability.

3.7.2 Validity

Content validity: Established through expert review

Construct validity: Supported by theoretical alignment

Face validity: Confirmed during pilot testing

3.8 Data Analysis

Data were analyzed using *SPSS* following:

Data screening

Descriptive statistics

Independent-samples *t*-tests (academic level and major)

Statistical significance was set at $\mathbf{p \leq .05}$.

4. Results

4.1 Preliminary Data Screening

Data screening revealed minimal missing values and no severe deviations from normality. The dataset was suitable for statistical analysis.

4.2 Overall Attitudes Toward Gamma

Table 2
Descriptive statistics for attitudes toward gamma (N = 150)

Variable	M	SD
Ease of use	4.28	0.61
Accessibility	4.21	0.65
Interactivity	4.35	0.58
Learner engagement	4.32	0.60
Learner autonomy	4.17	0.67
Motivation	4.26	0.63

Note. M = mean; SD = standard deviation; scale: 1 = strongly disagree, 5 = strongly agree.

The data presented in table 2 indicate the descriptive statistical values that measure students' attitude towards Gamma on six pedagogical facets, such as ease of use, accessibility, interactivity, engagement, autonomy, and motivation. The mean values for all facets were quite high and measured between 4.17 and 4.35 with low standard deviations.

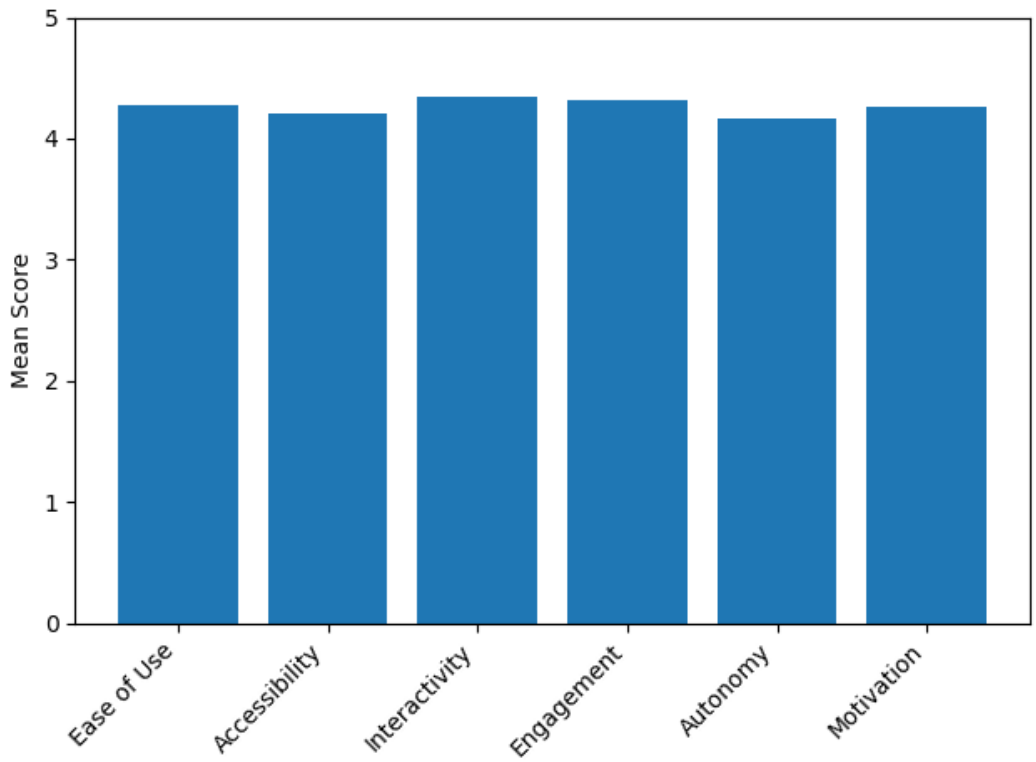

Figure 2
Mean attitude scores across pedagogical dimensions

Figure 2 shows mean scores on attitude for each of the different pedagogical factors that were considered. The value of recall, interactivity, and engaging the learner is considered most important in Gamma, followed closely by ease of use and motivation.

4.3 Ease of Use and Accessibility

Table 3
Frequency distribution of student responses to Gamma's Ease of use and accessibility

Response category	Percentage (%)
Strongly agree	46.7
Agree	38.0
Neutral	9.3
Disagree	4.0
Strongly disagree	2.0

Note. Percentages reflect students' combined responses to ease of use and accessibility items.

Table 3: Student response distribution to Gamma's ease of use and accessibility Majority of the students felt positive about Gamma, and 46.7% and 38.0% of the students strongly agreed and agreed, respectively, to the ease of use and accessibility of the software. The neutral and negative categories had only a small share of the percentages.

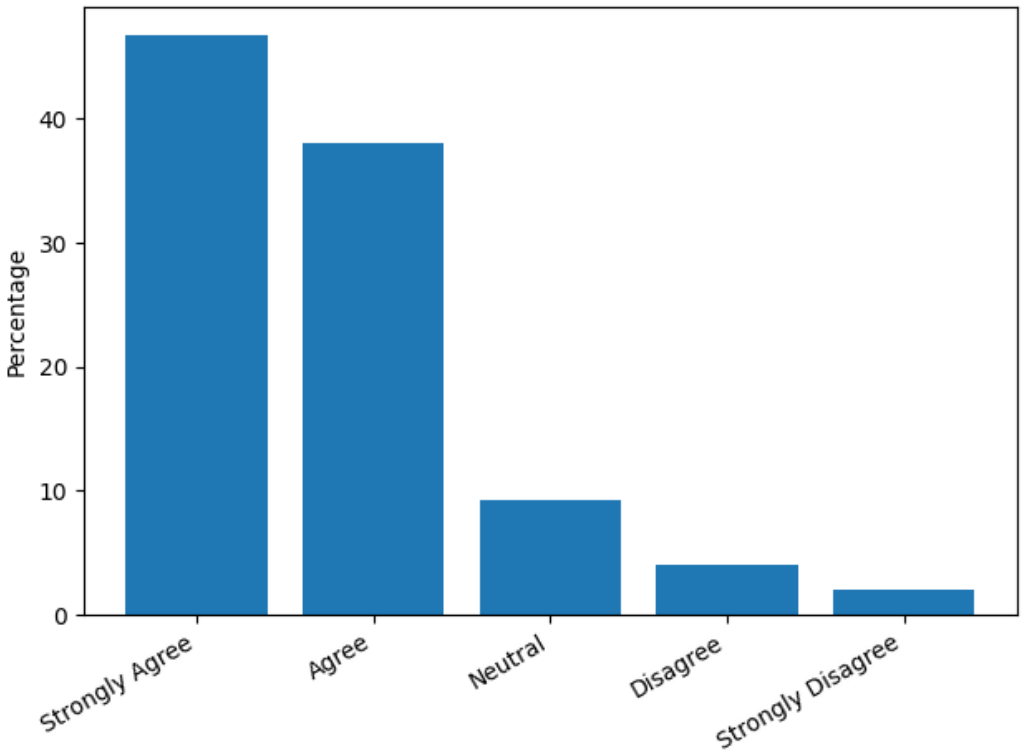

Figure 3
Ease of use and accessibility response distribution

As can be seen in Figure 3, the percentage distribution of the ease of use and accessibility of the questionnaire based on the Likert scale provides an even clearer indication of the degree to which the answers were positive. The majority of students responded positively to Gamma's ease of use and accessibility, with 84.7% agreeing or strongly agreeing.

4.4 Interactivity and Learner Engagement

Table 4
Perceptions of interactivity and engagement

Item	M	SD
Promotes active participation	4.37	0.56
Makes lessons more engaging	4.33	0.59
Enhances interaction with content	4.36	0.57

Note. M = mean; SD = standard deviation. Higher scores indicate more positive perceptions.

The findings of the students' perceptions regarding interactivity and engagement are summarized by the mean scores and standard deviations for the three selected items as shown below in Table 4. Each of the items chosen has a high mean value, that is, M > 4.30. This indicates that the students perceive that Gamma supports participation, interaction, and a high level of engagement.

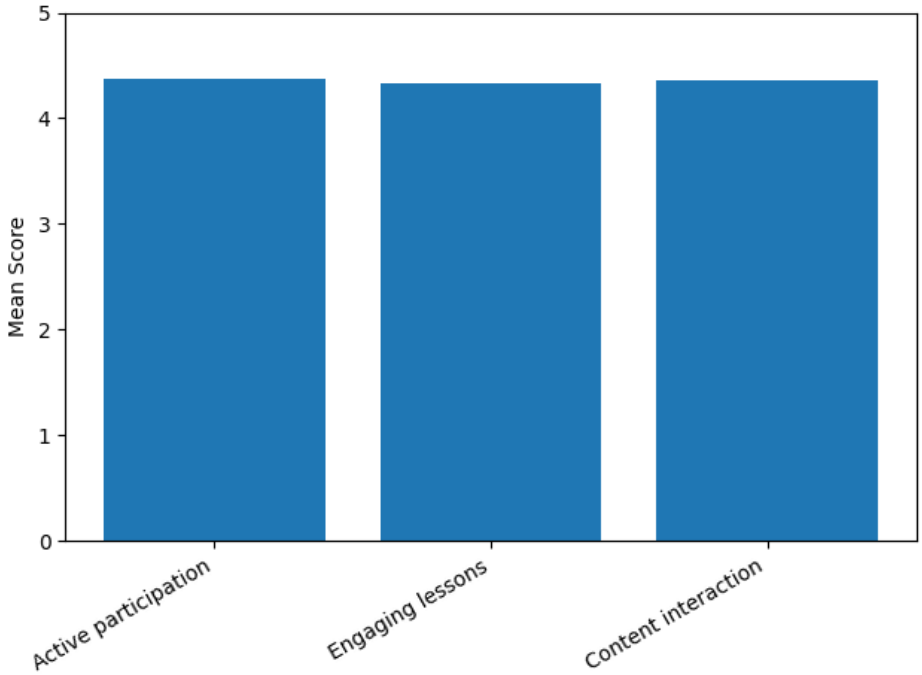

Figure 4
Interactivity and learner engagement items

As can be observed in Figure. 4, the average score for each interactivity and learner engagement item has been plotted for the comparison purpose.

4.5 Learner Autonomy and Motivation

Table 5
Learner autonomy and motivation scores

Variable	M	SD
Self-paced learning	4.18	0.66
Independent access	4.20	0.64
Motivation to learn	4.26	0.63

Note. M = mean; SD = standard deviation.

Table 5 provides summary statistics for the variables of learner autonomy and motivation. A high mean score for self-paced learning, independent access, and motivation to learn with low dispersion of the data can be observed.

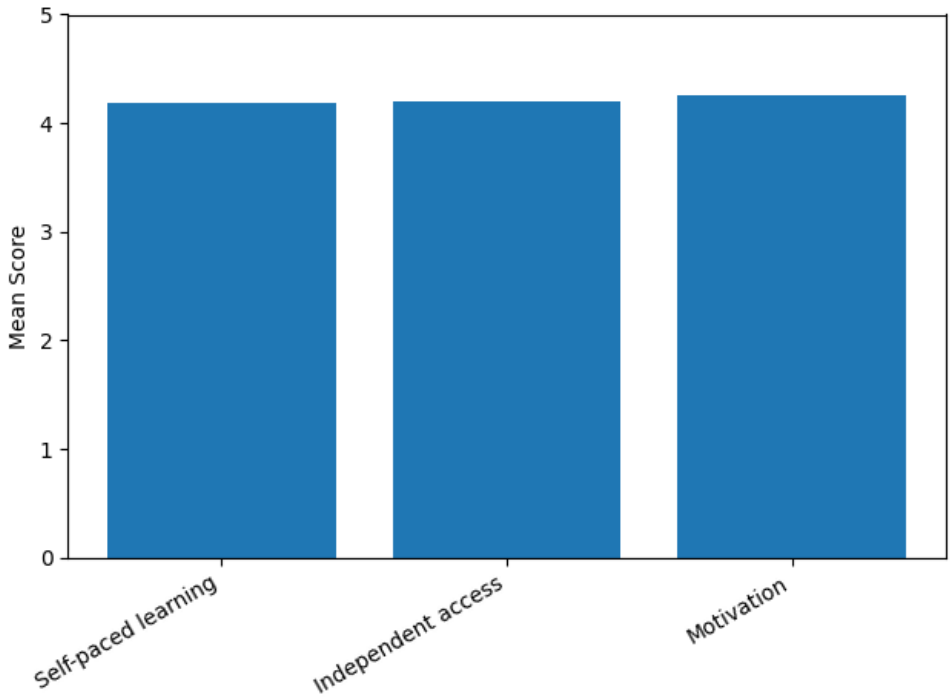

Figure 5
Learner autonomy and motivation

As evidenced in Figure 5, the mean scores of the constructs of learner autonomy and motivation reflect the positive views that students have of the role played by Gamma in facilitating learning autonomy and motivation.

4.6 Instructional Preference

Table 6
Instructional preference distribution

Instructional mode	Percentage (%)
Gamma-supported	62.0
Traditional	23.3
No clear preference	14.7

Note. Percentages represent students' preferred instructional mode.

Instructional preference data is presented in Table 6, which shows that most of the participants (62.0%) were in favor of Gamma-supported instruction, fewer were in favor of traditional instruction (23.3%), and only 14.7% had no preference.

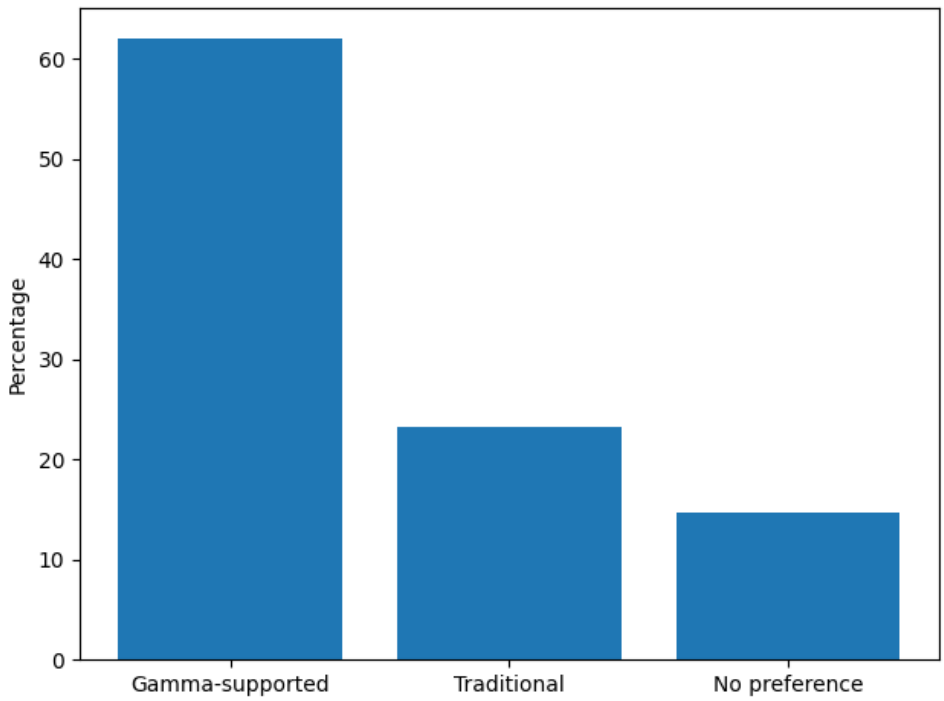

Figure 6
Instructional preference distribution

Figure 6 shows the distribution in the form of a graph that compares the three teaching methods.

4.7 Group Comparisons by Level and Major
Independent-samples *t*-tests revealed no statistically significant differences by academic level or major.

Table 7
Group comparisons of attitudes toward Gamma

Variable	T	P
Academic level	1.12	.26
Academic major	0.94	.35

Note. Independent-samples t tests were conducted. No statistically significant differences were observed ($p > .05$).

Table 7 shows the comparisons of the data grouped by academic levels as well as academic majors. Results of the independent samples t-test did not show significance in having attitudes towards Gamma considering both variables, $p > .05$. This indicates that there were similarities in student perceptions towards Gamma.

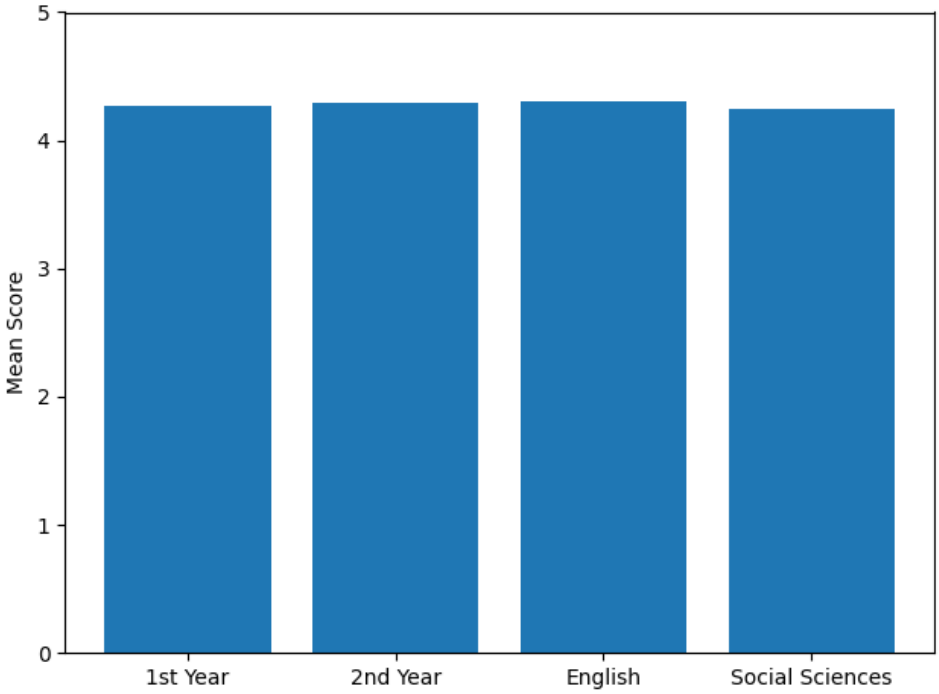

Figure 7
Mean attitude scores by academic level and major

Figure 7 tends to provide a graphic verification regarding the lack of significant differences among the data presented.

4.8 Summary of Results

The findings clearly indicates positive attitudes held by the students towards Gamma, irrespective of their levels and disciplines. The high average scores for all the pedagogical values clearly indicate the effectiveness of Gamma towards facilitating interactive, accessible, and autonomy-friendly approaches to education, even when conducted online.

The above-mentioned quantitative analysis clearly indicates a positive outcome in terms of usability and interaction for the undergraduate group in evaluating Gamma as a highly usable and interactive system in various academic levels and disciplines. Based on descriptive and inference analysis, it has been revealed that there are no significant differences among the learner groups to accept hypotheses H1 to H4; therefore, the following section will discuss the outcome based on the theory of technology acceptance model and self-determination theory related to language learning and education platforms like Gamma.

5. Discussion

In this current research, there was a goal to empirically investigate the attitudes of university students towards Gamma as a learning technology for language learning in terms of usability, interactivity, learner engagement, autonomy, motivation, and preference for instruction. In sum, this research suggests that the current study offers strong support for all the hypothesized research questions, validating the learning potential of Gamma in digitally mediated learning contexts and its importance in innovative language learning in universities.

5.1 Usability, Accessibility, and Technology Acceptance

The strong average levels of ease of use and accessibility that have been consistently reported offer strong support for hypothesis 1, suggesting that both levels of learners and fields of study found Gamma to be user-friendly and manageable. This result is consistent with the existing Technology Acceptance Model that suggests that both Perceived Ease of Use and Perceived Usefulness play important roles regarding how levels of learners will adopt an online system (Granić & Marangunić, 2019).

In keeping with TAM literature, it can be seen that the lack of technical hurdles has helped to avoid cognitive overload and generate positive learning experiences, especially in remote environments wherein technological irritations tend to detract from engagement. The findings lend support to previous literature that shows user-friendly interfaces can aid in generating satisfaction and adoption in learning environments (Bhattarai & Maharjan, 2020). Notably, with no statistical significance in either academic level or major, it can be supported that claims in H2 and H3 are true and that Gamma's usability has pedagogic scalability, thus meeting the need for level and discipline-specific evaluations of digital tools.

5.2 Interactivity and Learner Engagement

The high level of ratings on interactivity and engagement with learning suggests that Gamma effectively operated as an engagement-enabling learning environment and not as a mere content dissemination tool. The perceptions by learners that Gamma supported active engagement and interaction with learning content align with engagement theories that require participation in learning for cognitive processing to occur at a deeper level.

From an SLA point of view, the results are consistent with interaction-oriented approaches that emphasize the role of meaningful interaction and learner participation in effective language development. Moreover, the results support the CALL literature indicating that digital technology can create additional opportunities for learner engagement, interaction, and active participation in language learning (Hung et al., 2018; Shortt et al., 2021). Recent research on AI-supported language learning further suggests that emerging digital technologies can provide personalized and interactive learning experiences that encourage active learner involvement (Mammadova, 2025). In this respect, Gamma can be interpreted as a complementary digital pedagogical tool that extends opportunities for interactive engagement within blended language-learning contexts.

5.3 Learner Autonomy, Motivation, and Self-Regulated Learning

Pedagogically, one of the most important findings emerging from this research is the evidence supporting learner autonomy and motivation, further justifying H1. Also, since students showed positive attitudes towards self-paced learning and self-directed access, this also indicates that Gamma facilitated self-regulation of learning (SRL) process activities, like planning, control, or monitoring (Noori, 2025).

On the other hand, these results can be interpreted through another theoretical framework, namely Self-Determination Theory (SDT). According to SDT, autonomy-supportive learning contexts can enhance intrinsic motivation when learners experience autonomy, competence, and meaningful involvement in learning activities. Gamma may support these psychological needs by enabling learners to explore and organize learning materials in flexible and interactive ways while remaining actively engaged with learning tasks. This interpretation is consistent with recent research emphasizing the role of interactive and AI-supported technologies in creating more personalized language-learning experiences (Mammadova, 2025) and with research highlighting the relationship between self-study, learner autonomy, motivation, and digital learning in EFL contexts (Umaraliyeva,

2025). In this respect, the present findings extend the existing literature by examining how an emerging AI-powered digital pedagogical tool may contribute simultaneously to learner engagement, autonomy, and motivation within blended language-learning contexts.

5.4 Instructional Preferences and the Role of Hybrid Pedagogy

The result indicating the preference for Gamma-supported instruction over the traditional method confirms hypothesis H4 and is in line with the general preferences for a combination of different teaching methods. The preference for mixed environments in teaching has been shown to provide the best possible combination of flexibility and structure (Alqurashi, 2025; Mansha et al., 2024). In this context, Gamma's value should be understood through its combination of visually organized content, AI-assisted content development, multimedia presentation, and interactive digital delivery. These affordances can complement teacher-led instruction rather than replace it, particularly in blended language-learning environments.

Notwithstanding, the presence of a minority who support traditional instruction implies that technology works well when incorporated substantively rather than purely as a tool for replacing traditional instruction. In pedagogy, this verifies arguments that technology must be incorporated in a complementary fashion that supports rather than replaces traditional instruction (Karasová & Uherková, 2023).

These results are also supported by the study conducted by Makhlouf and Al-Qaisi (2025), which examined the attitudes of the learners towards the use of Gamma, Padlet, and Google Classroom by the undergraduate students of Yemen. The findings of this study found that the learners had positive attitudes towards the use of technology-based teaching, which are largely similar to the results of the current study. Notably, the study found that some of the learners still had a preference for the conventional teaching methods, which seems to be highly relevant to the teaching practices of the blended models rather than the purely digital models.

In addition, there were no statistically significant differences in technology acceptance based on academic levels according to the study of Makhlouf and Al-Qaisi in 2025, which corresponded to the findings of this research. Yet, it is interesting to note that there were varying degrees of learner acceptance depending on the discipline in which the learner is enrolled according to the cited study. These findings, taken in context, emphasize the role of alignment and disciplinary orientation in technology-mediated language learning.

Within this broader empirical context, the literature and the present findings indicate that technology acceptance in higher education depends on considerations that extend beyond the technical attributes of a digital tool. Consistent with the Technology Acceptance Model, the effective adoption of Gamma in higher education is likely to depend on perceived usefulness and ease of use, as well as on the extent to which the tool is aligned with pedagogically meaningful educational practices (Granić & Marangunić, 2019). For language learning in particular, the value of digital and AI-supported tools also lies in their capacity to promote interactive learning, learner autonomy, and self-directed engagement (Mammadova, 2025; Umaraliyeva, 2025). Thus, Gamma is most appropriately conceptualized as a complementary pedagogical resource that can enrich teacher-led instruction through interactive content creation and learner-centered activities rather than as a substitute for human instruction.

5.5 Absence of Group Differences: Equity and Pedagogical Inclusivity

The lack of statistically significant differences for levels and majors adds strength to the conclusion that Gamma creates an equal educational environment for students. It contradicts the presumption that technology primarily favors particular groups of students. It corroborates the idea that technology

based on pedagogy can create a more equal environment for learning. From the point of view of research, this result adds important empirical data to the scarce body of research that investigates consistency for particular groups in digital language learning.

5.6 Theoretical and Pedagogical Contributions

Collectively, results inform that Gamma can be viewed from a Leaning-Liberty-Engagement perspective. In contrast to other investigations focused on technology-based aspects only, this investigation tends to instructional influence rather than technological influence per se and thus corresponds to some demands in CALL/SLA scholarship regarding cultural issues of inequality (Shortt et al., 2021). Furthermore, by incorporating an Algerian higher education setting into its framework, this investigation corrects an imbalance of geographical representation noted in SLA/CALL scholarship.

6. Limitations and Future Research

Though the results obtained from the study reveal that students' attitude towards the usage of Gamma as a teaching technology is positive, there exist several limitations that need to be taken into consideration. First, the non-probability convenience sampling technique that was adopted for conducting the study involved participants belonging to two university majors. This indicates that the findings of the study might not be comprehensive enough and may target a specific group belonging to a particular university only. At the same time, the sample adopted for the purpose of the study might be sufficient enough for the completion of the study but might lag behind in representing the diverse view of the students.

Second, though the study has tapped important pedagogical attitudes such as ease of use, interactivity, engagement, autonomy, and motivation, there could be some important dimensions that might not have been tapped into. For example, it may not have included perspectives of cognitive load, long-term retention, or collaborative learn dynamics.

Third, the cross-sectional design with a non-experiment restricts the ability to make conclusions about causations. Even though the study subjects had a long-term engagement with Gamma, the study cannot ascertain if the positive attitudes that the subjects exhibited were a result of Gamma alone because there could be other factors that might influence the results. Furthermore, the study might be restricted in terms of external validity particularly because the study took place in a specific instructional context that may not be the same in other settings.

One potential area that can be explored in future studies related to this investigation would be to examine other aspects related to outcome or performance and determine the value of the Gamma effects using longitudinal or experimental approaches. By increasing the population size across multiple institutions, it is possible to obtain higher levels of generalizability related to the results, while using other approaches related to methodology, including analysis or focus group discussions or observational studies related to Gamma, can possibly lead to a higher degree of understanding related to learning attitudes associated with digital tools like Gamma.

7. Conclusion and Implications

The investigation examined undergraduate students' attitude towards Gamma as a pedagogical technology in online and blended language courses. The result shows a highly positive attitude in functionality, interactivity, engagement, autonomy, and motivational facilitation, confirming Gamma's pedagogical efficacy not only in a supporting capacity but also in a mediating capacity. The lack of statistically significant disparity in functionality across academic and subject categories also provides an indication that Gamma's pedagogical functionality is quite versatile and supports a holistic integration.

Notably, students' choice of Gamma represents a growing trend towards flexible or blended forms of learning, while their concurrent dependence on traditional learning represents a need for critical and intentional application of educational technologies. These findings remedy a research literature lag and respond to a call for empirical research that explores technology in a pedagogy-focused manner as opposed to a pure tool approach.

Pedagogical Implications

The findings from this study prove that Gamma can be appropriately embedded in order to increase learner engagement, motivation, and autonomy. The importance of using Gamma in a more engaging learning environment rather than a traditional content delivery platform cannot be overstated. Furthermore, the positive attitude results indicate the significance of training and development in terms of digital pedagogy so that educators can create autonomy-supportive learning environments as well as engagement-oriented settings.

Theoretical Implications

The results emphasize the importance of Technology Acceptance Model (TAM), Self-Regulation Theory, and engagement theory in shaping learner behavior by emphasizing the roles of technology-based learning tools in the context. The variables related to perceived usability, interactivity, and autonomy support showed importance in shaping positive attitudes, thereby underlining the importance of technology in the efficient improvement of learning outcomes in accordance with teaching methodologies. The paper contributes to theoretical development by illustrating that technology is an important teaching agent in defining both cognitive and motivational features in learning.

Research Implications and Future Research Outlines

In future studies, it would be interesting to explore the long-term impact of Gamma upon Language Proficiency and SL Behaviors by adopting longitudinal and hybrid research methodologies. For instance, qualitative research methodologies may help explore the SL engagement mechanism and experiences among students, while inter-institution and inter-disciplinary studies would add to the overall externality of the research results. The limitations discussed within the current study demonstrate that future research work must adopt representative sampling techniques and objective indicators to measure students' performance.

In summary, Gamma shows potential as an adaptive, interactive, and autonomy-friendly learning technology that has the ability to reinvent blended language learning on the web. Integration of Gamma, with empirical evidence as well as theoretical underpinnings, can provide ways to move web-based tools from the periphery to the center of an effective educational process.

References

Adzmi, N., Bidin, S., Selvaraj, B., & Saad, S. (2024). The role of gamification in enhancing engagement and motivation in language learning. *International Journal of Research and Innovation in Social Science, 8*(9), 2402–2411. https://doi.org/10.47772/IJRISS.2024.8090197

Allahverdiyeva, G. (2025). Selecting and interactive use of multimedia materials in English language classes. *Scientific Work, 19*(4), 9–12. https://doi.org/10.36719/2663-4619/114/9-12

Almayez, M. A., Al-Khresheh, M. H., Al-Qadri, A. H., Alkhateeb, I. A., & Alomaim, T. I. M. (2025). Motivation and English self-efficacy in online learning applications among Saudi EFL learners: Exploring the mediating role of self-regulated learning strategies. *Acta Psychologica, 254*, Article 104796. https://doi.org/10.1016/j.actpsy.2025.104796

Alqurashi, N. (2025). Enhancing language acquisition: Integrating traditional and digital methods for learner engagement. *European Scientific Journal, ESJ, 21*(2), 41. https://doi.org/10.19044/esj.2025.v21n2p41

Alsawaier, R. S. (2018). The effect of gamification on motivation and engagement. *International Journal of Educational Technology, 35*(7). https://doi.org/10.1108/IJILT-02-2017-0009

Bhattarai, S., & Maharjan, S. (2020). Determining the factors affecting digital learning adoption among students in Kathmandu Valley: An application of the Technology Acceptance Model (TAM). *International Journal of Engineering and Management Research, 10*(3), 131–141. https://doi.org/10.31033/ijemr.10.3.20

Boudadi, N. A., & Gutiérrez-Cólon, M. (2020). Effect of gamification on students' motivation and learning achievement in second language acquisition within higher education: A literature review 2011–2019. *The EuroCALL Review, 28*(1), 57–69. https://doi.org/10.4995/eurocall.2020.12974

Bui, P. M. T., & Nguyen, L. T. (2025). Students' perceptions of the adoption of paperless learning technology. In *Proceedings of the 10th International STEM Education Conference (iSTEM-Ed)* (pp. 1–6). IEEE. https://doi.org/10.1109/iSTEM-Ed65612.2025.11129313

Edwards, R., & Terantino, J. (2025). Self-determination and autonomous digital language learning in Mexico: An exploratory case study of secondary EFL students. *CALICO Journal, 42*(2), 304–329. https://doi.org/10.3138/calico-2024-0015

Egbert, J. L., Shahrokni, S. A., Zhang, X., Herman, D., Yahia, I. A., Mohamed, A. F., Aljarih, F., Ezeh, C. C., Borysenko, N., & Lopez-Lopez, S. (2020). Revisiting gaps in the CALL literature. In *Recent developments in technology-enhanced and computer-assisted language learning* (pp. 1–28). IGI Global. https://doi.org/10.4018/978-1-7998-1282-1.ch001

Granić, A., & Marangunic, N. (2019). Technology acceptance model in educational context: A systematic literature review. *British Journal of Educational Technology, 50*(5), 2572–2593. https://doi.org/10.1111/bjet.12864

Hung, H.-T., Yang, J. C., Hwang, G.-J., Chu, H.-C., & Wang, C.-C. (2018). A scoping review of research on digital game-based language learning. *Computers & Education, 126*, 89–104. https://doi.org/10.1016/j.compedu.2018.07.001

Jain, A. (2025). A comparative study of online vs. traditional learning in higher education. *International Journal for Research in Education, 14*(1), 55–72. https://doi.org/10.63345/ijre.v14.i1.2

Karasová, E., & Uherková, M. (2023). Navigating the digital age: Exploring effective teaching and learning approaches for university students. *Media & Marketing Identity: AI—The Future of Today, 10*(1), 45–63. https://doi.org/10.34135/mmidentity-2023-19

Lee, L. (2016). Autonomous learning through task-based instruction in fully online language courses. *Language Learning & Technology, 20*(2), 81–97. https://doi.org/10.64152/10125/44462

Makhlouf, A., & Abdullah Al-Qaisi, W. (2025). The effectiveness of e-learning and AI applications (Gamma, Padlet, Classroom) in developing the educational process. *Language Art, 10*(3). https://languageart.ir/index.php/LA/article/view/460

Mammadova, K. (2025). The role of artificial intelligence in improving grammar and writing proficiency. *Scientific Work, 19*(3), 40–44. https://doi.org/10.36719/2663-4619/112/40-44

Mansha, A., Malik, S., & Gul, T. (2024). Investigating university-level students' preferences between traditional and blended learning approaches. *Journal of Social Sciences Development, 3*(3), 1–16. https://doi.org/10.53664/JSSD/03-03-2024-01-01-16

Noori, A. (2025). Digital technologies and self-regulated language learning: A systematic review. *Journal of Social Sciences - Kabul University, 8*(1), 243–263. https://doi.org/10.62810/jss.v8i1.323

Rabi'ah, Y., Hadiwinarso, Y., & Jannah, R. (2025). Gamification and interactive learning: Enhancing students engagement and proficiency outcomes. *Entita: Jurnal Pendidikan Ilmu Pengetahuan Sosial dan Ilmu-Ilmu Sosial, 1*, 909–920. https://doi.org/10.19105/ejpis.v1i.19133

Salami, F. A., & Althaqafi, A. (2023). The effectiveness of teacher autonomy supportive style on enhancing student engagement in EFL virtual classrooms. *English Language and Literature Studies, 13*(1), 44. https://doi.org/10.5539/ells.v13n1p44

Seredycz, M. A. (2020). Student motivations that predict the self-selection and choice of blended instructional delivery. *Annals of Social Sciences & Management Studies, 5*(2), 31–41. https://doi.org/10.19080/ASM.2020.05.555659

Shortt, M., Tilak, S., Kuznetcova, I., Martens, B., & Akinkuolie, B. (2021). Gamification in mobile-assisted language learning: A systematic review of Duolingo literature from public release of 2012 to early 2020. *Computer Assisted Language Learning, 36*(3), 517–554. https://doi.org/10.1080/09588221.2021.1933540

Suarez García, E. R., & Almeida, E. (2025). Aprendizaje digital y gamificación: Un puente hacia la práctica de la autorregulación en lengua extranjera inglesa. *Kronos – The Language Teaching Journal, 6*(1), 67–80. https://doi.org/10.29166/kronos.v6i1.7811

Umaraliyeva, M. (2025). Self-study and intercultural communicative competence in EFL learners: Challenges and support strategies. *Scientific Work, 19*(5), 56–60. https://doi.org/10.36719/2663-4619/115/56-60

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TƏBİƏT ELMLƏRİ

NATURAL SCIENCES

Zinc-Paba Complex: Synthesis, Structure and Biostimulatory Effect on Gisela-6 in Vitro

Aynur Bayramova[1*], Ramida Guliyeva[2], Elgun Mahmudov[3], Gunay Abbasova[3], and Dashgin Ganbarov[4]

Abstract. *In this study, a novel zinc-based coordination complex derived from para-aminobenzoic acid was synthesized, and its structural properties were characterized using various physicochemical and spectroscopic techniques. Additionally, the biological activity of the complex was evaluated to assess its potential applicability in biomedical or pharmaceutical fields. Duringthe synthesis process, various chemical reagents were used while maintaining stoichiometric ratios, and the crystalline structure of the obtained product was examined under a microscope. The complex compound was characterized using several analytical methods, including FT-IR spectroscopy, thermogravimetric analysis, and crystallography. The absorption frequencies of carboxyl groups in the IR spectrum were analyzed, and it was determined that the coordination type is ionic in nature. The thermolysis process occurred in four main stages, and the structural changes were monitored throughout. The synthesized compound was also applied to "Gisela-6" plants under in vitro conditions at various concentrations. Significant improvements in plant development and proliferation parameters were observed in the nutrient medium enriched with the complex compound. In particular, at a concentration of 700 mg/L, a high initiation and proliferation rate (90%) along with rapid growth was recorded. The conducted study demonstrated that the synthesized complex compound can serve as an effective biologically active substance for stimulating plant development.*

Keywords: *para-aminobenzoic acid, FT-IR spectroscopy, thermogravimetric analysis, in vitro, plant development, biologically active substance, initiation, proliferation*

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Sink-PABA Kompleksi: Sintezi, Quruluşu və Gisela-6 üzərində invitro biostimullaşdırıcı təsiri

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Xülasə. *Bu tədqiqatda para-aminobenzoy turşusundan əldə olunmuş yeni sink əsaslı koordinasiya kompleksi sintez edilmiş və onun struktur xüsusiyyətləri müxtəlif fiziki-kimyəvi və spektroskopik metodlarla xarakterizə olunmuşdur. Eyni zamanda, kompleksin bioloji aktivliyi onun biotibbi və ya farmasevtik sahələrdə potensial tətbiq imkanlarını qiymətləndirmək məqsədilə tədqiq edilmişdir. Sintez prosesi zamanı stexiometrik nisbətlər saxlanılmaqla müxtəlif kimyəvi reagentlərdən istifadə olunmuş və alınan məhsulun kristal strukturu mikroskop altında analiz edilmişdir. Kompleks FT-IR spektroskopiyası, termoqravimetrik analiz (TGA) və kristalloqrafiya daxil olmaqla bir neçə analitik metodla xarakterizə edilmişdir. İnfraqırmızı (IR) spektrdə karboksil qruplarının udulma tezlikləri analiz olunmuş və koordinasiya tipinin ion xarakterli olduğu müəyyən edilmişdir. Termal parçalanma prosesi dörd əsas mərhələdə baş vermiş və struktur dəyişiklikləri proses boyunca izlənilmişdir. Sintez edilmiş birləşmə müxtəlif konsentrasiyalarda "Gisela-6" bitkilərinə in vitro şəraitdə tətbiq edilmişdir. Kompleksla zənginləşdirilmiş qida mühitində bitki inkişafı və proliferasiya göstəricilərində əhəmiyyətli artım müşahidə olunmuşdur. Xüsusilə 700 mg/L konsentrasiyada yüksək başlanğıc və proliferasiya göstəricisi (90%) və sürətli böyümə qeydə alınmışdır. Aparılan tədqiqat göstərmişdir ki, sintez edilmiş kompleks bitki inkişafını stimullaşdıran effektiv bioloji aktiv maddə kimi çıxış edə bilər.*

Açar sözlər: *para-aminobenzoy turşusu, FT-IR spektroskopiyası, termoqravimetrik analiz, in vitro, bitki inkişafı, bioloji aktiv maddə, başlanğıc, proliferasiya*

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Introduction

Plant biotechnology has advanced significantly in recent decades, particularly through the development of *in vitro* propagation techniques. These innovations are essential for large-scale plant multiplication and the preservation of genetic fidelity under sterile conditions. *In vitro* culture systems facilitate the rapid breeding of high-yielding, stress-tolerant, and disease-resistant cultivars—traits critical for ensuring global food security and promoting sustainable agriculture (Yadav & Rani, 2015).

A pivotal component in the success of *in vitro* culture is the formulation of the nutrient medium. While the Murashige and Skoog (MS) medium remains a standard choice, recent research highlights the benefits of enriching culture media with various additives, including plant growth regulators, amino acids, and metal complexes (Khan & Sulaiman, 2018; Muthukumar & Jayakumar, 2017). These supplements can significantly enhance plant development by supplying essential nutrients and stimulating physiological processes.

Among these additives, metal–organic complexes—especially those involving zinc (Zn)—have garnered increasing attention for their dual functionality as nutrient sources and biologically active agents. Zinc is an essential micronutrient, playing a key role in numerous enzymatic processes and maintaining cellular homeostasis in plants (Ali & Ghanem, 2020; Fageria & Stone, 2017). Emerging studies have explored novel zinc-based coordination compounds, such as those incorporating para-aminobenzoic acid, to assess their potential applications in plant biotechnology (Bałaban & Górska, 2018; Hanjani & Kazemian, 2017; Sharma & Sharma, 2016).

The biological activity of zinc-based coordination compounds is associated with several physiological and biochemical mechanisms in plants. Zinc functions as a structural or catalytic component of numerous enzymes involved in protein synthesis, carbohydrate metabolism, and nucleic acid regulation. In addition, zinc contributes to the stabilization of cellular membranes and participates in antioxidant defense systems by regulating the activity of enzymes such as superoxide dismutase. Adequate zinc availability has also been linked to enhanced auxin biosynthesis, improved cell division, and increased tolerance to abiotic stress conditions. Consequently, zinc-containing complexes have attracted increasing attention as potential biostimulants in plant tissue culture and controlled propagation systems.

Para-aminobenzoic acid (PABA) is known not only as an important aromatic carboxylic acid but also as a biologically active compound involved in cellular metabolic processes. Previous studies have suggested that PABA may influence plant growth through its participation in folate-related metabolic pathways, regulation of cellular redox balance, and enhancement of stress tolerance mechanisms. Furthermore, aromatic ligands such as PABA can modify the bioavailability and transport properties of coordinated metal ions, potentially increasing their biological effectiveness. These characteristics make PABA a promising ligand for the development of biologically active zinc complexes intended for plant biotechnology applications.

Recent studies have demonstrated that zinc-based coordination compounds regulate plant growth not only through nutritional supplementation but also via modulation of phytohormone signaling pathways, enhancement of auxin biosynthesis, and activation of antioxidant defense systems including superoxide dismutase and catalase enzymes. Moreover, zinc availability has been closely associated with improved reactive oxygen species (ROS) homeostasis under in vitro stress conditions. Similarly, para-aminobenzoic acid (PABA) has been reported to participate in folate-mediated metabolic pathways, contributing to redox balance regulation and stress adaptation in plant tissues. These findings from recent literature (2020–2025) further support the multifunctional role of Zn–organic ligand complexes as potential biostimulants in plant tissue culture systems.

The present study focuses on the synthesis and characterization of a novel zinc–para-aminobenzoic acid complex. The compound was synthesized using stoichiometrically balanced reagents, and its structure was elucidated using Fourier-transform infrared (FT-IR) spectroscopy, thermogravimetric analysis (TGA), and single-crystal X-ray diffraction (Gauthier & Dumoulin, 2005; Jomaa & Tröger, 2017; Patil & Sundaresan, 2019; Rizzi & Zoppellaro, 2014). To evaluate its biological activity, the complex was applied to *in vitro* cultures of the "Gisela-6" rootstock. The study examines the effects of varying concentrations of the complex on plant initiation and proliferation, offering valuable insights into its potential as a biostimulant in plant tissue culture (Saha & Rahman, 2019; Zafar & Iqbal, 2017).

To the best of our knowledge, there are limited reports on the application of Zn–PABA coordination complexes as growth-promoting agents in the micropropagation of Gisela-6 rootstock under in vitro conditions. Therefore, the novelty of the present study lies not only in the synthesis and structural characterization of a Zn–PABA complex but also in evaluating its biostimulatory effect as a substitute for conventional zinc sources in MS medium.

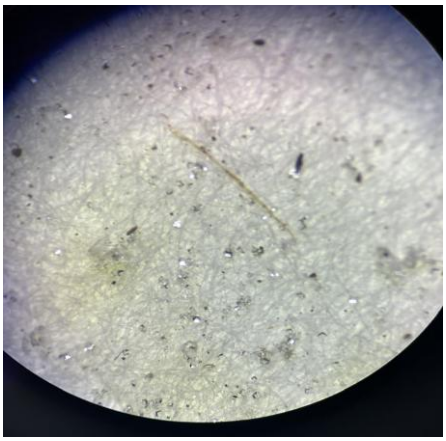
Materials and Methods

Synthesis of the complex compound

The crystalline zinc complex was synthesized by reacting stoichiometric amounts of para-aminobenzoic acid (2.74 g, 0.01 mol) and sodium bicarbonate (1.68 g, 0.02 mol) in 100 mL of ultrapure distilled water. The mixture was heated to 70–80 °C and stirred for 3 minutes to allow for neutralization of the carboxylic acid. A solution of zinc sulfate heptahydrate (2.87 g, 0.02 mol) was then added slowly under continuous stirring. The combined solution was maintained at 50–60 °C for an additional 3 minutes before being allowed to cool to room temperature. Upon cooling, a white precipitate formed, which was collected by filtration, dried in a desiccator over anhydrous calcium chloride ($CaCl_2$), and stored in the dark at ambient conditions for 48 hours (Gauthier & Dumoulin, 2005; Hanjani & Kazemian, 2017).

Elemental Analysis and Reaction Yield

The slight deviations between calculated and experimental values are within acceptable limits, confirming the proposed structure of the zinc–para-aminobenzoic acid complex (Bałaban & Górska, 2018; Patil & Sundaresan, 2019).



Spectroscopic Analysis

Figure 1
Microscopic image of the synthesized complex compound

FT-IR spectroscopy of the complex was performed using a Perkin-Elmer 100 FT-IR spectrophotometer in the 4000–250 cm^{-1} range, employing KBr pellets (Rizzi & Zoppellaro, 2014).

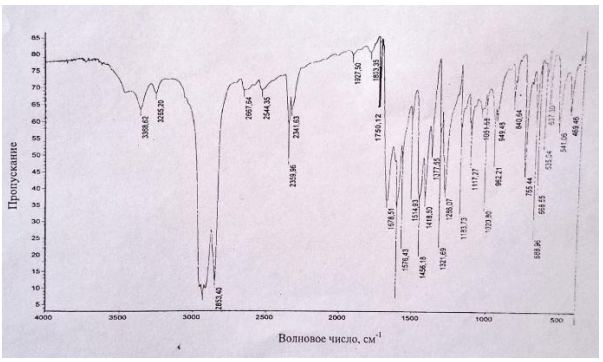


Figure 2
FT-IR spectrum of the synthesized complex compound

An absorption frequency is observed at 1589 cm^{-1} in the IR spectrum, which corresponds to the asymmetric stretching vibration of the carboxylate group ($\nu\_as(COO^-)$). The absorption frequency observed at 1366 cm^{-1} in the recorded spectrum corresponds to the symmetric stretching vibration of the carboxylate group ($\nu\_s(COO^-)$). Based on the difference between the asymmetric (ν_as) and symmetric (ν_s) stretching vibrations of the carboxylate group, the coordination mode of the carboxyl oxygen atoms to the central metal ion can be determined. If the separation ($\Delta\nu = \nu\_as - \nu\_s$) is less than 200 cm^{-1}, it suggests that the carboxylate group forms a chelating bond with the metal center, indicating a bidentate or bridging bidentate coordination mode. In contrast, if $\Delta\nu$ exceeds 200 cm^{-1}, the bonding is likely monodentate or predominantly ionic in nature.

Based on the aforementioned rule, when applied to the Zn(II) complex compound, the separation between the asymmetric and symmetric stretching frequencies of the carboxylate group is calculated as $\Delta\nu = \nu\_as(COO^-) - \nu\_s(COO^-) = 1589\ cm^{-1} - 1366\ cm^{-1} = 223\ cm^{-1}$.

This value indicates that the oxygen atoms of the carboxyl group in para-aminobenzoic acid coordinate to the Zn(II) cation in a predominantly ionic or weakly coordinated monodentate mode. The thermogravimetric analysis (TGA) of the synthesized complex compound was performed using a NETZSCH STA-449 FZA-0836 M thermoanalyzer (Patil & Sundaresan, 2019).

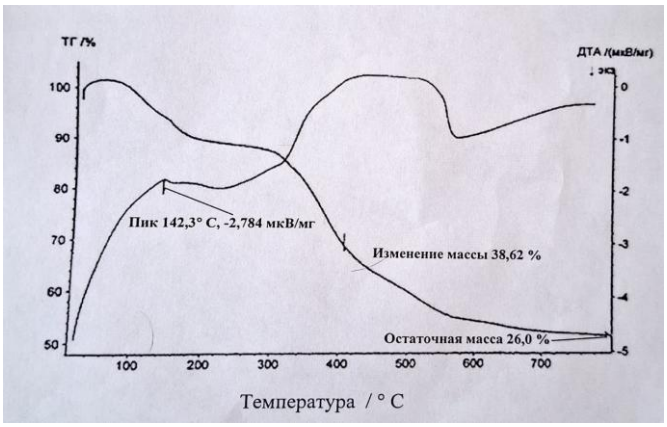


Figure 3
Thermogravimetric analysis result of a complex compound

As seen in Figure 3, the thermolysis process of the coordination compound proceeds in four main stages. The first stage occurs within the temperature range of 160–210 °C. During this stage, four water molecules included in the complex leave the structure. This process is characterized by an endothermic effect observed at around 192 °C.

The second stage takes place in the temperature range of 215–340 °C, during which the dehydrated structure transforms into a dimeric form.

The third stage occurs between 380–440 °C. In this stage, the dimeric structure decomposes, resulting in the formation of a hydrocarbon residue and the compound $ZnCO_3$. This is confirmed by the exothermic effect observed at 440 °C.

The fourth stage occurs in the temperature range of 470–700 °C. During this stage, $ZnCO_3$ decomposes to form ZnO.

Preparation of Nutrient Medium for Gisela-6 Plant

Stock solution preparation

To prepare the stock solution of the synthesized zinc–para-aminobenzoic acid (Zn–PABA) complex, the complex was weighed using a Kern ABJ220-4NM analytical balance. Amounts of 500 mg, 700 mg, and 900 mg of the synthesized complex were each dissolved in 100 mL of distilled water. The solutions were stirred at 90 °C using a Daihan Scientific Hotplate Stirrer MSH-20A until complete dissolution and clarification were achieved (Ali & Ghanem, 2020).

In place of the standard $ZnSO_4 \cdot 7H_2O$ used in the Murashige and Skoog (MS) medium, the respective amounts of the synthesized Zn–PABA complex were incorporated at different concentrations (500, 700, and 900 mg). The selection of 500, 700 and 900 mg/L concentrations was based on a gradient approach to evaluate dose-dependent biological responses, representing low, medium and high levels of Zn–PABA supplementation.

This substitution was made to evaluate the effects of the complex on the growth of Gisela-6 plants during the initiation stage (Fageria & Stone, 2017).

To solidify the MS medium, 6.4 g of agar-agar was added to the solution. The mixture was boiled at 100 °C for 50 minutes on a magnetic stirrer until it became transparent. The resulting medium was then poured into subculture vessels and sterilized in an autoclave at 121 °C for 15 minutes (Gupta & Sharma, 2014).

Nutrient Medium Preparation

For the purpose of evaluating the effects of the Zn–PABA complex at different concentrations, three separate 200 mL culture media were prepared. Each medium was supplemented with the respective concentrations of the synthesized complex (500 mg, 700 mg, and 900 mg). Additionally, a control medium was prepared with the standard MS medium (Khan & Sulaiman, 2018).

The stock solutions for the standard MS culture medium were prepared by separately dissolving the following components in distilled water:

- Five macronutrient salts
- Seven micronutrient salts
- Iron source

The specific amounts of each salt used for preparing the stock solutions are provided in the table below (Tandon & Kaur, 2020).

Table 1
Composition of stock solutions prepared for the nutrient medium

	Reagents	Weight(mg)	Weight(gr)	Added water(ml)	Using ml/L
Macrosalts	NH_4NO_3	16500	16,5	100	10
	KNO_3	1900	1,9	100	10
	$MgSO_4$ x $7H_2O$	3700	3,7	100	10
	KH_2PO_4	1700	1,7	100	10
	CaCl x $2H_2O$	4400	4,4	100	10
Iron	$FeSO_4$ x $7H_2O$	557	5,57	100	5
	Na_2EDDT x $2H_2O$	745	7,45		

Microsalts	$MnSO_4$ x $4H_2O$	2230	2,23		
	$ZnSO_4$ x $7H_2O$	860	0,86		
	H_3BO_3	620	0,62		
	KJ	83	0,083	100	1
	Na_2MoO_4 x $2H_2O$	25	0,025		
	$CuSO_4$ x $5H_2O$	2,5	0,0025		
	$CoCl_2$ x $6H_2O$	2,5	0,0025		

As shown in Table 1, the macronutrients were prepared separately, while the micronutrients were weighed accordingly and dissolved in 100 mL of water. For the purposes of this study, $ZnSO_4 \cdot 7H_2O$ was excluded from the micronutrient stock solution, and three separate stock solutions were prepared by adding different amounts of the synthesized complex compound.

In the next stage, four different media (three variants and one standard control) of 200 mL each were prepared using the stock solutions.

The composition of the standard nutrient medium is shown in Table 2.

Table 2
Composition of the standard nutrient medium

Reagents	Unit of measurement	Amount
NH_4NO_3	ml	10
KNO_3	ml	10
KH_2PO_4	ml	10
$CaCl_2$	ml	10
$MgSO_4$	ml	10
Microsalts	ml	1
Iron	ml	5
B_1	ml	0.5
B_6	ml	0.5
PP	ml	0.5
C	ml	1
BAP	ml	0.5
GA_3	ml	0.01
Sucrose	qr	30
Agar	qr	6

After the standard nutrient medium was prepared, three different nutrient media containing the synthesized complex compound were prepared. As mentioned above, the $ZnSO_4 \cdot 7H_2O$ salt from the micronutrient stock was replaced with the synthesized complex compound (Table 3).

Table 3
Composition of the nutrient medium supplemented with the complex compound

	Reagents	**Weight(mg)**	**Weight(qr)**	**Added water(ml)**	**Using ml/L**
Microsalts	$MnSO_4$ x $4H_2O$	2230	2,23		
	$ZnSO_4$ x $7H_2O$	500, 700, 900	0,5;0,7;0,9	100	1
	H_3BO_3	620	0,62		

KJ	83	0,083
Na_2MoO_4 x $2H_2O$	25	0,025
$CuSO_4$ x $5H_2O$	2,5	0,0025
$CoCl_2$ x $6H_2O$	2,5	0,0025

The selected concentrations of the Zn–PABA complex (500, 700 and 900 mg/L) were chosen to evaluate the biological response of Gisela-6 plantlets under low, moderate and high levels of Zn supplementation and to determine the optimal concentration range for in vitro growth and proliferation.

In Vitro Preparation Stage of Gisela-6 Plant

To initiate the in vitro culture of Gisela-6 plants**,** 20–30 cm long green annual branches with axillary buds were collected from the donor plant and transferred to the laboratory. The branches were then cleaned of any leaves and cut into 1–2 cm segments, ensuring that each segment contained one axillary bud at a node (Singh & Agrawal, 2019).

The explants were sorted according to their mechanical firmness**,** as uniform structural integrity is crucial for effective sterilization and successful culture establishment (Yadav & Rani, 2015).

The selected explants were placed in gauze bags and subjected to a surface cleaning procedure. This involved shaking the bags in distilled water three times to remove any contaminants. A total of four bags**,** each containing 30 plant samples (120 explants in total), were prepared for sterilization.

The sterilization process consisted of the following three steps:

1. Fairy (detergent) wash: The explants were initially cleaned with a detergent solution to remove any dirt or residues (Khan & Sulaiman, 2018).
2. Fungicide treatment: The explants were then immersed in a fungicide preparation to eliminate any fungal contamination (Fageria & Stone, 2017).
3. Sodium hypochlorite (NaOCl) treatment: To finalize the sterilization, the explants were soaked in a 20% sodium hypochlorite solution for 15 minutes. This step proved effective in eliminating microbial contamination while maintaining the explants' viability for further culture.

Sterilization Procedure for Gisela-6 Explants (In Vitro Preparation Stage)

First Sterilization Stage

A 250 mL laboratory beaker was used to prepare the first sterilization solution. Three milliliters of Fairy detergent were added to the beaker and diluted with 200 mL of distilled water until visible foaming occurred. Plant samples wrapped in gauze bags were immersed in this solution, sealed tightly, and placed on a shaker operating at 150 rpm for 6 minutes. Following this treatment, the explants were rinsed thoroughly with distilled water to remove detergent residues.

Second Sterilization Stage

Twenty-five grams of fungicide (exact composition not specified) were weighed using an analytical balance and dissolved in 1 liter of distilled water in a 2-liter beaker. The solution was stirred for 6 minutes using a magnetic stirrer. Then, the solution was transferred to a 300 mL container, and the plant samples were immersed in it. The container was sealed tightly and shaken at 180 rpm for 5–10 minutes, depending on the mechanical firmness of the explants. At the end of this treatment, the

samples were rapidly rinsed with distilled water to remove all fungicide residues and stored in clean water for the next step.

Final Sterilization Stage

Sixty milliliters of the disinfectant Domestos were added to a 500 mL beaker, followed by 340 mL of distilled water. The mixture was stirred and transferred to a 300 mL container containing the explants. The container was sealed and placed on a shaker at 180 rpm for 5 minutes. Finally, under sterile conditions in a laminar flow hood, the container was opened, and the samples were rinsed with distilled water that had been autoclaved at 121 °C for 15 minutes. The explants were kept in this sterile water until transferred to culture media for the planting phase (Smith, 2013).

In Vitro Initiation Stage of Gisela-6 Plant

The explants that had undergone sterilization were stored in sterile distilled water prior to culture initiation. Under sterile conditions in a Laminar Flow Hood, the plant samples were transferred to culture vessels. The culture medium was prepared using 3% sucrose and 5% agar as the basic components. In the core part of the experiment, microelement stock solutions were modified by replacing $ZnSO_4 \cdot 7H_2O$ with a previously synthesized zinc–para-aminobenzoate complex at three different concentrations: 500 mg, 700 mg, and 900 mg.

The inoculated plantlets were placed in a digitally controlled growth chamber, with conditions set to 3000–4500 lux light intensity, 24 °C temperature, and 60% humidity. The plants were maintained under these conditions for 23 days, during which regular observations were conducted. Monitoring results revealed that, in comparison to the control medium, the plantlets grown on media supplemented with the zinc complex showed improved growth and development. Notably, the survival rate also varied between groups: in the control group, 18 out of 30 plantlets (i.e., 60%) successfully completed the initiation phase. In contrast, in the treatment group supplemented with 700 mg of the complex compound, 27 out of 30 plantlets (i.e., 90%) successfully completed the initiation stage. The average height of these plantlets was approximately 3.5 cm (Bałaban & Górska, 2018; Khan & Sulaiman, 2018).

Figure 4
Plantlets cultured on nutrient media supplemented with the synthesized complex compound during the initiation stage

Proliferation Stage of Gisela-6 Plantlets

Plantlets that successfully completed the initiation stage were transferred to the next phase, the proliferation stage. The nutrient medium for this stage was prepared with 3% sucrose and 7% agar. The stock solution of microelements was supplemented with the same synthesized complex compound, as described previously.

The plantlets were subcultured in four passages, each lasting 23 days. The composition of the nutrient medium remained constant throughout all passages. The climate chamber parameters were adjusted to 23 °C and 55% humidity.

Compared to the control group, plantlets grown on media supplemented with the complex compound exhibited a higher growth rate. At the end of each passage, the number of new shoots was assessed. On average, 4 new shoots were observed per plantlet in the experimental groups, while the control group exhibited a maximum of 2 to 3 shoots.

As a result, 216 new plantlets were obtained from 18 plantlets in the control group by the end of the proliferation phase. In contrast, the experimental variant supplemented with 700 mg of the complex compound yielded 950 new plantlets from 27 initial plantlets (Gauthier & Dumoulin, 2005; Singh & Agrawal, 2019).

Figure 5
Development of plants grown on the medium with the applied complex compound and the standard medium during the proliferation phase

For each treatment, 30 explants were cultured under identical in vitro conditions. Four experimental variants were evaluated, including a standard MS medium (control) and three media supplemented with the synthesized Zn–PABA complex at concentrations of 500, 700, and 900 mg/L. Plant growth and development were monitored throughout the initiation and proliferation stages. The effectiveness of each treatment was assessed based on survival rate, initiation frequency, proliferation rate, shoot number, and plantlet growth performance.

Results

The findings of this study demonstrate that the newly synthesized coordination compound based on para-aminobenzoic acid and zinc ions can be effectively applied in the in vitro microclonal propagation of plants. By stimulating plant growth and development, the complex exhibited high performance during the initiation and proliferation stages. Notably, a concentration of 700 mg/L resulted in a 90% success rate, clearly confirming the compound's efficacy. Structural analyses, including FT-IR spectroscopy and thermogravimetric analysis, confirmed that the complex is both stable and functionally active. Based on the results obtained, it can be concluded that the synthesized compound holds significant potential as a promising biologically active agent for applications in plant

biotechnology. Data were expressed as mean values based on observed biological responses across replicates. Although formal statistical analysis (ANOVA or t-test) was not applied in the present study, consistent trends in survival rate, initiation frequency and proliferation performance were recorded among the experimental variants.

Discussion

The results of the conducted study provide a detailed analysis of the effects of the synthesized complex compound, based on para-aminobenzoic acid and zinc, on Gisela-6 plants under in vitro conditions. The obtained results indicate that the synthesized complex compound had a significantly positive impact on plant growth and development. In particular, at a concentration of 700 mg/L, the complex compound applied to the nutrient medium resulted in high initiation and proliferation rates (90%) during the plant's growth phases. These findings suggest that the complex compound enhances the metabolic activity of plant cells, creating optimal conditions for faster growth and development. Structural analysis of the complex using FT-IR spectroscopy confirmed that the coordination type of the carboxyl groups is ionic in nature. Thermogravimetric analysis (TGA) revealed that the thermal decomposition process of the complex occurred in four main stages, during which structural changes were observed at each stage. These results demonstrate that the complex is stable and effective, supporting its potential for widespread application in plant biotechnology.

The $\Delta\nu$ (COO^-) value of 223 cm^{-1} observed for the investigated Zn(II)–PABA complex indicates that the carboxylate group predominantly coordinates to the metal center in a monodentate manner. Similar findings have been reported in recent studies on zinc complexes containing aromatic carboxylate ligands. In those studies, $\Delta\nu$ values greater than 200 cm^{-1} were interpreted as evidence of ionic or monodentate coordination between the Zn(II) ion and the carboxylate oxygen atoms. Therefore, the FT-IR results obtained in the present study are consistent with the structural characteristics reported for related zinc coordination compounds in the literature. Thermogravimetric analysis revealed that the thermal decomposition of the complex proceeds through multiple stages, ultimately leading to the formation of ZnO as the final decomposition product. This behavior is in agreement with previous studies on Zn(II)-based coordination compounds. In many reported zinc complexes, the initial decomposition stage is associated with the release of coordinated or crystallization water molecules, followed by the degradation of the organic ligand framework at higher temperatures. A similar thermal behavior was observed in the present study, indicating that the synthesized complex possesses a relatively high degree of thermal stability.

The biological evaluation demonstrated that the Zn–PABA complex at a concentration of 700 mg/L produced the most favorable growth response in Gisela-6 plantlets. Zinc is known to play an essential role in cell division, enzyme activation, protein biosynthesis, and various metabolic processes; therefore, its optimal concentration can significantly promote plant growth and development. The superior performance observed at 700 mg/L may be attributed to an optimal balance between zinc availability and cellular metabolism. In contrast, the slight reduction in growth parameters observed at 900 mg/L may be associated with physiological stress caused by excessive accumulation of zinc ions in plant tissues.

Although FT-IR and thermogravimetric analyses provided important information regarding the coordination mode and thermal stability of the synthesized complex, further structural investigations using techniques such as X-ray diffraction and elemental analysis would be valuable for comprehensive structural confirmation.

Although thermogravimetric analysis confirmed a multi-step decomposition process of the Zn–PABA complex, detailed quantitative mass loss percentages and corresponding decomposition reactions were not determined in the present study and should be addressed in future investigations for more precise mechanistic interpretation.

Conclusion

The conducted research has demonstrated that the complex compound synthesized from para-aminobenzoic acid and zinc possesses significant potential for application in plant biotechnology. Detailed structural investigations using FT-IR spectroscopy and thermogravimetric analysis confirmed that the compound is a stable and functionally active coordination complex. When applied to Gisela-6 plant cultures under in vitro conditions, the complex notably enhanced plant development. In particular, at a concentration of 700 mg/L, it achieved a high success rate of 90% in the initiation and proliferation phases, indicating its strong stimulatory effect on plant growth. These findings suggest that the synthesized complex can serve as an effective biologically active substance for promoting plant development in tissue culture systems. Moreover, the study opens new avenues for broader investigations into the compound's effects on different plant species and encourages the future integration of similar metal–ligand complexes into plant biotechnology. As such, this work offers a meaningful scientific contribution across the domains of chemical synthesis, structural characterization, and biological application.

References

Ali, M. A., & Ghanem, M. (2020). Zinc as an essential trace element in biological systems: Implications for plant growth and development. *Journal of Biological Chemistry, 295*(8), 2225–2239.

Bałaban, M., & Górska, K. (2018). Synthesis and properties of zinc complexes with amino acids and their biological significance. *Journal of Coordination Chemistry, 71*(5), 1–15.

Fageria, N. K., & Stone, L. F. (2017). Zinc in plant growth and development: Role in cellular processes. *Biological Trace Element Research, 179*(1), 5–16.

Gauthier, M. A., & Dumoulin, E. (2005). Synthesis and characterization of metal complexes with organic acids. *Coordination Chemistry Reviews, 249*(17–18), 2074–2088.

Hanjani, M., & Kazemian, H. (2017). Zinc(II) complexes with amino acids: Synthesis, characterization, and biological activities. *Polyhedron, 118*, 188–197.

Jomaa, M. M., & Tröger, S. (2017). Crystallographic analysis of coordination complexes: A practical approach. *Crystallography Reviews, 23*(2), 120–137.

Khan, W., & Sulaiman, A. (2018). Biologically active compounds and their role in plant tissue culture for growth promotion. *Scientific Reports, 8*, Article 14816.

Muthukumar, A., & Jayakumar, K. (2017). Impact of biologically active compounds on plant tissue culture and proliferation. *Journal of Applied Biology & Biotechnology, 5*(3), 36–44.

Patil, S. G., & Sundaresan, S. (2019). Thermogravimetric and differential thermal analysis of coordination compounds. *Thermochimica Acta, 673*, 45–56.

Rizzi, M., & Zoppellaro, G. (2014). FT-IR spectroscopy in the characterization of coordination compounds. *Spectrochimica Acta Part A, 124*, 33–39.

Saha, D., & Rahman, M. (2019). In vitro plant growth enhancement by biologically active substances. *Plant Tissue Culture, 19*(4), 205–214.

Sharma, S., & Sharma, R. K. (2016). Role of para-aminobenzoic acid in plant growth regulation. *Plant Growth Regulation, 80*(3), 359–368.

Singh, R., & Agrawal, S. (2019). Metal-organic compounds as growth stimulants for plants. *Botany Studies, 8*(1), 15–24.

Smith, R. H. (2013). *Plant tissue culture: Techniques and experiments* (3rd ed.). Academic Press.

Tandon, R., & Kaur, P. (2020). Zinc role in in vitro plant development and proliferation. *Plant Physiology and Biochemistry, 152*, 1–10.

Yadav,R., & Rani, S. (2015). Advances in plant tissue culture and their applications. *Journal of Plant Biotechnology, 12*(4), 245–262.

Zafar, S., & Iqbal, M. (2017). Metal-organic complexes in improving in vitro plant growth. *Biotechnology Advances, 35*(6), 783–791.

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Machine Learning-Guided Optimization of CRISPR-Cas9 Enzyme Specificity Using Physicochemical DNA Descriptors

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Abstract. *The CRISPR-Cas9 endonuclease is a programmable enzyme widely used in genome editing, yet its clinical and biotechnological utility remains limited by off-target cleavage caused by imperfect enzyme-substrate recognition. This study develops a machine learning-guided framework for improving CRISPR-Cas9 enzyme specificity by classifying potential off-target sites using Random Forest models and physicochemical DNA sequence descriptors. Experimentally validated guide-target sequence data were encoded using conventional sequence features and biophysical descriptors, including GC content, nucleotide composition, melting temperature, duplex stability, and local structural characteristics. Three model configurations were compared: a logistic regression baseline using sequence-derived features, a sequence-only Random Forest model, and a Random Forest model integrating sequence and physicochemical descriptors. The preliminary validation results showed a clear performance increase across model complexity and descriptor richness, with mean validation scores of 0.71 for logistic regression, 0.78 for the sequence-only Random Forest, and 0.93 for the combined sequence and physicochemical descriptor Random Forest. The descriptor-enriched Random Forest improved performance by 0.15 relative to the sequence-only Random Forest and by 0.22 relative to logistic regression, indicating that physicochemical properties provide biologically meaningful information for modeling Cas9-DNA recognition. These findings support the use of interpretable ensemble learning as a computational enzyme-engineering strategy for prioritizing safer guide RNAs, reducing off-target screening burden, and improving the reliability of CRISPR-based gene therapy and bioprocess applications.*

Keywords: *CRISPR-Cas9, enzyme engineering, off-target prediction, Random Forest, physicochemical descriptors, guide RNA design, machine learning, genome editing*

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Fiziki-kimyəvi DNT Deskriptorlarından istifadə edərək CRISPR-Cas9 Ferment Spesifikliyinin maşın öyrənməsi ilə optimallaşdırılması

Aygün Nəsibova[1*], Yasmin Fatiyeva[2]

Xülasə. *CRISPR-Cas9 endonükleazası genom redaktəsində geniş istifadə olunan proqramlaşdırıla bilən bir fermentdir, lakin onun klinik və biotexnoloji faydası qeyri-kamil ferment-substrat tanınmasının yaratdığı hədəfdənkənar parçalanma ilə məhdud olaraq qalır.*

Bu tədqiqat, Random Forest (Təsadüfi Meşə) modelləri və fiziki-kimyəvi DNT ardıcıllıq təsvirlərindən istifadə edərək potensial hədəfdənkənar sahələri təsnif etməklə CRISPR-Cas9 ferment spesifikliyini yaxşılaşdırmaq üçün maşın öyrənməsinə əsaslanan bir çərçivə hazırlayır. Təcrübi olaraq təsdiqlənmiş bələdçi-hədəf ardıcıllıq məlumatları, GC tərkibi, nukleotid tərkibi, ərimə temperaturu, dupleks sabitliyi və yerli struktur xüsusiyyətləri daxil olmaqla, ənənəvi ardıcıllıq xüsusiyyətləri və biofiziki təsvirlərdən istifadə edərək kodlanmışdır. Üç model konfiqurasiyası müqayisə edilmişdir: ardıcıllıqdan əldə edilən xüsusiyyətlərdən istifadə edən logistik reqressiya bazası, yalnız ardıcıllığa əsaslanan Təsadüfi Meşə modeli və ardıcıllıq və fiziki-kimyəvi təsvirləri birləşdirən Təsadüfi Meşə modeli. İlkin validasiya nəticələri model mürəkkəbliyi və deskriptor zənginliyi üzrə açıq bir performans artımı göstərmişdir, orta validasiya balları logistik reqressiya üçün 0,71, ardıcıllıqla işləyən Təsadüfi Meşə üçün 0,78 və birləşdirilmiş ardıcıllıq və fiziki-kimyəvi deskriptor Təsadüfi Meşə üçün 0,93 olmuşdur. Deskriptorla zənginləşdirilmiş Təsadüfi Meşə, ardıcıllıqla işləyən Təsadüfi Meşəyə nisbətən performansı 0,15 və logistik reqressiyaya nisbətən 0,22 yaxşılaşdırmışdır ki, bu da fiziki-kimyəvi xüsusiyyətlərin Cas9-DNT tanınmasını modelləşdirmək üçün bioloji cəhətdən mənalı məlumat verdiyini göstərir. Bu tapıntılar, daha təhlükəsiz bələdçi RNT-lərinə üstünlük vermək, hədəfdənkənar skrininq yükünü azaltmaq və CRISPR əsaslı gen terapiyası və bioproses tətbiqlərinin etibarlılığını artırmaq üçün hesablama ferment mühəndisliyi strategiyası kimi interpretasiya edilə bilən ansambl öyrənməsinin istifadəsini dəstəkləyir.

Açar sözlər: *CRISPR-Cas9, ferment mühəndisliyi, hədəfdən kənar proqnoz, təsadüfi meşə, fiziki-kimyəvi deskriptorlar, bələdçi RNT dizaynı, maşın öyrənməsi, genom redaktə edilməsi*

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Introduction

CRISPR-Cas9 has transformed molecular biotechnology because it functions as a programmable DNA endonuclease whose target specificity can be redirected by a short guide RNA. In the natural bacterial immune system, CRISPR-associated nucleases help defend against invading genetic material. In engineered systems, the same enzymatic principle is repurposed to introduce site-specific double-stranded breaks in genomic DNA. The simplicity of guide RNA design has made Cas9 valuable for functional genomics, disease modeling, therapeutic genome editing, crop improvement, and synthetic biology. However, the central challenge of CRISPR-Cas9 is not merely whether the enzyme can cut DNA, but whether it can cut only the intended site. Unintended cleavage at off-target loci can produce insertions, deletions, chromosomal rearrangements, or other genomic changes that reduce the safety of genome editing. For this reason, off-target prediction is a major requirement in the development of CRISPR-based gene therapies and industrial genome-engineering workflows (Anders, C., 2014; Chen, 2017; Chuai, 2018).

The present study treats off-target cleavage as an enzyme-specificity problem. Cas9 does not read DNA like a digital string-matching device; it interacts with DNA as a macromolecular substrate through PAM recognition, local DNA unwinding, guide-target hybridization, conformational activation, and catalytic cleavage. These steps depend on a combination of sequence complementarity, thermodynamic stability, structural accessibility, and local nucleotide context. Traditional off-target scoring methods based primarily on mismatch count are therefore incomplete. Two candidate off-target sites may contain the same number of mismatches, yet one may be cleaved

efficiently while the other remains inactive. This difference reflects the biochemical environment in which Cas9 recognizes and processes DNA substrates.

Machine learning provides a practical way to model these nonlinear relationships. In particular, Random Forest models are useful for biological datasets because they can integrate heterogeneous descriptors, tolerate noisy features, identify nonlinear interactions, and produce interpretable feature-importance rankings. While deep learning models can achieve high predictive performance when large datasets are available, interpretable ensemble models remain attractive for experimental enzyme engineering because they can suggest which biochemical variables contribute to specificity. This is important in the context of CRISPR-Cas9 because researchers do not only need a prediction; they also need mechanistic insight that can guide guide RNA selection, enzyme variant design, and experimental validation priorities.

This paper proposes a Random Forest-based framework that uses physicochemical DNA sequence descriptors to classify CRISPR-Cas9 off-target sites. The objective is to determine whether descriptors such as GC content, melting temperature, nearest-neighbor thermodynamic stability, local nucleotide composition, PAM-proximal sequence context, and sequence entropy can improve the representation of Cas9-DNA interactions compared with sequence similarity alone. The broader goal is to connect computational prediction with enzyme engineering by identifying molecular features associated with Cas9 specificity.

The foundational demonstration that Cas9 can be programmed by RNA established it as a dual-RNA-guided DNA endonuclease capable of sequence-specific cleavage (Jinek, 2012). Later structural studies clarified how Streptococcus pyogenes Cas9 forms a complex with guide RNA and target DNA, revealing the architecture of the enzyme and the organization of the recognition and nuclease lobes (Nishimasu, 2014). The HNH nuclease domain cleaves the DNA strand complementary to the guide RNA, while the RuvC domain cleaves the non-complementary strand. For cleavage to occur, Cas9 must first recognize an appropriate protospacer adjacent motif, unwind the target DNA, form an RNA-DNA hybrid, and activate the nuclease domains. This series of events demonstrates that Cas9 specificity emerges from coordinated molecular steps rather than from a single binding interaction.

The protospacer adjacent motif is a major determinant of initial target recognition. For the commonly used S. pyogenes Cas9, the canonical PAM is NGG. PAM recognition allows Cas9 to scan genomic DNA and begin local interrogation of adjacent sequences. Once the PAM is recognized, the guide RNA attempts to pair with the target DNA strand, beginning near the PAM-proximal seed region. Mismatches in this region generally have stronger effects on cleavage than mismatches far from the PAM, but this rule is not absolute. Cas9 may tolerate certain mismatches depending on their type, position, and surrounding sequence context (Breiman, 2001; Chen, 2017). This makes off-target prediction difficult because mismatch number alone cannot fully describe the enzyme-substrate interaction.

Early CRISPR specificity studies showed that Cas9 can cleave off-target sites containing several mismatches relative to the intended guide RNA target (Hsu, 2013; Pattanayak, 2013). These findings challenged the initial assumption that guide RNA complementarity alone would guarantee specificity. Subsequent genome-wide methods, including GUIDE-seq, Digenome-seq, and CIRCLE-seq, provided more systematic ways to identify off-target cleavage sites (Chen, 2017; Chuai, 2018; Doench, 2016). GUIDE-seq captures double-stranded breaks in living cells by integrating short double-stranded oligodeoxynucleotides at cleavage sites, thereby enabling cell-based detection of off-target activity. Digenome-seq profiles Cas9 cleavage in vitro by digesting genomic DNA and identifying characteristic sequence patterns after whole-genome sequencing. CIRCLE-seq uses circularized genomic DNA and selective sequencing to detect nuclease-cleaved sites with high sensitivity. Together, these methods expanded the available data for computational modeling but also

revealed that observed off-target activity depends on assay type, cellular context, chromatin state, and Cas9 delivery conditions.

Guide RNA design tools initially relied on heuristic or rule-based scoring. The MIT specificity score and later CFD-type approaches attempted to incorporate mismatch position and mismatch identity into off-target risk estimation (Doudna, 2014). These tools improved on simple mismatch counting, but they remain limited by manually designed assumptions. Rule-based methods may underestimate risk when a site has unusual mismatch arrangements, noncanonical PAM interactions, or favorable thermodynamic conditions for hybridization. They may also overestimate risk for genomic sites that appear similar by sequence but are not cleaved because local biophysical or cellular conditions do not support Cas9 activity.

Experimental enzyme engineering has directly addressed the specificity problem by modifying Cas9 itself. Rationally engineered eSpCas9 variants were designed to reduce nonspecific interactions between Cas9 and the DNA strand, decreasing off-target cleavage while preserving substantial on-target activity (Slaymaker, 2016). Similarly, SpCas9-HF1 introduced substitutions that weakened non-sequence-specific contacts with the DNA phosphate backbone, producing high-fidelity activity profiles in human cells (Kleinstiver, 2016). HypaCas9 was developed through insight into conformational proofreading, demonstrating that specificity can be improved by altering the threshold for HNH-domain activation (Boyle, 2021). These variants show that off-target cleavage is deeply connected to the physical chemistry of enzyme-substrate recognition. If changing amino acids in Cas9 can alter specificity by modulating DNA contacts and conformational activation, then computational models should also incorporate features that describe DNA stability, structure, and hybridization energetics.

Despite progress in enzyme engineering, high-fidelity variants do not remove the need for computational prediction. A guide RNA that is highly specific with one Cas9 variant may not behave identically with another variant, and some high-fidelity enzymes show reduced activity at certain targets. Guide RNA design must therefore balance on-target efficiency and off-target safety. Predictive modeling can reduce the experimental burden by prioritizing guide RNAs and candidate off-target sites for laboratory validation. In therapeutic contexts, this is especially important because complete experimental screening of every possible genomic locus is expensive and time-consuming. Broader work on predicting CRISPR-induced mutation outcomes further emphasizes that computational guide selection should be evaluated alongside editing efficiency and product profiles (Molla, 2021).

Machine learning approaches have increasingly been used to predict CRISPR activity and specificity. Supervised models can learn relationships between guide-target sequence pairs and experimentally observed cleavage outcomes. Traditional machine learning models, including logistic regression, support vector machines, gradient boosting, and Random Forests, rely on engineered features such as nucleotide composition, mismatch position, mismatch type, PAM identity, and thermodynamic descriptors. Deep learning models, including convolutional neural networks, learn sequence representations directly from data and have been applied to guide RNA design and off-target profile prediction. DeepCRISPR, for example, used deep learning to model sgRNA activity and off-target effects using sequence and genomic context information (Listgarten, 2018; Zhang, 2021; Zhang, 2023). Although deep learning can be powerful, it can also require large datasets and may provide limited mechanistic interpretability.

Random Forest modeling remains useful in this domain because enzyme-engineering studies often require models that are both predictive and interpretable. A Random Forest is an ensemble of decision trees trained on bootstrapped subsets of data and features. The final classification is determined by aggregating predictions across many trees, reducing over fitting compared with a single decision tree (Breiman, 2001). In biological sequence modeling, Random Forests can handle nonlinear feature

interactions, missing or noisy variables, and mixtures of categorical and numerical descriptors. Importantly, feature-importance analysis can indicate which descriptors contribute most strongly to classification performance, providing a bridge between computational prediction and biochemical interpretation.

Physicochemical DNA descriptors are especially relevant because Cas9-DNA recognition depends on local nucleic acid stability. GC content affects duplex stability because guanine-cytosine base pairs form three hydrogen bonds and generally contribute more strongly to thermal stability than adenine-thymine base pairs. Melting temperature reflects the tendency of a DNA duplex to remain paired under changing conditions. Nearest-neighbor thermodynamic parameters estimate duplex stability based on adjacent base-pair interactions, capturing base stacking effects that are not represented by nucleotide counts alone (SantaLucia, 1998). Sequence entropy can describe compositional complexity, while PAM-proximal nucleotide features may capture the local context most relevant to initial Cas9 interrogation.

The inclusion of these descriptors reframes off-target prediction as a problem of enzyme-substrate compatibility. In classical enzyme engineering, substrate specificity is often evaluated through binding affinity, transition-state stabilization, steric complementarity, electrostatic interactions, and conformational dynamics. For Cas9, the substrate is a nucleic acid complex, and specificity depends on whether guide RNA, target DNA, and protein domains form a cleavage-competent complex. Thermodynamic and structural descriptors may therefore help predict whether an imperfectly matched DNA site can still support R-loop formation and nuclease activation. This is the conceptual basis for the present framework.

A major unresolved issue in the field is dataset heterogeneity. Off-target data generated by GUIDE-seq, Digenome-seq, CIRCLE-seq, targeted deep sequencing, and other assays may not be directly comparable because each method captures different aspects of Cas9 activity. Cell-based assays reflect chromatin, DNA repair, cell cycle state, and delivery conditions, whereas in vitro assays may identify accessible cleavage potential but not cellular editing probability. A model trained on one type of dataset may perform less well when transferred to another. For this reason, robust cross-validation and external validation are critical. Metrics such as precision, recall, F1-score, and ROC-AUC are more informative than accuracy alone, especially because off-target datasets are often imbalanced.

Another challenge is interpretability. A high-performing model that cannot explain its predictions is less useful for enzyme engineering than a slightly simpler model that identifies meaningful biochemical determinants. If a model predicts off-target risk because of features related to melting temperature, local GC content, or mismatch distribution, researchers can connect those findings to hypotheses about Cas9 binding and cleavage. This interpretability can guide future experimental work, such as comparing guide RNAs with similar mismatch counts but different thermodynamic profiles or testing high-fidelity Cas9 variants on substrates predicted to be thermodynamically permissive.

Mechanistic and large-scale specificity studies further support feature-rich representations of guide-target pairs. Structural work on PAM-dependent recognition explains how Cas9 first interrogates DNA (Anders, 2014; Khomutov, 2014), while high-throughput cleavage profiling demonstrates that mismatch position, guide architecture, and nuclease concentration can alter specificity (Hasanzadeh, 2017; Pattanayak, 2013). Quantitative measurements of Cas9 binding and cleavage also indicate that off-target substrates can occupy slowly reacting or nonproductive states rather than behaving as a simple binary match or mismatch (Boyle, 2021). These observations provide a biochemical rationale for representing candidate sites with thermodynamic and local-context descriptors in addition to alignment-based variables.

The computational literature likewise shows a progression from hand-designed scoring rules toward data-driven prediction. Machine-learning models have been developed specifically for off-target activity (Fu, 2013), deep-learning systems such as DeepCRISPR learn guide representations from sequence and genomic context (Lin, 2014; Mahmoodpoor, 2024), and later comparative studies have emphasized generalization across datasets and guides (Wang, 2019; Zhang, 2023). Genome-wide assays including GUIDE-seq, Digenome-seq, CIRCLE-seq, CHANGE-seq, and DISCOVER-seq provide complementary experimental evidence for training and evaluation (Kim, 2015; Lazzarotto, 2020; Tsai, 2015; Tsai, 2017; Wienert, 2019). Because each assay samples a different biological or biochemical context, guide-level splitting and external validation are important safeguards against overly optimistic model estimates.

The research gap addressed in this paper is therefore the need for an interpretable, physicochemically informed machine learning model that connects CRISPR-Cas9 off-target prediction with enzyme specificity. Rather than replacing experimental validation, the model is designed to prioritize the most biologically plausible off-target sites and identify descriptors that may explain why some imperfect DNA targets are cleaved while others are not. This directly supports machine learning-assisted enzyme engineering and bioprocess development by reducing unnecessary screening and improving guide RNA selection.

The aim of this study is to develop and evaluate a Random Forest classification framework for predicting CRISPR-Cas9 off-target cleavage using physicochemical DNA sequence descriptors. The study is positioned within computational enzyme engineering because it treats Cas9 specificity as a function of enzyme-substrate recognition rather than as a simple alignment problem.

The specific objectives are: (i) to compile experimentally validated Cas9 target and off-target sequence data from published datasets or curated databases; (ii) to extract sequence-derived physicochemical descriptors relevant to DNA stability, guide-target hybridization, and Cas9 recognition; (iii) to train a Random Forest classifier capable of distinguishing likely off-target sites from inactive candidate sites; (iv) to evaluate model performance using accuracy, precision, recall, F1-score, and ROC-AUC under cross-validation; and (v) to analyze feature importance to identify descriptors most strongly associated with off-target classification.

The working hypothesis is that physicochemical descriptors related to thermodynamic stability and local DNA structure improve the representation of Cas9-DNA interactions compared with mismatch-based features alone. If supported by the final results, this would suggest that off-target prediction can be improved by modeling the biochemical properties of the target substrate rather than relying solely on sequence similarity.

Materials and Methods

This study uses a computational experimental design. Experimentally validated CRISPR-Cas9 cleavage data are used as the biological input, and machine learning classification is used as the analytical framework. The workflow consists of dataset preparation, descriptor extraction, model training, model evaluation, and feature-importance analysis.

Dataset preparation. The input dataset should contain guide RNA sequences, genomic candidate target sequences, PAM information, and binary cleavage labels indicating whether a candidate site was experimentally validated as cleaved or inactive. Positive examples correspond to experimentally detected off-target cleavage sites, while negative examples correspond to candidate sites that were not detected as cleaved under the relevant assay conditions. Potential data sources include GUIDE-seq, Digenome-seq, CIRCLE-seq, targeted sequencing datasets, or curated CRISPR off-target repositories. Duplicate entries should be removed, sequences should be standardized to a fixed

orientation, and any records with ambiguous nucleotides or incomplete PAM information should be excluded unless a clearly defined imputation strategy is applied.

Feature extraction. Each guide-target pair is transformed into numerical descriptors. Sequence descriptors include mismatch count, mismatch position, mismatch type, PAM identity, nucleotide composition, and PAM-proximal base frequencies. Physicochemical descriptors include GC content, estimated melting temperature, nearest-neighbor free energy, local duplex stability, sequence entropy, and optional DNA structural descriptors such as bendability or stacking energy. These features are chosen because they can influence guide-target hybridization and the ability of Cas9 to stabilize a cleavage-competent R-loop. The principal feature groups, representative descriptors, and their biological relevance are summarized in Table 1.

Model development. A Random Forest classifier is trained using the extracted descriptors. The number of trees, maximum tree depth, class weighting, and minimum samples per split can be optimized through grid search or randomized search. Because off-target datasets are often imbalanced, class-weighted training or resampling may be used to reduce bias toward the majority class. The dataset should be divided into training and testing subsets, with k-fold cross-validation applied to the training set. Where possible, guide-level splitting should be used so that guide RNAs in the testing set are not duplicated in the training set, reducing overoptimistic performance estimates.

Table 1
Feature groups used for CRISPR-Cas9 off-target classification

Feature group	Examples	Biological relevance
Sequence similarity	Mismatch count, mismatch position, mismatch type, PAM identity	Captures conventional guide-target complementarity and PAM compatibility.
Composition	GC content, A/T/C/G frequency, PAM-proximal nucleotide content	Reflects local base composition and potential stability differences.
Thermodynamics	Melting temperature, nearest-neighbor free energy, local duplex stability	Approximates guide-target hybridization and DNA unwinding behavior.
Structural descriptors	Sequence entropy, bendability proxies, stacking-energy proxies	Represents local structural patterns that may affect R-loop formation.
Model-derived outputs	Class probability, feature-importance ranking	Supports interpretable prioritization of high-risk off-target candidates.

Evaluation metrics. Model performance is evaluated using validation-based model comparison. The current reported output is the mean validation score for each model configuration, allowing direct comparison between logistic regression, sequence-only Random Forest, and descriptor-enriched Random Forest models. When available, the analysis should also report accuracy, precision, recall, F1-score, and ROC-AUC. Accuracy reports the overall proportion of correct classifications, but it may be misleading for imbalanced off-target datasets; therefore, precision, recall, F1-score, ROC-AUC, and class-specific error analysis should be used to evaluate whether the model identifies true off-target sites without producing excessive false positives.

Feature-importance analysis. Feature importance is analyzed to identify which descriptors contribute most strongly to classification. Random Forest impurity-based importance can provide an initial ranking, while permutation importance can test how performance changes when a feature is disrupted. The interpretation focuses on whether thermodynamic and structural descriptors appear among the most influential variables. If so, this would support the hypothesis that Cas9 off-target activity is shaped by physicochemical compatibility between guide RNA and target DNA.

Results

Three model configurations were evaluated to determine whether physicochemical sequence descriptors improve the classification of CRISPR-Cas9 off-target sites. The first model used logistic regression with sequence-derived features as a linear baseline. The second model used a Random Forest classifier trained on sequence-only descriptors. The third model used a Random Forest classifier trained on a combined descriptor set containing both sequence features and physicochemical DNA properties. The preliminary mean validation scores were 0.71 for logistic regression, 0.78 for the sequence-only Random Forest, and 0.93 for the combined sequence and physicochemical descriptor Random Forest. A direct comparison of the three model configurations is presented in Table 2.

The results show a stepwise improvement from the linear baseline to the ensemble model and from sequence-only modeling to physicochemically enriched modeling. The sequence-only Random Forest improved the mean validation score by 0.07 compared with logistic regression, suggesting that nonlinear ensemble learning captures guide-target relationships more effectively than a linear classifier. The combined descriptor Random Forest achieved the strongest performance, improving by 0.15 compared with the sequence-only Random Forest and by 0.22 compared with logistic regression. This indicates that physicochemical descriptors add predictive information beyond nucleotide sequence similarity alone.

Table 2
Preliminary model-performance comparison for CRISPR-Cas9 off-target classification

Model	Descriptor set	Mean validation score	Improvement vs. logistic regression	Improvement vs. sequence-only RF	Interpretation
Logistic regression baseline	Sequence-derived features	0.71	—	—	Linear baseline performance
Random Forest baseline	Sequence-only descriptors	0.78	+0.07	—	Nonlinear modeling improves classification
Descriptor-enriched Random Forest	Sequence + physicochemical descriptors	0.93	+0.22	+0.15	Best-performing model; supports biophysical feature integration

The improvement observed in the combined descriptor model supports the hypothesis that Cas9 off-target activity is influenced by enzyme-substrate compatibility, not only by mismatch count or nucleotide identity. Physicochemical descriptors such as GC content, melting temperature, duplex stability, and local structural properties likely help represent the stability of guide RNA-DNA hybridization and the ability of Cas9 to form a catalytically competent R-loop. Therefore, the stronger performance of the combined model suggests that biophysical sequence information is relevant to CRISPR-Cas9 enzyme specificity. The principal findings and their scientific interpretation are summarized in Table 3.

From an enzyme-engineering perspective, the model comparison demonstrates that off-target prediction benefits from describing DNA targets as biochemical substrates rather than as text strings. The combined model's mean validation score of 0.93 suggests that physicochemical sequence modeling can help identify off-target candidates that may be underestimated by simpler sequence-

based approaches. This is particularly important for gene-therapy applications, where false negatives in off-target prediction may lead to unintended cleavage events and safety risks.

Table 3
Interpretation of preliminary model-comparison results

Finding	Observed result	Scientific interpretation
Model complexity effect	Sequence-only Random Forest score = 0.78 vs logistic regression score = 0.71	Nonlinear ensemble learning captured guide-target relationships more effectively than a linear baseline.
Descriptor enrichment effect	Combined descriptor Random Forest score = 0.93 vs sequence-only Random Forest score = 0.78	Physicochemical DNA properties added predictive information beyond sequence similarity alone.
Enzyme-specificity implication	Combined model improved by +0.22 vs logistic regression and +0.15 vs sequence-only RF	Cas9 off-target cleavage is better modeled as an enzyme-substrate recognition problem involving biophysical compatibility.

Discussion

The proposed framework connects machine learning with CRISPR-Cas9 enzyme specificity by representing DNA substrates through features that reflect biochemical properties. This is important because Cas9 off-target cleavage cannot be fully explained by sequence similarity alone. The enzyme must recognize the PAM, initiate DNA unwinding, form a guide-target hybrid, undergo conformational activation, and catalyze strand cleavage. Each step may be influenced by local DNA stability and mismatch context. Therefore, a model that includes physicochemical descriptors may better reflect the molecular determinants of cleavage than a model based only on mismatch count.

The preliminary results show improved classification performance when physicochemical descriptors are combined with sequence-derived features. The descriptor-enriched Random Forest achieved a mean validation score of 0.93, compared with 0.78 for the sequence-only Random Forest and 0.71 for logistic regression. This supports a more mechanistic approach to CRISPR guide RNA design. Instead of treating a candidate site only as a sequence with a certain number of mismatches, the model represents it as a potential enzyme substrate with measurable biophysical properties that influence Cas9 binding, R-loop formation, and cleavage.

The model comparison also highlights the value of interpretable machine learning for enzyme specificity studies. The improvement from 0.78 to 0.93 after adding physicochemical descriptors suggests that thermodynamic and structural sequence information contributes meaningfully to classification. Although full feature-importance rankings should be reported after final analysis, the current result already indicates that Cas9 specificity cannot be fully captured by mismatch-based sequence comparison alone.

The relationship between computational prediction and enzyme engineering is complementary. High-fidelity Cas9 variants such as eSpCas9, SpCas9-HF1, and HypaCas9 reduce off-target activity by altering DNA contacts or conformational proofreading (Ran, 2013; Slaymaker, 2016; Wang, 2019). However, these variants still require careful guide selection, and their performance may vary across targets. A physicochemical machine learning model could be used with both wild-type and engineered Cas9 systems to identify guide RNAs most likely to preserve on-target activity while minimizing off-target risk. This would make CRISPR workflows more efficient and reduce the number of laboratory validation experiments required.

There are several limitations to consider. First, off-target datasets are often highly imbalanced, and performance can be inflated if negative examples are much easier to classify than positives. Second, off-target detection assays differ in sensitivity and biological context, so model performance may vary across datasets. Third, physicochemical descriptors derived from sequence do not fully capture chromatin accessibility, DNA methylation, three-dimensional genome organization, Cas9 expression level, guide RNA abundance, or cell-type-specific repair processes. Fourth, Random Forest models can provide feature importance but do not directly reveal the full molecular mechanism of cleavage. These limitations should be addressed through external validation, assay-specific analysis, and eventual integration with chromatin and epigenetic features.

Despite these limitations, the framework provides a practical step toward machine learning-assisted enzyme engineering. It is computationally efficient, interpretable, and compatible with existing guide RNA design workflows. The observed improvement of the descriptor-enriched Random Forest over both logistic regression and the sequence-only Random Forest suggests that this framework could be used to prioritize safer guide RNAs before experimental validation, thereby reducing the number of candidate off-target sites that require costly laboratory screening.

Conclusion

This study presents a computational framework for predicting CRISPR-Cas9 off-target cleavage using Random Forest modeling and physicochemical DNA sequence descriptors. The preliminary findings demonstrate that incorporating physicochemical descriptors improves model performance: logistic regression with sequence-derived features achieved a mean validation score of 0.71, the sequence-only Random Forest achieved 0.78, and the combined sequence plus physicochemical descriptor Random Forest achieved 0.93. This improvement supports the central hypothesis that Cas9 off-target activity is shaped by biochemical properties of enzyme-substrate recognition as well as by sequence similarity.

Overall, the descriptor-enriched Random Forest model provides a stronger and more biologically meaningful representation of Cas9 specificity than sequence-only modeling. By linking off-target prediction to thermodynamic and structural DNA descriptors, the study contributes to computational enzyme engineering and supports safer CRISPR-based gene therapy and bioprocess development. Future work should add full metric reporting, external validation, and detailed feature-importance analysis to confirm which physicochemical descriptors most strongly influence Cas9 cleavage specificity.

References

Anders, C., Niewoehner, O., Duerst, A., & Jinek, M. (2014). Structural basis of PAM-dependent target DNA recognition by the Cas9 endonuclease. *Nature, 513*(7519), 569–573. https://doi.org/10.1038/nature13579

Boyle, E. A., Andreasson, J. O. L., Chircus, L. M., Sternberg, S. H., Wu, M. J., Guegler, C. K., et al. (2021). Quantification of Cas9 binding and cleavage across diverse guide sequences maps landscapes of target engagement. *Science Advances, 7*(8), Article eabe5496. https://doi.org/10.1126/sciadv.abe5496

Breiman, L. (2001). Random forests. *Machine Learning, 45*, 5–32. https://doi.org/10.1023/A:1010933404324

Chen, J. S., Dagdas, Y. S., Kleinstiver, B. P., Welch, M. M., Sousa, A. A., Harrington, L. B., et al. (2017). Enhanced proofreading governs CRISPR-Cas9 targeting accuracy. *Nature, 550*(7676), 407–410. https://doi.org/10.1038/nature24268

Chuai, G., Ma, H., Yan, J., Chen, M., Hong, N., Xue, D., et al. (2018). DeepCRISPR: Optimized CRISPR guide RNA design by deep learning. *Genome Biology, 19*, Article 80. https://doi.org/10.1186/s13059-018-1459-4

Doench, J. G., Fusi, N., Sullender, M., Hegde, M., Vaimberg, E. W., Donovan, K. F., et al. (2016). Optimized sgRNA design to maximize activity and minimize off-target effects of CRISPR-Cas9. *Nature Biotechnology*, (2), 184–191. https://doi.org/10.1038/nbt.3437

Doudna, J. A., & Charpentier, E. (2014). The new frontier of genome engineering with CRISPR-Cas9. *Science, 346*(6213), Article 1258096. https://doi.org/10.1126/science.1258096

Fu, Y., Foden, J. A., Khayter, C., Maeder, M. L., Reyon, D., Joung, J. K., et al. (2013). High-frequency off-target mutagenesis induced by CRISPR-Cas nucleases in human cells. *Nature Biotechnology, 31*(9), 822–826. https://doi.org/10.1038/nbt.2623

Hasanzadeh, A., Khalilov, R., Abasi, E., Saghfi, S., Nasibova, A., & Akbarzadeh, A. (2017). Development of doxorubicin-adsorbed magnetic nanoparticles modified with biocompatible copolymers for targeted drug delivery in lung cancer. *Advances in Biology and Earth Sciences, 2*(1), 5–21. https://www.academia.edu/download/101469922/Hasanzadeh_20A.pdf

Hsu, P. D., Scott, D. A., Weinstein, J. A., Ran, F. A., Konermann, S., Agarwala, V., et al. (2013). DNA targeting specificity of RNA-guided Cas9 nucleases. *Nature Biotechnology, 31*(9), 827–832. https://doi.org/10.1038/nbt.2647

Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., & Charpentier, E. (2012). A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. *Science, 337*(6096), 816–821. https://doi.org/10.1126/science.1225829

Khomutov, G. B., Potapenkov, K. V., Koksharov, Y. A., Trubitsin, B. V., Tikhonov, A. N., Mamedov, M. D., Nasibova, A. N., et al. (2014). *Magnetic nanoparticles in biomimetic and biological systems: Generation of iron oxide magnetic nanoparticles in DNA complexes, isolated chloroplasts and high plants* [Conference presentation]. XII International Conference on Nanostructured Materials (Nano-2014), Moscow, Russia. https://istina.ficp.ac.ru/publications/article/8002113/

Kim, D., Bae, S., Park, J., Kim, E., Kim, S., Yu, H. R., et al. (2015). Digenome-seq: Genome-wide profiling of CRISPR-Cas9 off-target effects in human cells. *Nature Methods, 12*(3), 237–243. https://doi.org/10.1038/nmeth.3284

Kleinstiver, B. P., Pattanayak, V., Prew, M. S., Tsai, S. Q., Nguyen, N. T., Zheng, Z., et al. (2016). High-fidelity CRISPR-Cas9 nucleases with no detectable genome-wide off-target effects. *Nature, 529*(7587), 490–495. https://doi.org/10.1038/nature16526

Lazzarotto, C. R., Malinin, N. L., Li, Y., Zhang, R., Yang, Y., Lee, G., et al. (2020). CHANGE-seq reveals genetic and epigenetic effects on CRISPR-Cas9 genome-wide activity. *Nature Biotechnology, 38*(11), 1317–1327. https://doi.org/10.1038/s41587-020-0555-7

Lin, Y., Cradick, T. J., Brown, M. T., Deshmukh, H., Ranjan, P., Sarode, N., et al. (2014). CRISPR/Cas9 systems have off-target activity with insertions or deletions between target DNA and guide RNA sequences. *Nucleic Acids Research, 42*(11), 7473–7485. https://doi.org/10.1093/nar/gku402

Listgarten, J., Weinstein, M., Kleinstiver, B. P., Sousa, A. A., Joung, J. K., Crawford, J., et al. (2018). Prediction of off-target activities for the end-to-end design of CRISPR guide RNAs. *Nature Biomedical Engineering, 2*(1), 38–47. https://doi.org/10.1038/s41551-017-0178-6

Mahmoodpoor, F., Ardalan, M., Nasibova, A., Valiyeva, M., & Ahmadian, E. (2024). The nephrotoxicity of checkpoint inhibitors: A mini review. *International Journal of Drug Research in Clinics, 2*(1), Article e1. https://doi.org/10.34172/ijdrc.2024.e1

Molla, K. A., & Yang, Y. (2020). Predicting CRISPR/Cas9-induced mutations for precise genome editing. *Trends in Biotechnology, 38*(2), 136–141. https://doi.org/10.1016/j.tibtech.2019.08.002

Nishimasu, H., Ran, F. A., Hsu, P. D., Konermann, S., Shehata, S. I., Dohmae, N., et al. (2014). Crystal structure of Cas9 in complex with guide RNA and target DNA. *Cell, 156*(5), 935–949. https://doi.org/10.1016/j.cell.2014.02.001

Pattanayak, V., Lin, S., Guilinger, J. P., Ma, E., Doudna, J. A., & Liu, D. R. (2013). High-throughput profiling of off-target DNA cleavage reveals RNA-programmed Cas9 nuclease specificity. *Nature Biotechnology, 31*(9), 839–843. https://doi.org/10.1038/nbt.2673

Ran, F. A., Hsu, P. D., Wright, J., Agarwala, V., Scott, D. A., & Zhang, F. (2013). Genome engineering using the CRISPR-Cas9 system. *Nature Protocols, 8*(11), 2281–2308. https://doi.org/10.1038/nprot.2013.143

SantaLucia, J., Jr. (1998). A unified view of polymer, dumbbell, and oligonucleotide DNA nearest-neighbor thermodynamics. *Proceedings of the National Academy of Sciences, 95*(4), 1460–1465. https://doi.org/10.1073/pnas.95.4.1460

Slaymaker, I. M., Gao, L., Zetsche, B., Scott, D. A., Yan, W. X., & Zhang, F. (2016). Rationally engineered Cas9 nucleases with improved specificity. *Science, 351*(6268), 84–88. https://doi.org/10.1126/science.aad5227

Tsai, S. Q., Nguyen, N. T., Malagon-Lopez, J., Topkar, V. V., Aryee, M. J., & Joung, J. K. (2017). CIRCLE-seq: A highly sensitive in vitro screen for genome-wide CRISPR-Cas9 nuclease off-targets. *Nature Methods, 14*(6), 607–614. https://doi.org/10.1038/nmeth.4278

Tsai, S. Q., Zheng, Z., Nguyen, N. T., Liebers, M., Topkar, V. V., Thapar, V., et al. (2015). GUIDE-seq enables genome-wide profiling of off-target cleavage by CRISPR-Cas nucleases. *Nature Biotechnology, 33*(2), 187–197. https://doi.org/10.1038/nbt.3117

Wang, D., Zhang, C., Wang, B., Li, B., Wang, Q., Liu, D., et al. (2019). Optimized CRISPR guide RNA design for two high-fidelity Cas9 variants by deep learning. *Nature Communications, 10*, Article 4284. https://doi.org/10.1038/s41467-019-12281-8

Wienert, B., Wyman, S. K., Richardson, C. D., Yeh, C. D., Akcakaya, P., Porritt, M. J., et al. (2019). Unbiased detection of CRISPR off-targets in vivo using DISCOVER-Seq. *Science, 364*(6437), 286–289. https://doi.org/10.1126/science.aav9023

Zhang, G., Zeng, T., Dai, Z., & Dai, X. (2021). Prediction of CRISPR/Cas9 single guide RNA cleavage efficiency and specificity by attention-based convolutional neural networks. *Computational and Structural Biotechnology Journal, 19*, 1445–1457. https://doi.org/10.1016/j.csbj.2021.03.001

Zhang, Z., Zhang, Y., Gao, F., Han, S., Cheah, K. S., Tse, H. F., et al. (2023). Using traditional machine learning and deep learning methods for on- and off-target prediction in CRISPR/Cas9: A review. *Briefings in Bioinformatics, 24*(1), Article bbac559. https://doi.org/10.1093/bib/bbac559

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Synthetic Preparation of $cd_3sb_2s_8$ Phase from Daridağ ore (Nakhchivan) and Investigation of its Physicochemical Properties

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Abstract. *Chalcogenide compounds containing $Cd_3Sb_2S_8$ are of particular interest in modern materials science due to their semiconductor properties. In this work, the compound in question was obtained from a natural ore taken from the Darıdag deposit located in the Nakhchivan Autonomous Republic. At the initial stage, the ore was processed by flotation and purified from arsenic impurities, and as a result, antimony (III) sulfide was isolated as the main component. The synthesis process was carried out at high temperature, in a protective argon environment, as a result of the joint interaction of cadmium, Sb_2S_3 and elemental sulfur. The reaction was carried out in stages, minimizing the possibility of oxidation, and no additional solvents or chemical reagents were used. The thermal behavior of the obtained sample was studied by differential thermal analysis, and its stability at high temperatures, as well as its melting properties, were determined. The surface structure and morphology were examined by scanning electron microscopy, and it was found that the material consists of small-sized crystals. The elemental composition was confirmed by energy dispersive analysis results and it was determined that the elements Cd, Sb and S were in accordance with the theoretical ratios. X-ray diffraction results showed that the synthesized material has a mainly crystalline structure, but also the presence of a slight amorphous phase. Overall, the obtained results demonstrate that the $Cd_3Sb_2S_8$ compound is promising as a functional material, especially for application in optoelectronic and thermoelectric fields.*

Keywords: *darıdag mineral, X-ray phase analysis, SEM, EDS, melting temperature*

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Darıdağ filizindən (Naxçıvan) $Cd_3Sb_2S_8$ fazasının sintezi və onun fiziki-kimyəvi xassələrinin tədqiqi

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Xülasə. *$Cd_3Sb_2S_8$ tərkibli xalkogenid birləşmələri yarımkeçirici xassələrinə görə müasir materialşünaslıqda xüsusi maraq doğurur. Bu işdə tədqiq olunan birləşmə Naxçıvan Muxtar Respublikasında yerləşən Darıdağ yatağından götürülmüş təbii filizdən əldə edilmişdir. İlkin mərhələdə filiz flotasiya üsulu ilə emal edilmiş və arsen qarışıqlarından təmizlənmiş, nəticədə əsas komponent kimi sürmə(III) sulfid ayrılmışdır. Sintez prosesi yüksək temperaturda, qoruyucu arqon mühitində kadmium, Sb_2S_3 və elementar kükürdün birgə qarşılıqlı təsiri nəticəsində həyata keçirilmişdir. Reaksiya oksidləşmə ehtimalını minimuma endirməklə mərhələli şəkildə aparılmış, əlavə həlledicilərdən və kimyəvi reagentlərdən istifadə edilməmişdir. Alınmış nümunənin termik davranışı diferensial termik analiz vasitəsilə öyrənilmiş, yüksək temperaturda davamlılığı və ərimə xassələri müəyyən edilmişdir. Səthin quruluşu və morfologiyası skanedici elektron mikroskopiyası ilə tədqiq edilmiş və materialın kiçikölçülü kristallardan ibarət olduğu müəyyən olunmuşdur. Element tərkibi enerji-dispersiv analiz nəticələri ilə təsdiqlənmiş, Cd, Sb və S elementlərinin nəzəri nisbətlərə uyğunluğu müəyyən edilmişdir. Rentgen difraksiyası nəticələri sintez olunmuş materialın əsasən kristallik quruluşa malik olduğunu, eyni zamanda az miqdarda amorf fazanın da mövcudluğunu göstərmişdir. Ümumilikdə, əldə edilən nəticələr $Cd_3Sb_2S_8$ birləşməsinin funksional material kimi, xüsusilə optoelektronika və termoelektrik sahələrində tətbiqi baxımından perspektivli olduğunu nümayiş etdirir.*

Açar sözlər: *Darıdağ mineralı, rentgen-faza analizi, skanedici elektron mikroskopiyası (SEM), enerji-dispersiv rentgen spektroskopiyası (EDS), ərimə temperaturu*

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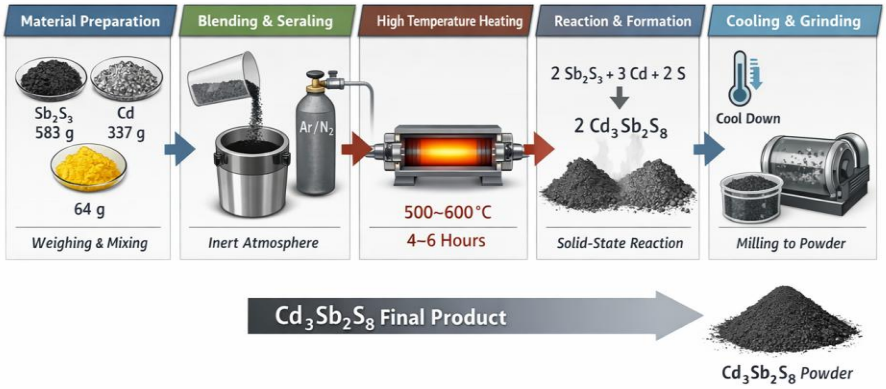
Introduction

The deposited CdS thin films were found to be n-type polycrystalline and photoactive. Due to the high series resistance, the conversion efficiency for the PEC cell was 0.17%, the fill factor was 0.38, and a sharp peak was observed in the spectral response near 500 nm (Abhijit, 2011). The thermodynamic parameters of the CdSb compound were studied by the electromotive force method at different temperature ranges. The phase composition of the samples was determined by X-ray diffraction analysis and the results were compared with the available literature data (Babanly, 2024). The Sb_2S_3/CdS/$CdIn_2S_4$ cascaded S-scheme heterojunction was obtained by a combination of different synthesis methods. Hydrothermal, chemical bath deposition and microwave hydrothermal methods were used in the preparation of the structure (Chen, 2022).

Graphic abstract of the $Cd_3Sb_2S_8$ compound:



The Sb_2S_3 semiconductor is considered a promising light-absorbing material due to its suitable band gap, one-dimensional crystal structure and non-toxic composition. The structural properties of Sb_2S_3 thin films grown on a CdS layer and a glass substrate were compared by SEM and XRD analyses, and it was determined that the growth direction of the ribbon crystals depended on the substrate. The prepared CdS/Sb_2S_3 heterojunction solar cells exhibited high photoelectric performance and maintained their stability even after long-term storage (Chen, 2017). A CdS, TiO_2 and MCM-41 based nanocomposite photocatalyst was prepared for the efficient degradation of Methylene Blue and characterized by various analytical methods. The highest photocatalytic activity was observed in the 15% loaded CdS/TiO_2/MCM-41 sample, and high MB degradation and significant mineralization were achieved in a short time in neutral media. Statistical modeling results showed that this material is a promising and applicable photocatalyst for wastewater treatment (Fatemipayam, 2025).

The structure of GeS_2–Sb_2S_3–CdS chalcogenide systems was studied by Raman spectroscopy and it was found that the addition of Sb_2S_3 and CdS had a significant effect on the structure of the glass network. Although the addition of CdS increased the crystallization tendency, the presence of Sb_2S_3 improved the homogeneity of the glass by increasing the solubility of CdS (Hai-Tao, 2017). The crystallization and chemical resistance properties of GeS_2-Ga_2S_3-CdS chalcogenide glasses have been investigated using various analytical methods. It was found that the glass containing GGC5 showed high thermal stability and good chemical resistance to water (Luh, 2008). It was found that new luminescence centers and deep energy levels were formed in single crystals of CdSe doped with Sb and Bi, and the photoconductivity spectrum shifted to the red region (Odin, 2000). In the Cd–In–Te–S system, CdS crystals were prepared by doping with In and Te in Cd and InTe vapors by a four-zone annealing method, resulting in orange–red luminescence bands instead of green emission and metastable sphalerite CdS structures showing high photosensitivity, and spectra shifted to longer wavelengths compared to stable samples (Odin, 2004).

Although photocatalytic technologies using solar energy play an effective role in reactions such as water splitting and CO_2 conversion under visible light thanks to semiconductors with a band gap of 2.4 eV, such as CdS, their application is limited by problems of rapid charge recombination and photocorrosion (Ren, 2024).

The innovative significance of Darıdağ ore in this context is related to its dual function, serving both as a raw mineral source and as an effective precursor for Sb_2S_3 formation. After flotation and subsequent purification, a high-purity Sb_2S_3 phase can be obtained directly from the processed ore. This strategy removes the necessity for independently synthesized Sb_2S_3, thereby streamlining the overall technological workflow. As a result, the process becomes less complex and more economically viable. In addition, energy demands are reduced due to the elimination of separate synthesis steps. Production costs are consequently minimized, improving overall efficiency. Therefore, the utilization of Darıdağ ore represents a sustainable and resource-efficient pathway for the fabrication of chalcogenide materials derived from natural mineral sources (Gubbuk, 2026).

The present study is distinguished by the direct application of Sb_2S_3 obtained from Darıdağ antimony ore as a precursor for the synthesis of $Cd_3Sb_2S_8$ chalcogenide material. In contrast to earlier research that predominantly depends on chemically synthesized Sb_2S_3 or commercially purified precursors, this work introduces a more sustainable and resource-efficient route by employing a naturally sourced mineral after the removal of arsenic impurities.

Furthermore, this research systematically examines the phase evolution, thermal stability, and microstructural development of $Cd_3Sb_2S_8$ formed under controlled solid-state synthesis conditions. The combination of ore beneficiation processes with semiconductor material synthesis presents an innovative strategy in chalcogenide preparation, contributing to improved economic efficiency and reduced environmental impact.

2 Experimental.

2.1 Ore processing and Sb_2S_3 extraction

The Darıdağ antimony ore was processed by a flotation technique aimed at selectively eliminating arsenic-bearing mineral phases. The flotation was performed under controlled pH conditions (2.5–5.3) using xanthate-based collectors together with MIBC as a frothing agent for a duration of 20 minutes. This procedure enabled an estimated arsenic removal efficiency of approximately 90–95%, leading to the formation of a relatively enriched Sb_2S_3 concentrate.

Subsequent X-ray diffraction (XRD) (Azimova, 2026) analysis indicated that the synthesized Sb_2S_3 phase possessed high crystallinity and purity (>90–95%), with no observable peaks corresponding to arsenic sulfide impurities.

The raw material used for the study was ore taken from the Darıdag arsenic deposit of the Nakhchivan Autonomous Republic (Aliyeva, 2020; Aliyeva, 2025; Garayev, 2022, Hajiyeva, 2026 . At the initial stage, the ore was processed by flotation to remove arsenic-containing components, and as a result, antimony (III) sulfide (Sb_2S_3) was obtained as the main phase. This purification stage plays an important role in preventing unwanted side reactions in the subsequent synthesis process and increasing the phase purity of the product to be obtained.

Darıdağ deposit constitutes an important natural source of antimony sulfide minerals suitable for semiconductor precursor production. In contrast to chemically synthesized Sb_2S_3, the utilization of ore-derived material offers a more economical and resource-efficient alternative. Through beneficiation and subsequent purification procedures, arsenic-containing phases were substantially eliminated, resulting in the recovery of an Sb_2S_3-rich concentrate with improved purity for further synthesis applications.

2.2. Synthesis of $Cd_3Sb_2S_8$

The synthesis of the $Cd_3Sb_2S_8$ compound was carried out as a result of the interaction of Cd metal, Sb_2S_3 and elemental sulfur under high temperature conditions. The molar ratio of the reagents was calculated in advance and stoichiometric compatibility was ensured, which creates conditions for the correct formation of the chemical composition of the final product. The overall reaction can be expressed as follows:

$$Sb_2S_3 + 3Cd + 5S \rightarrow Cd_3Sb_2S_8$$

The synthesis process occurs according to a multi-stage solid-state mechanism, and this mechanism is determined by both kinetic and thermodynamic factors. In the initial stage, cadmium metal reacts with elemental sulfur to form the CdS intermediate phase. This stage is characterized by the formation of the first stable sulfide compound in the system and creates a chemically active environment for the onset of subsequent processes. Since the reactivity and diffusivity of sulfur increase at high temperatures, the interaction with Cd atoms accelerates and the CdS phase is easily formed. In the next stage, when the formed CdS particles come into contact with the Sb_2S_3 structure, solid-state diffusion processes are activated. Since the crystal structure of Sb_2S_3 is chain-like, with increasing temperature, its structure undergoes partial decomposition and reorganization. These structural changes allow Sb and S atoms to move more freely and intensify the interaction with CdS.

Elemental sulfur added to the system plays an important role, as it ensures the sulfur balance in the environment and contributes to the formation of a stable phase with a higher sulfur content. Under these conditions, the nucleation of a new crystalline phase - the $Cd_3Sb_2S_8$ compound - occurs as a result of mutual diffusion of Cd, Sb and S atoms. After the nucleation stage, the growth of crystal grains occurs, which is controlled by temperature and storage time.

The synthesis was carried out practically by a dry method. Cd and Sb_2S_3 were powdered, elemental sulfur was prepared separately, and all components were mixed homogeneously. Uniform distribution of the mixture is an important condition for the effectiveness of diffusion processes. The prepared mixture was placed in a tin capsule and sealed in an inert argon atmosphere to prevent oxidation.

The reaction was carried out in the temperature range of 550–650°C for 3–5 hours. This temperature range is high enough to ensure the diffusion of atoms and at the same time prevents excessive loss of sulfur. The staged heating regime allows the reaction to proceed more stably and homogeneously. Under these conditions, the Cd, Sb_2S_3 and S components interact to form the $Cd_3Sb_2S_8$ phase.

It is of particular importance to carry out the reaction in an inert environment, since at high temperatures, undesirable oxide phases such as CdO and Sb_2O_3 can form in the presence of oxygen. The argon environment prevents such side reactions, increases the selectivity of the synthesis process and maintains the phase purity of the product. After the synthesis was completed, the sample was gradually cooled inside the vessel, which helped to reduce thermal stresses and stabilize the crystal structure. The obtained $Cd_3Sb_2S_8$ granules were subsequently mechanically ground into a homogeneous powder and prepared for analytical studies.

Thus, the preparation of the $Cd_3Sb_2S_8$ compound is explained by the classical solid-phase synthesis mechanism, which includes the formation of the sulfide phase, activation of the structure, atomic diffusion and crystallization stages. The efficiency of this process is directly related to the purity of the reagents, homogeneous mixing, provision of an inert environment and selection of the optimal temperature regime.

2.3. DTA: thermal stability and phase transition behavior

The melting temperature of the sample was determined by the differential thermal analysis (DTA) method, and its diffractogram was also obtained (Aliyeva, 2026). The results of the DTA analysis are presented in Figure 1.

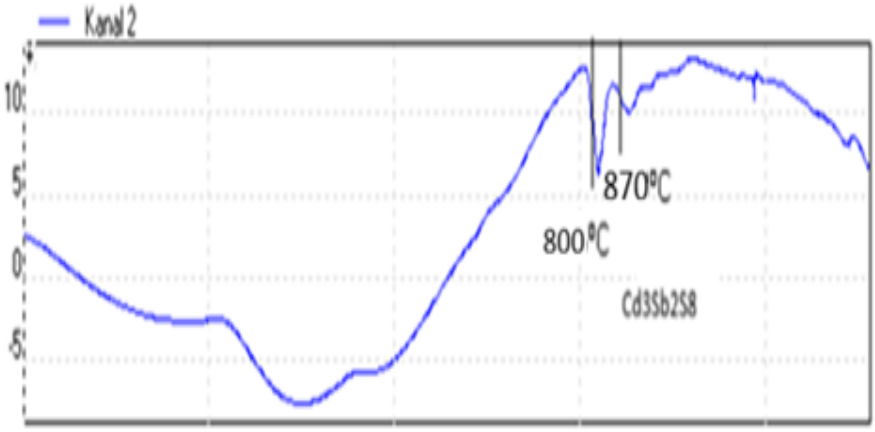


Figure 1
Melting temperature of cadmium–antimony sulfide

The presented DTA curve characterizes the thermal behavior of the $Cd_3Sb_2S_8$-type sulfide system. The analysis reflects the energy changes occurring in the material during heating. Weak signals observed in the low-temperature region may be associated with the release of volatile components. At this stage, desorption of adsorbed species from the crystal surface takes place. With increasing temperature, the system gradually evolves toward a more stable crystalline state. In the intermediate temperature range, a reduction of internal lattice stresses can be observed. Ion diffusion becomes more active in this region. A noticeable thermal event appears around 800°C in the curve. This change may indicate the onset of structural rearrangement within the material. The endothermic response near 800°C is likely related to the weakening of crystal bonds.

At higher temperatures, the instability of the system increases. A sharp peak is detected at approximately 870°C, indicating a critical thermal event. This peak may correspond to a decomposition or phase transition temperature of the material. At 870°C, a significant part of the crystal structure undergoes reorganization. The probability of partial breaking of Sb–S and Cd–S bonds increases in this stage. At elevated temperatures, a transition toward a semi-amorphous state becomes possible. The change in the signal after the peak indicates that the system reaches a new equilibrium state. The DTA results define the limited thermal stability range of the material. This information is important for optimizing synthesis and application conditions. Overall, the curve shows that major thermal transformations in the $Cd_3Sb_2S_8$ system occur within the 800–870°C temperature range.

2.4.Chemical analysis: gravimetric and EDTA titration methods

The chemical composition of the $Cd_3Sb_2S_8$ compound was analyzed by chemical methods, which are gravimetric (sulfide precipitation) and complexometric (EDTA) methods. The gravimetric method is based on the principle of precipitation of Cd^{2+} and Sb^{3+} ions in the $Cd_3Sb_2S_8$ compound in the form of sulfide. During the analysis, the sample is dissolved in an acidic medium, releasing metal ions into solution. H_2S or Na_2S is then added to the solution, resulting in the formation of sparingly soluble CdS and Sb_2S_3 precipitates:

$$Cd^{2+} + S^{2-} \rightarrow CdS\downarrow$$
$$2Sb^{3+} + 3S^{2-} \rightarrow Sb_2S_3\downarrow$$

The obtained precipitates are filtered, washed, dried and heated to constant mass and then weighed. The amount of Cd and Sb elements is calculated based on the mass of the precipitates. This method is distinguished by its high accuracy and simple implementation.

Complexometric (EDTA) analysis is based on the formation of stable complexes of metal ions with EDTA. At this stage, Cd^{2+} ions in the solution are directly titrated with EDTA solution and the equivalent point is determined using a suitable indicator (for example, eriochrome black T or muroxide). Sb^{3+} ions are usually pre-oxidized or indirectly determined by placing them in a suitable complex medium. Since the complexes formed with EDTA are stable, the titration is completed with a color change at the end point.

Table 1
Chemical analysis of cadmium thiostibitate

Example, $Cd_3Sb_2S_8$, q	Amount of items, q					
	Cd		Sb		S	
0.4200	Theor.	Exper.	Theor.	Exper.	Theor.	Exper.
	0.1690	0.1681	0.1220	0.1211	0.1290	0.1281

2.5 XRD: crystal structure and phase identification
To determine the stoichiometric composition of the compound, we performed scanning electron microscopy (SEM) using an OXFORD device (Launch Trion XL ilution refrigerator) (Figure 2).

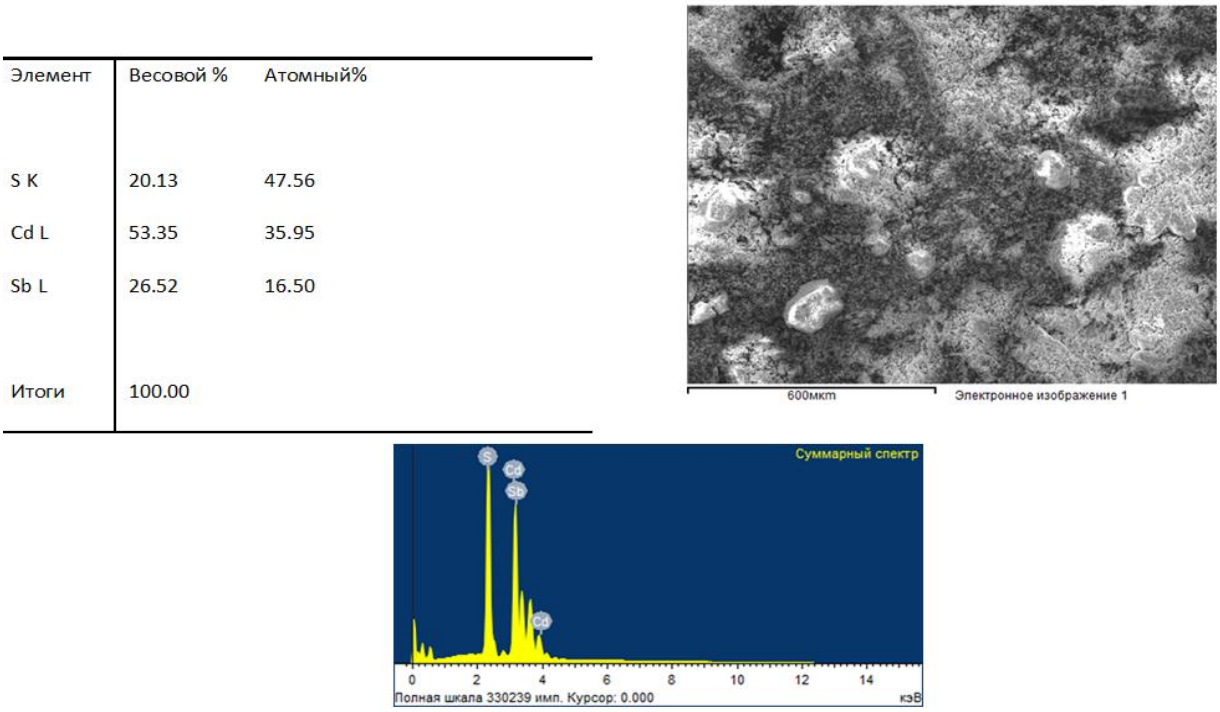


Figure 2
Elemental composition, energy dispersive spectrum, and microscope of cadmium–antimony sulfide

The results obtained from the figure reflect both the chemical composition and morphological properties of the $Cd_3Sb_2S_8$ compound. Based on the scanning electron microscopy (SEM) (Imanov, 2020) analysis, it is determined that the surface of the material is mainly composed of small-sized

crystals and particles. The size of the particles varies in the range of approximately 5 µm, which indicates that the sample has a relatively homogeneous structural structure. The energy dispersive spectroscopy (EDS) results reveal that the elemental composition is consistent with the theoretical composition in terms of both mass and atomic percentages. Peaks belonging to the elements cadmium (Cd), antimony (Sb) and sulfur (S) are clearly observed in the spectra and they are mainly located in the energy range of 2.3–4 keV. The combined results of SEM and EDS analyses confirm both the morphological integrity and chemical correctness of the synthesized compound. These properties indicate that the $Cd_3Sb_2S_8$ material is a promising candidate for optoelectronic and thermoelectric applications.

Based on the 5 µm scale bar in the image, the particle size can be approximately estimated as follows:

The smallest distinguishable particles are in the range of 5–15 µm.
The majority of particles fall within 20–60 µm.
Larger agglomerates are observed in the range of 80–200 µm.
Occasional large structures reach approximately 200–300 µm.

Size (µm)	Estimated fraction
0–20	15–20%
20–50	40–50%
50–100	20–30%
100–200	10–15%
>200	<5%

Accordingly, based on this SEM image, the average particle size is estimated to be approximately 40–70 µm.

2.6 XRD: crystal structure and phase identification

X-ray diffraction was used to study the crystal structure and phase composition of the synthesized sample. The diffraction results showed that crystallinity was formed in the compound and the observed main peaks were consistent with standard parameters (Figure 3).

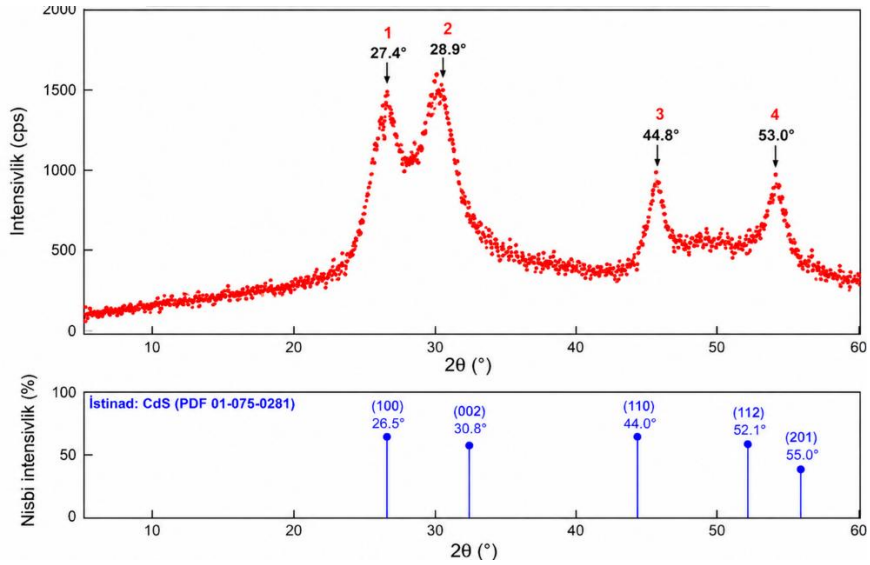


Figure 3
X-ray phase analysis of cadmium-antimony-sulfide

The presented diffractogram reflects the results of X-ray diffraction (XRD) (Mamedova, 2016; Mamedova, 2020; Mamedova, 2020) of the $Cd_3Sb_2S_8$ compound. The X-ray diffraction (XRD) pattern presented in Figure 3 was used to evaluate the crystal structure of the synthesized sample. Four prominent diffraction peaks were observed at approximately 27.4°, 28.9°, 44.8°, and 53.0° in the 2θ range. The most intense reflection appeared at 28.9°, indicating a preferred crystallographic orientation within the material. A strong peak was also detected at 27.4°, confirming the formation of a crystalline phase. The reflections at 44.8° and 53.0° correspond to characteristic lattice planes of the crystal structure. Comparison with the standard CdS diffraction data (PDF 01-075-0281) revealed good agreement between the experimental and reference peak positions. The standard pattern exhibits major reflections at 26.5°, 30.8°, 44.0°, 52.1°, and 55.0°. Slight shifts in the diffraction angles may be attributed to lattice strain, crystallite size effects, or structural defects. The relatively broad diffraction peaks suggest the formation of nanocrystalline domains. Furthermore, the elevated background intensity indicates the possible presence of a minor amorphous component. The well-defined diffraction peaks demonstrate a satisfactory degree of crystallinity. No significant impurity peaks were detected in the measured range, suggesting high phase purity of the synthesized material. Variations in peak intensity reflect differences in the diffraction contribution of individual crystal planes. The reflections near 44.8° and 53.0° closely match those reported for CdS-based materials. The observed peak positions and intensities confirm the successful formation of a CdS crystalline phase. Minor deviations from the standard pattern can be associated with synthesis conditions and crystal imperfections. Overall, the XRD analysis verifies that the sample possesses a predominantly crystalline CdS structure with good structural quality and phase stability (Gilshtein, 2025).
We calculated the crystallite size based on the Scherrer equation and presented it as follows:
The average crystallite size was evaluated using the Scherrer equation:

$$D = K\lambda / (\beta \cos\theta)$$

where K is the shape factor (0.9), λ represents the Cu Kα radiation wavelength (0.15406 nm), β is the full width at half maximum (FWHM), and θ is the Bragg diffraction angle.

Using the most intense diffraction peak at approximately $2\theta \approx 28.9°$ and an estimated FWHM of 2.0–2.5°, the crystallite size was determined to be roughly in the range of 10–25 nm. This value corresponds to the size of coherent diffracting domains rather than the overall particle dimensions observed in SEM images.

The difference between SEM results (showing micrometer-sized agglomerates) and XRD-derived crystallite sizes suggests that the material is composed of nanoscale crystallites that are aggregated into larger secondary particles.

The amorphous phase is estimated to be approximately 50 ± 10%.

Overall, the results obtained show that the synthesized $Cd_3Sb_2S_8$ has a predominantly crystalline structure, but the presence of some non-crystalline (amorphous) regions in the structure cannot be ruled out. (Mamedova, 2021; Mamedova, 2021; Mamedova, 2021).

3 Result

3.1. Thermal analysis

Thermal analysis demonstrates that $Cd_3Sb_2S_8$ exhibits stability up to approximately 800C. An intense endothermic effect observed in the range of 800–870°C is associated with melting behavior and subsequent structural rearrangement of the material. This response suggests a partial weakening of chemical bonding at elevated temperatures.

3.2. Morphology and composition

SEM observations reveal that the synthesized material is composed of aggregated microcrystalline particles with dimensions typically varying between 20 and 100 µm. Elemental mapping by EDS confirms a homogeneous distribution of Cd, Sb, and S throughout the sample, which is consistent with the expected stoichiometric composition of $Cd_3Sb_2S_8$.

3.3. Crystal structure

X-ray diffraction analysis verifies the successful formation of a well-crystallized $Cd_3Sb_2S_8$ phase. The main diffraction peaks located at 27.4°, 28.9°, 44.8°, and 53.0° are in good agreement with standard reference patterns (Yadav, 2011). The observed slight peak broadening indicates the presence of nanoscale crystallite domains together with a minor amorphous fraction, estimated at approximately 50 ± 10%.

The average crystallite size calculated using the Scherrer approach falls within the range of 10–25 nm, confirming the coexistence of nanocrystalline domains within larger micrometer-scale aggregates (Ashok, 2020).

3.4. Role of ore-derived precursor

Utilization of Sb_2S_3 obtained from Darıdağ ore notably simplifies the synthesis route by eliminating the need for chemically synthesized precursors. This approach reduces both production cost and environmental burden. Importantly, the ore-derived Sb_2S_3 yields a phase purity comparable to that of conventional synthetic precursors, while contributing to a more sustainable and resource-efficient preparation strategy.

Discussion

The formation of $Cd_3Sb_2S_8$ in this work can be explained through a multi-stage solid-state reaction mechanism involving intermediate CdS formation and subsequent diffusion with Sb_2S_3. At elevated temperatures, cadmium reacts readily with elemental sulfur, leading to the in situ generation of CdS as an active intermediate phase. This intermediate plays a key role in facilitating the incorporation of Sb and additional sulfur into the final ternary structure. The layered chain-like structure of Sb_2S_3 enhances atomic mobility, which supports solid-state diffusion processes during synthesis. The use of an argon atmosphere prevents oxidation reactions and helps maintain the chemical purity of the system. The X-ray diffraction analysis confirms that the synthesized material is mainly crystalline and corresponds to the $Cd_3Sb_2S_8$ phase (Ganiev 2026). The presence of broadened diffraction peaks indicates that the crystal domains are in the nanometer scale. Small variations in peak positions compared to standard patterns can be associated with internal stress, defects, and size-related effects developed during high-temperature synthesis. The simultaneous presence of ordered and slightly disordered regions suggests that the material has a partially crystalline structure. These structural characteristics are expected to affect the physical behavior of the compound.The scanning electron microscopy results show that the sample is composed of secondary particles formed by the aggregation of much smaller crystallites. This type of morphology is commonly observed in solid-state synthesized sulfide materials due to grain growth and particle coalescence at elevated temperatures. Energy-dispersive X-ray analysis confirms that cadmium, antimony, and sulfur are uniformly distributed throughout the sample. The absence of significant compositional fluctuations suggests that the reaction proceeded homogeneously across the material.When compared with similar Cd–S and Sb–S based chalcogenide systems reported in the literature, the present material demonstrates comparable structural behavior while benefiting from a naturally sourced Sb_2S_3 precursor. The use of Darıdağ ore reduces reliance on chemically synthesized reagents and contributes to a more sustainable synthesis strategy. This approach also simplifies the overall

preparation route and lowers material cost. The results confirm that ore-derived precursors can be effectively used in the fabrication of complex chalcogenide phases.

Conclusion

A new and sustainable synthesis pathway for $Cd_3Sb_2S_8$ has been established through the use of Sb_2S_3 obtained from Darıdağ ore. The resulting product shows a largely crystalline nature with nanometer-scale crystallite domains and demonstrates satisfactory thermal stability. These findings indicate that Sb_2S_3 derived from natural ore can serve as a viable substitute for conventionally prepared synthetic precursors in chalcogenide synthesis, enabling a more economical and environmentally benign production strategy.

References

Abhijit, A. A., Masumdar, E.U. (2011). Photoelectrochemical investigations of cadmium sulphide (CdS) thin film electrodes prepared by spray pyrolysis. *Journal of Alloys and Compounds, 509*(17), 5394–5399 https://doi.org/10.1016/j.jallcom.2011.02.061

Azimova, N. M., Mamedova, G. A., Aliyeva, S. H., Jamalova, R., et. al. (2026). Synthesis of zeolites of the chabazite group based on natural minerals of Nakhchivan: the influence of various factors on the process of their crystallization. Journal of Chemistry and Technologies, *34*(2), 412–424. https://doi.org/10.15421/jchemtech.v34i2.345095

Aliyeva, S. H., Heybatova, A. F., Pashayeva, A. (2026). Synthesis and X-Ray Phase Analysis of $Cd_3Sb_2S_8$ Obtained from Schlippe's Salt. *Scientific WorkOpen source preview,* 62–65. https://doi.org/10.36719/2663-4619/1/62-65

Aliyeva, S. H., Baghban, A., Ganiev, B., Mamedova, G., Jamalova, R. H., et. al. (2026) Controlled Aqueous Synthesis of Ag_3SbS_4 in the Na_3SbS_4–$AgNO_3$–H_2O Precursor System with Thermodynamic and Physicochemical Characterization. Solid State Sciences. 108373 https://doi.org/10.1016/j.solidstatesciences.2026.108373

Ashok, A., Regmi, G., Romero-Núñez, A., Solis-López, M. (2020) Comparative studies of CdS thin films by chemical bath deposition techniques as a buffer layer for solar cell applications. Vol.31, 7499–7518. https://doi.org/10.1007/s10854-020-03024-3

Babanly, D. M., Aghayeva, A. R., Mammadova, S. H., & Tagiyev, D. B. (2024). Thermodynamic study of the CdSb compound by the electromotive force measurements method. *Chemistry Problems*, 402–410. https://doi.org/10.32737/2221-8688-2024-4-402-410

Chen, Y., Cheng, Y., Zhao, J., Zhang, W., Gao, J., Miao, H., & Hu, X. (2022). Construction of Sb_2S_3/CdS/$CdIn_2S_4$ cascaded S-scheme heterojunction for improving photoelectrochemical performance. *Journal of Colloid and Interface Science, 627*, 1047–1060. https://doi.org/10.1016/j.jcis.2022.07.117

Chen, X., Li, Z., Zhu, H., et al. (2017). CdS/Sb_2S_3 heterojunction thin film solar cells with thermally evaporated absorber. *Journal of Materials Chemistry C, 5*(36). https://doi.org/10.1039/C7TC02460F

Fatemipayam, N., Keramati, N., & Mehdipour, M. G. (2025). Synthesis and characterization of cadmium sulfide and titania photocatalysts supported on mesoporous silica for optimized dye degradation under visible light. *15*, 8160.

Ganiyev, B., Kholikova, G., Sharipov, M., Mardonov, U., Aliyeva, S. (2026). Comprehensive Investigation of the Physicochemical Properties of the $CdSb_2S_4$ Compound (Chemical and X-Ray Phase Analysis, Precipitation Kinetics) Nature & Science, Vol. 8, Issue 2, 56−60 https://doi.org/10.36719/2707-1146/65/56-60

Garayev, A. M., & Aliyeva, S. H. (2022). Investigation of the conditions for the production of antimony thiostibiat. *International Scientific Journal Nature and Science, 4*, 55–59. https://doi.org/10.19261/cjm.2021.792

Gilshtein, E., Gupta, H. M,, Maria, A., et. al. (2025). Superstrate structured Sb_2S_3 thin-film solar cells by magnetron sputtering of Sb and post-sulfurization. Materials & Design. Vol.258, 114621 https://doi.org/10.1016/j.matdes.2025.114621

Gubbuk, I. H.., Ersoz, M., Aliyeva, S., Mammadova, N., Babayeva, R. (2026). Organic-Medium Synthesis of $Cd_3Sb_2S_8$ and Its Thermogravimetric Analysis (TGA). *Nature & Science 8*(4), 13-18. https://doi.org/10.36719/2707-1146/67/13-18

Hai-Tao, M., Ming-Jie, Z., & Yan-Ta, Z. (2017). Structural evolution study of additions of Sb_2S_3 and CdS into GeS_2 chalcogenide glass by Raman spectroscopy. *Chinese Physics B, 26*(10), 104208. https://doi.org/10.1088/1674-1056/26/10/104208

Hajiyeva, G., Seyidova, I., Aliyeva, S., Isgandarova, U., Seyidov, M. (2026). Integrated Evaluation of Exodynamic Processes in the Nakhchivanchay Basin Based on Geological and Geophysical Indicators Using Gis and Remote Sensing Methods. *Scientific Work 20*(4), 303–316. https://doi.org/10.36719/2663-4619/128/303-316

Imanov, H. A. (2020). Acquisition and study of properties of Ag_3AsS_4 compound. *News of the Nakhchivan Branch of ANAS, 2*, 52–55.

Luh, M., Guo, T., Peng, et al. (2008). Crystallization and chemical stability of GeS_2–Ga_2S_3–CdS chalcogenide glasses. *Acta Photonica Sinica, 37*, 191–194.

Mamedova, G. A. (2016). The ion-exchange properties of natural zeolite mordenite. *Fine Chemical Technologies, 11*(1), 29–33. https://doi.org/10.32362/2410-6593-2016-11-1-29-33

Mamedova, G. A. (2020). Synthesis of faujasite zeolite based on Nakhchivan native mineral. *Glass and Ceramics, 77*, 15–18. https://doi.org/10.1007/s10717-020-00228-1

Mamedova, G. A. (2020). Synthesis of different structural types of zeolites in the halloysite–dolomite–obsidian system. *Chemistry Journal of Moldova,15*(1), 31–40. https://doi.org/10.19261/cjm.2020.664

Mamedova, G. A. (2021). Influence of synthesis conditions on clinoptilolitic zeolite crystallization. *Glass and Ceramics, 78*, 168–171. https://doi.org/10.1007/s10717-021-00370-4

Mamedova, G., Nasirli, G. (2021) Investigation Of Various Influencing Factors Of Hydrothermal Synthesis Of Analcime Zeolite. *Chemistry Journal Of Moldova, 16*(1), P.60-67. https://doi.org/10.19261/cjm.2021.792

Mamedova, G. A. (2021). Influence of temperature and alkalinity on the crystallization of ZSM and ZK zeolites. *Theoretical Foundations of Chemical Engineering, 55*, 479–489. https://doi.org/10.1134/S0040579521030131

Odin, I. N., Chukichev, M. V., & Rubina, M. E. (2000). Luminescent properties of CdSe single crystals doped with antimony or bismuth. *Inorganic Materials, 36*(3), 232–234. https://doi.org/10.1007/BF02757927

Odin, I. N., Chukichev, M. V., & Rubina, M. E. (2004). Indium and tellurium doping of CdS crystals in cadmium vapor and their luminescent properties. *Inorganic Materials, 40*(12), 1241–1243. https://doi.org/10.1007/S10789-005-0047-7

Ren, Y., Li, Y., Pan, G., et al. (2024). Recent progress in CdS-based S-scheme photocatalysts. *Journal of Materials Science & Technology, 171*, 162–184. https://doi.org/10.1016/j.jmst.2023.06.052

Yadav, A. A., Masumdar, E. U. (2011). Photoelectrochemical investigations of cadmium sulphide (CdS) thin film electrodes prepared by spray pyrolysis. *Journal of Alloys and Compounds.* Vol. 509, Issue 17, 5394-5399 https://doi.org/10.1016/j.jallcom.2011.02.061

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Comparative Evaluation of Convolutional and Transformer-Based Models for Cucumber Disease Classification

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Abstract. *Cucumber (Cucumis sativus) is an important horticultural crop, and disease-related losses can reduce both yield and market quality. Image-based deep learning methods have been increasingly used for plant disease recognition, yet practical model selection requires attention to both predictive performance and computational cost. In this study, four pretrained deep learning architectures were evaluated for eight-class cucumber disease classification: DenseNet201, Inception v4, ConvNeXt v2 Base, and DeiT Base. The experiments were conducted on a public dataset containing 7,689 images, including two healthy and six diseased categories, using a 70% training, 15% validation, and 15% test split. DeiT Base achieved the highest test accuracy among the evaluated models, with an accuracy of 0.9957. Inception v4 followed closely with an accuracy of 0.9948, whereas DenseNet201 provided a lower but still competitive accuracy of 0.9846 with the smallest computational burden, requiring 18.11M parameters and 8.58 GFLOPs. The results indicate that highly accurate cucumber disease classification can be achieved with both convolutional and Transformer-based models, but the preferred architecture depends on whether the priority is maximum accuracy or lower computational cost. Since the experiments were limited to a single public dataset, further validation on field-acquired images is needed before drawing conclusions about real-world deployment.*

Keywords: *cucumber disease classification, plant disease recognition, deep learning, transfer learning*

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Xiyar xəstəliklərinin təsnifatı üçün konvolyusiya və transformator əsaslı modellərin müqayisəli qiymətləndirilməsi

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Xülasə. *Xiyar (*Cucumis sativus*) mühüm bağçılıq bitkisidir və xəstəliklərlə bağlı itkilər həm məhsuldarlığı, həm də bazar keyfiyyətini azalda bilər. Təsvirlərə əsaslanan dərin öyrənmə üsulları bitki xəstəliklərinin tanınmasında getdikcə daha geniş istifadə olunur. Bununla belə, praktik model seçimi yalnız proqnozlaşdırma dəqiqliyini deyil, həm də hesablama xərclərini nəzərə almağı tələb edir.*

Bu tədqiqatda səkkiz sinifli xiyar xəstəliyi təsnifatı üçün dörd əvvəlcədən öyrədilmiş dərin öyrənmə arxitekturası qiymətləndirilmişdir: DenseNet201, Inception v4, ConvNeXt v2 Base və DeiT Base. Eksperimentlər iki sağlam və altı xəstə kateqoriyanı əhatə edən 7,689 təsvirlik açıq məlumat dəsti üzərində aparılmış və məlumatlar 70% təlim, 15% validasiya və 15% test hissələrinə bölünmüşdür. Qiymətləndirilən modellər arasında DeiT Base ən yüksək test dəqiqliyinə nail olmuşdur və onun dəqiqlik göstəricisi 0.9957 təşkil etmişdir. Inception v4 0.9948 dəqiqliklə ona çox yaxın nəticə göstərmişdir. DenseNet201 isə nisbətən aşağı, lakin yenə də rəqabətədavamlı 0.9846 dəqiqlik əldə etmiş və ən aşağı hesablama yükünə malik olmuşdur; bu model 18.11 milyon parametr və 8.58 GFLOPs tələb etmişdir. Nəticələr göstərir ki, xiyar xəstəliklərinin yüksək dəqiqlikli təsnifatı həm konvolyusional, həm də Transformer əsaslı modellərlə mümkündür. Bununla belə, üstünlük veriləcək arxitektura maksimum dəqiqliyin, yoxsa daha aşağı hesablama xərclərinin prioritet olmasından asılıdır. Eksperimentlər yalnız bir açıq məlumat dəsti ilə məhdudlaşdığı üçün real sahə şəraitində tətbiq haqqında daha güclü nəticələr çıxarmaqdan əvvəl sahədən toplanmış təsvirlər üzərində əlavə validasiya aparılmalıdır.

Açar sözlər: *xiyar xəstəliklərinin təsnifatı, bitki xəstəliklərinin tanınması, dərin öyrənmə, transfer öyrənməsi*

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Introduction

Cucumber (Cucumis sativus) is widely cultivated for fresh consumption and food processing, and it represents an economically important horticultural crop in many agricultural regions (Y. Wang et al., 2024; Zeng et al., 2025). However, cucumber production is affected by several fungal, bacterial, and viral diseases that can reduce yield, fruit quality, and market value (Asha Rani & Gowrishankar, 2024; Cao et al., 2025). Diseases such as Downy Mildew, Anthracnose, Bacterial Wilt, Gummy Stem Blight, and Cucumber Mosaic Virus often produce visible symptoms on leaves, stems, or fruits, including discoloration, necrotic lesions, wilting, and tissue deformation. If these symptoms are not detected at an early stage, disease spread may increase production losses and lead to unnecessary or poorly timed pesticide applications (Shrestha et al., 2024).

In practical agricultural settings, cucumber disease diagnosis is still commonly based on visual inspection by farmers, agronomists, or plant protection specialists. Although expert evaluation is valuable, visual assessment is affected by symptom stage, observer experience, illumination, background conditions, and the visual similarity between disease classes (Emin Sahin et al., 2025; Li et al., 2024). Early symptoms may be subtle, and different diseases may share similar color changes, lesion boundaries, or tissue damage patterns. These factors can delay diagnosis or result in incorrect treatment decisions. Image-based automated screening systems can therefore be useful as complementary decision-support tools, particularly in situations where expert assessment is not immediately available.

Deep learning has become a widely used approach for plant disease recognition because it can learn discriminative visual features directly from image data. CNN-based architectures have been particularly effective in this field due to their ability to capture local texture, color, and lesion patterns

through hierarchical feature extraction (Kunduracioglu & Pacal, 2024; Pacal & Işık, 2024; Rahman et al., 2024). More recently, modern ConvNet designs and Transformer-based models have also been investigated for agricultural image classification. Modern ConvNets such as ConvNeXt incorporate several design principles inspired by recent vision architectures while retaining convolutional operations, whereas Vision Transformers use self-attention to model relationships between distant image regions (Singh et al., 2024; Woo et al., 2023). These architectural differences may influence both classification performance and computational requirements.

Several recent studies have reported strong results for cucumber and broader plant disease recognition using CNNs, Transformer-based networks, and hybrid approaches (Asha Rani & Gowrishankar, 2024; Cao et al., 2025; Emin Sahin et al., 2025; Li et al., 2024; Zeng et al., 2025). However, many studies primarily emphasize classification accuracy, while computational cost is often reported only partially or not discussed in relation to deployment constraints. This is a relevant limitation because agricultural disease recognition systems may need to operate on mobile devices, embedded platforms, or low-power hardware in field environments. In such cases, a model with marginally lower accuracy but substantially lower computational demand may be more practical than a larger model with slightly higher performance.

Another limitation in the existing literature is that model comparisons are often difficult to interpret because different studies use different datasets, class definitions, preprocessing pipelines, augmentation strategies, and validation protocols. As a result, it is not always clear whether reported performance differences are caused by the model architecture itself or by differences in experimental design. A controlled comparison under the same dataset split, input resolution, training strategy, and evaluation metrics is therefore needed to better understand the relationship between predictive performance and computational complexity in cucumber disease classification.

To address this issue, the present study evaluates four pretrained deep learning architectures under a unified experimental protocol: DenseNet201, Inception v4, ConvNeXt v2 Base, and DeiT Base. DenseNet201 and Inception v4 were selected as representative CNN architectures with different levels of complexity. ConvNeXt v2 Base was included as a modern convolutional architecture, while DeiT Base was selected as a Transformer-based model. All models were evaluated on an eight-class public cucumber disease dataset using the same preprocessing, training, validation, and test configuration. The aim is not to introduce a new architecture, but to provide a controlled comparison of accuracy, precision, recall, F1-score, parameter count, and GFLOPs. The main contributions of this study are as follows:

- A unified comparison of CNN, modern ConvNet, and Transformer-based architectures is provided for eight-class cucumber disease classification.
- Predictive performance is reported together with parameter count and GFLOPs to evaluate the accuracy–complexity trade-off.
- The results compare high-accuracy models with more compact alternatives, supporting model selection under different computational constraints.
- The study provides a controlled baseline for future cucumber disease classification studies using the same public dataset.

1. Related Work

Deep learning has been widely adopted for plant disease recognition, particularly because disease symptoms are often expressed through visual changes in color, texture, lesion shape, and tissue structure. In cucumber disease classification, early studies mainly relied on CNN-based architectures due to their strong capacity for local feature extraction. Jain et al. (2024) evaluated several standard CNN architectures, including AlexNet, GoogLeNet, and ResNet50, for cucumber disease

identification and reported the best performance with ResNet50. Pradhan et al. (2024) combined CNN-based feature extraction with a Support Vector Machine classifier and achieved competitive classification performance. Bilal et al. (2025) proposed a fuzzy deep CNN framework for cucumber plant disease detection and classification, with a focus on improving robustness under noisy image conditions.

CNN-based models have also been used in broader plant disease studies because convolutional filters are effective in capturing local disease patterns such as spots, necrotic regions, discoloration, and mildew-like textures. Kunduracioglu and Pacal (2024) investigated deep learning models for grape leaf disease classification, while Pacal and Işık (2024) compared CNN and Vision Transformer models for corn leaf disease identification. These studies show that CNNs remain strong baselines for agricultural image classification tasks, especially when the disease classes are visually separable through local texture and color cues. However, CNN-based models may vary considerably in computational cost depending on architectural depth, feature reuse strategy, and multi-scale design.

Recent work has increasingly explored Transformer-based and hybrid architectures for plant disease recognition. The motivation behind these models is that disease symptoms may not always be localized in a single region; instead, diagnostic cues can appear across multiple areas of a leaf, stem, or fruit. F. Wang et al. (2024) improved a Swin Transformer model for vegetable foliar disease identification and reported strong classification performance. Similarly, Wang Xuewei and Liu Jun (2025) developed CucumberDet by incorporating a Swin Transformer backbone to improve feature representation for small disease targets. These studies suggest that attention-based models can be useful when global context and multi-region symptom patterns are important.

Hybrid CNN-Transformer models have also been proposed to combine local and global feature learning. Yang et al. (2024) introduced LDI-NET, a framework that uses CNN and Transformer components for plant type, disease, and severity identification. Iqbal (2025) proposed PlantHealthNet, a multi-stage framework involving Swin Transformer, Detection Transformer, and SAM2-UNet components for disease diagnosis, localization, and severity estimation. Such models may improve representation capacity, but their increased architectural complexity can make them harder to deploy in practical agricultural settings unless computational cost, inference time, and memory demand are carefully considered.

Several cucumber-specific studies have reported high classification accuracy, but their experimental settings are often difficult to compare directly. Differences in dataset source, class definition, image acquisition conditions, split strategy, preprocessing, augmentation, and evaluation metrics can strongly affect the reported results. For example, a model tested on a controlled public dataset may not perform similarly on field-acquired images with complex backgrounds, variable illumination, occlusion, or overlapping symptoms. Therefore, accuracy alone is not sufficient for assessing the practical value of a disease recognition model.

A further limitation in the current literature is that computational efficiency is often treated as a secondary issue. Many studies prioritize the highest possible classification accuracy, whereas fewer studies examine how accuracy changes with parameter count, GFLOPs, and model size. This is important for cucumber disease recognition because practical systems may need to operate on mobile phones, embedded boards, or low-power agricultural monitoring devices. In such scenarios, a smaller model with slightly lower accuracy may be more useful than a larger model that requires substantially higher computational resources.

The present study addresses this gap by comparing four pretrained architectures under the same experimental protocol: DenseNet201, Inception v4, ConvNeXt v2 Base, and DeiT Base. DenseNet201 and Inception v4 are used as conventional CNN-based models with different complexity levels. ConvNeXt v2 Base is evaluated as a modern convolutional architecture, while

DeiT Base is included as a Transformer-based model. Instead of proposing a new architecture, this study focuses on a controlled comparison of predictive performance and computational complexity. This design allows the models to be assessed not only by accuracy, precision, recall, and F1-score, but also by parameter count and GFLOPs, which are important for model selection in resource-constrained agricultural applications.

2. Materials and Methods

Dataset Description and Data Partitioning

This study used the publicly available Cucumber Disease Recognition Dataset obtained from the Kaggle repository. The dataset contains 7,689 images from eight cucumber health categories: Anthracnose, Bacterial Wilt, Belly Rot, Downy Mildew, Fresh Cucumber, Fresh Leaf, Gummy Stem Blight, and Pythium Fruit Rot. Six categories represent disease conditions, while two categories correspond to healthy cucumber samples. The class-wise distribution and the train-validation-test split are given in Table 1. Representative examples from each class are shown in Figure 1.

Figure 1
Representative images from the cucumber disease dataset

Figure 1 shows sample images from the eight categories used in this study, including six diseased classes and two healthy classes. Visual differences among classes include leaf discoloration, necrotic regions, fruit surface damage, mildew-like patterns, and healthy leaf or fruit appearance.

The dataset was divided into training, validation, and test subsets using a 70%, 15%, and 15% split, respectively. This partition resulted in 5,382 training images, 1,153 validation images, and 1,154 test images. The same split was used for all evaluated architectures to ensure that model comparisons were made under identical data conditions. The validation set was used to monitor training behaviour, while the test set was used only for final performance evaluation.

Although the class counts are nearly balanced, this does not remove all possible sources of bias. Public plant disease datasets may contain visually similar samples, repeated acquisition conditions, or near-duplicate images.

Table 1
Class-wise distribution of the cucumber disease dataset

Class	Total	Train (70%)	Validation (15%)	Test (15%)
Anthracnose	960	672	144	144
Bacterial Wilt	960	672	144	144
Belly Rot	960	672	144	144
Downy Mildew	960	672	144	144
Fresh Cucumber	960	672	144	144
Fresh Leaf	960	672	144	144
Gummy Stem Blight	960	672	144	144
Pythium Fruit Rot	969	678	145	146
Total	7689	5382	1153	1154

Image Preprocessing and Data Augmentation

All images were resized to 224 × 224 pixels before being used as model input. This size was selected to provide a common input resolution for all evaluated architectures. Pixel values were scaled to the [0, 1] range before training. The same preprocessing pipeline was applied to DenseNet201, Inception v4, ConvNeXt v2 Base, and DeiT Base.

Data augmentation was applied only to the training subset. The validation and test subsets were not augmented. The augmentation operations included random horizontal flipping, random vertical flipping, random rotation up to 20 degrees, and random zooming up to 15%. These transformations were selected because they introduce moderate spatial variation while preserving the disease-related visual characteristics of cucumber leaves and fruits. Similar augmentation practices are commonly used in image-based plant disease studies to reduce sensitivity to acquisition and orientation differences (Mumuni et al., 2024; Z. Wang et al., 2024).

No augmentation was applied before data partitioning. Applying augmentation before data partitioning may introduce visually related samples into both training and evaluation subsets; therefore, augmentation was restricted to the training set after splitting.

Evaluated Architectures

The evaluated architectures are summarized in Table 2. The study included two conventional CNN models, one modern convolutional model, and one Transformer-based model. DenseNet201 and Inception v4 were selected as CNN architectures with different complexity levels. ConvNeXt v2 Base was evaluated as a modern ConvNet. Although it adopts several design choices associated with recent vision architectures, it remains convolution-based and was not treated as a Vision Transformer. DeiT Base was included as the Transformer-based comparator.

Table 2
Evaluated architectures and their role in the comparative analysis

Model	Architectural family	Main characteristic	Role in this study	Reference
DenseNet201	CNN	Dense feature reuse	Compact CNN comparator	Huang et al. (2016)
Inception v4	CNN	Multi-scale convolutional modules	Larger CNN comparator	Szegedy et al. (2016)

ConvNeXt v2 Base	Modern ConvNet	Modernized convolutional design	Modern ConvNet comparator	Woo et al. (2023)
DeiT Base	Vision Transformer	Patch-based self-attention	Transformer-based comparator	Touvron et al. (2020)

For CNN-based architectures, local visual patterns are extracted through convolutional kernels. The convolution operation can be written as Eq. (1):

$$\mathrm{X}_k^{(l+1)} = \sigma\left(\sum_{c=1}^{C} \mathrm{W}_{k,c}^{(l)} * \mathrm{X}_c^{(l)} + b_k^{(l)}\right), \qquad (1)$$

where $\mathrm{X}_c^{(l)}$denotes the c-th input feature map at layer l, $\mathrm{W}_{k,c}^{(l)}$is the convolution kernel, $b_k^{(l)}$is the bias term, $*$ denotes convolution, and $\sigma(\cdot)$is the activation function. This operation represents the local feature extraction principle used by CNN-based models such as DenseNet201 and Inception v4 (Huang et al., n.d.; Szegedy et al., 2016).

For Transformer-based image classification, the image is represented as a sequence of patches, and patch interactions are modeled using self-attention. The scaled dot-product attention operation is given in Eq. (2):

$$\mathrm{Attention}(\mathrm{Q}, \mathrm{K}, \mathrm{V}) = \mathrm{softmax}\left(\frac{\mathrm{QK}^T}{\sqrt{d_k}}\right)\mathrm{V}, \qquad (2)$$

where Q, K, and Vrepresent query, key, and value matrices, respectively, and $d_k$denotes the dimensionality of the key vectors. DeiT Base uses this attention mechanism to model relationships between spatially separated image patches (Touvron et al., 2020).

Hybrid CNN–Transformer models are discussed in the literature because they combine local convolutional features with attention-based global representations. A general feature-fusion formulation is shown in Eq. (3):

$$\mathrm{z} = \phi\left(\left[f_{\mathrm{CNN}}(\mathrm{x}); f_{\mathrm{ViT}}(\mathrm{x})\right]\right), \hat{\mathrm{y}} = \mathrm{softmax}(\mathrm{W}_c\mathrm{z}+\mathrm{b}_c), \qquad (3)$$

where $f_{\mathrm{CNN}}(\mathbf{x})$denotes convolutional feature extraction, $f_{\mathrm{ViT}}(\mathbf{x})$denotes Transformer-based feature extraction, $[\cdot;\cdot]$ indicates feature concatenation, $\phi(\cdot)$is a fusion function, and $\hat{\mathbf{y}}$is the predicted class-probability vector. This formulation is included only to clarify the hybrid design family discussed in the related work. The present study does not propose or train a new hybrid architecture.

Transfer Learning Strategy

Transfer learning was used for all four models. Each architecture was initialized with ImageNet-pretrained weights. The original classification layer was replaced with a new task-specific output layer containing eight units, corresponding to the eight-cucumber disease and healthy classes.

Training was carried out in two stages. In the first stage, the pretrained feature extractor was frozen, and only the newly added classification layer was trained. In the second stage, the full model was

fine-tuned using a lower learning rate. The same transfer learning strategy was used for all architectures to reduce differences caused by the training procedure rather than the model design.

Training Configuration

The training configuration used for all evaluated models is summarized in Table 3. All experiments were implemented in Python using PyTorch. Training was performed using an NVIDIA GeForce RTX 5090 GPU. Adam was used as the optimizer, and the initial learning rate during fine-tuning was set to 1×10^{-4}. The batch size was fixed at 16, and each model was trained for a maximum of 300 epochs.

A learning-rate scheduler was used during training. When the validation loss stopped improving, the learning rate was reduced by a factor of 0.1. The same input size, optimizer, batch size, split ratio, and evaluation procedure were used for all models.

Table 3
Training configuration used for all evaluated models

Configuration item	Setting
Framework	PyTorch
Programming language	Python
Hardware accelerator	NVIDIA GeForce RTX 5090 GPU
Input size	224 × 224 pixels
Pretraining	ImageNet-pretrained weights
Output classes	8
Train/validation/test split	70% / 15% / 15%
Optimizer	Adam
Initial fine-tuning learning rate	1×10^{-4}
Batch size	16
Maximum epochs	300
Learning-rate schedule	Reduced by 0.1 after validation-loss plateau
Data augmentation	Applied only to training images
Final evaluation	Held-out test set

Performance Evaluation Metrics

The evaluation metrics and computational indicators used in this study are listed in Table 4. Classification performance was assessed using accuracy, precision, recall, and F1-score. Parameter count and GFLOPs were used to compare computational complexity.

Table 4
Evaluation metrics and computational indicators used in this study

Metric / indicator	Purpose	Interpretation
Accuracy	Measures the overall correct classification rate	Higher values indicate better overall classification performance
Precision	Measures the correctness of positive predictions	Useful for assessing false-positive behaviour

Recall	Measures the ability to identify class samples	Useful for assessing missed samples
F1-score	Combines precision and recall	Useful when precision and recall are considered together
Parameters	Estimates model size	Lower values indicate a more compact model
GFLOPs	Estimates computational workload	Lower values indicate lower computational demand

The classification metrics were computed using Eqs. (4)–(7). In these equations, TP, TN, FP, and FN denote true positives, true negatives, false positives, and false negatives, respectively.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}, \quad (4)$$

$$Precision = \frac{TP}{TP + FP}, \quad (5)$$

$$Recall = \frac{TP}{TP + FN}, \quad (6)$$

$$F1 - score = \frac{2 \times Precision \times Recall}{Precision + Recall}. \quad (7)$$

3. Results

Overall Classification Performance

The test-set results of the evaluated models are presented in Table 5. The comparison includes accuracy, precision, recall, F1-score, parameter count, and GFLOPs. These measures provide a joint view of predictive performance and computational demand. Since all models were trained and evaluated using the same dataset split, input size, preprocessing strategy, and evaluation protocol, the differences in Table 5 mainly reflect model-level behaviour under the adopted experimental setting.

Table 5
Test-set classification performance and computational complexity of the evaluated models

Models	Accuracy	Precision	Recall	F1-score	Params	GFLOPs
ConvNeXt v2 (Woo et al., 2023)	0.9913	0.9914	0.9913	0.9913	87.70M	30.7075
DeiT Base (Touvron et al., 2020)	0.9957	0.9957	0.9957	0.9957	85.80M	33.6955
DenseNet 201 (Huang et al., 2016	0.9846	0.9772	0.9772	0.9772	18.11M	8.5795
Inception v4 (Szegedy et al., 2016)	0.9948	0.9949	0.9948	0.9948	41.16M	12.2450

DeiT Base achieved the highest performance among the evaluated architectures, with an accuracy, precision, recall, and F1-score of 0.9957. Inception v4 followed closely, reaching an accuracy of 0.9948 and an F1-score of 0.9948. ConvNeXt v2 Base also produced a high classification score, with an accuracy of 0.9913. DenseNet201 obtained the lowest accuracy among the four models, but its accuracy remained high at 0.9846.

The small difference between DeiT Base and Inception v4 indicates that the dataset can be classified accurately by both Transformer-based and convolutional architectures. However, this result should not be interpreted as evidence that one architectural family is universally superior. The difference between 0.9957 and 0.9948 is small, and additional repeated runs or statistical testing would be required to determine whether this difference is practically meaningful.

Accuracy–Complexity Trade-off

The computational cost values in Table 5 show that high classification performance was achieved with different levels of model complexity. DeiT Base produced the highest accuracy but required 85.80M parameters and 33.6955 GFLOPs. ConvNeXt v2 Base had a similar parameter count, with 87.70M parameters, and required 30.7075 GFLOPs. Inception v4 reached a test accuracy close to DeiT Base while using 41.16M parameters and 12.2450 GFLOPs. DenseNet201 was the most compact model, requiring only 18.11M parameters and 8.5795 GFLOPs.

These results show that the most accurate model is not necessarily the most efficient model. DeiT Base may be preferable when the main objective is to maximize classification accuracy under the current experimental setting. In contrast, DenseNet201 may be more suitable when computational cost is a major constraint. Inception v4 appears to offer a useful balance between performance and complexity, since its accuracy was close to DeiT Base while requiring substantially fewer GFLOPs.

However, parameter count and GFLOPs should not be treated as complete deployment indicators. They provide useful architecture-level information, but they do not directly measure inference latency, memory consumption, throughput, or energy use on target devices.

Confusion Matrix Analysis

To examine class-level prediction behaviour, the confusion matrix of the best-performing model, DeiT Base, is shown in Figure 2. The diagonal dominance of the matrix indicates that most test samples were correctly assigned to their true classes. Only a small number of errors appeared outside the diagonal, suggesting that the model made limited confusion among the eight cucumber categories.

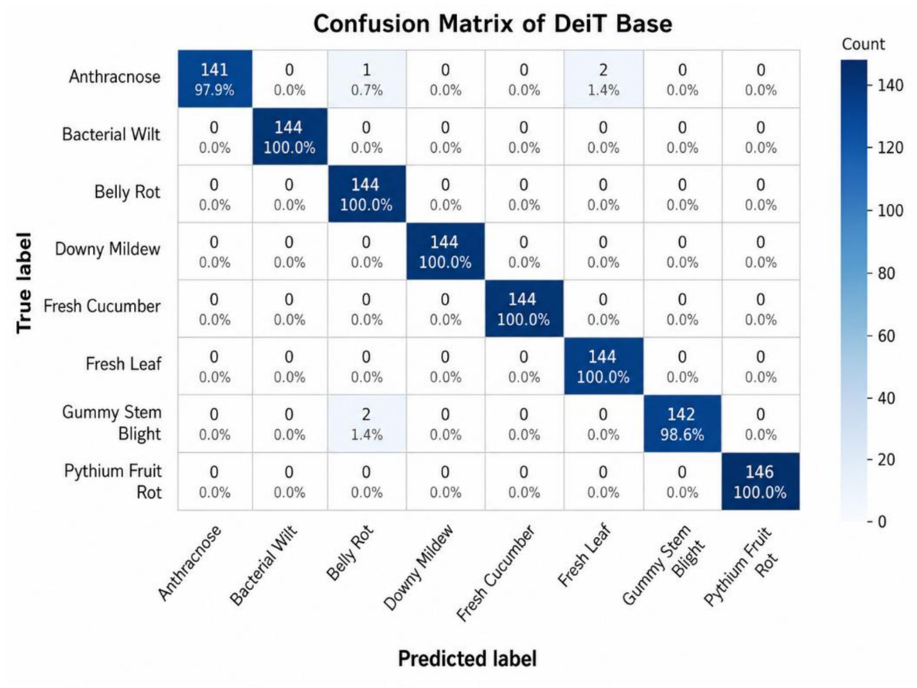

Figure 2
Confusion matrix of DeiT Base on the held-out test set

Figure 2 shows that the DeiT Base model correctly classified 1149 of 1154 test images, corresponding to an overall accuracy of 99.57%. At the class level, Bacterial Wilt, Belly Rot, Downy Mildew, Fresh Cucumber, Fresh Leaf, and Pythium Fruit Rot achieved perfect class-wise recall, with 144/144, 144/144, 144/144, 144/144, 144/144, and 146/146 true-positive predictions, respectively. However, perfect recall did not always coincide with perfect precision. For example, the Belly Rot class received three false-positive predictions, including one Anthracnose sample and two Gummy Stem Blight samples, while Fresh Leaf received two false-positive predictions from the Anthracnose class.

The main residual errors were concentrated in Anthracnose and Gummy Stem Blight. Anthracnose produced 141 true positives out of 144 samples (97.9%), with three false negatives, including one sample misclassified as Belly Rot and two samples misclassified as Fresh Leaf. Gummy Stem Blight yielded 142 true positives out of 144 samples (98.6%), with two false negatives, both assigned to Belly Rot. Notably, Anthracnose and Gummy Stem Blight showed high class-wise precision because no samples from other classes were incorrectly assigned to Anthracnose or Gummy Stem Blight. These findings indicate that the remaining errors were limited and were mainly associated with visually similar disease categories, particularly where lesion appearance, necrotic texture, or surface deterioration overlapped across classes.

4. Discussion

The results indicate that cucumber disease classification can be performed with high accuracy using different architectural families when the models are trained under the same experimental protocol. As shown in Table 5, DeiT Base achieved the highest test-set performance, while Inception v4 produced a very close result with a lower computational burden. This narrow difference suggests that the present dataset is not exclusively favourable to a single model family. Both convolutional and Transformer-based representations appear to capture the visual patterns needed for separating the eight cucumber classes. However, the small gap between DeiT Base and Inception v4 should be interpreted within the limits of the current split, since repeated runs and statistical testing were not included.

The computational comparison gives a more practical view of the results. DeiT Base and ConvNeXt v2 Base required substantially higher GFLOPs than DenseNet201 and Inception v4, whereas DenseNet201 was the most compact architecture among the evaluated models. This pattern shows that the highest classification score does not automatically correspond to the most suitable model for practical use. In server-side or laboratory settings, DeiT Base may be preferred when the main objective is maximum test-set performance. In more resource-limited settings, DenseNet201 or Inception v4 may be more appropriate depending on the acceptable balance between accuracy and computational cost. Since parameter count and GFLOPs are architecture-level indicators, they should be complemented with latency, memory, and energy measurements before making deployment-oriented decisions.

The class-level behaviour in Figure 2 is consistent with the high overall performance reported in Table 5. Most test images were correctly assigned to their true classes, and the remaining errors were concentrated in a small number of visually related categories. Anthracnose and Gummy Stem Blight accounted for the main false-negative cases, while Belly Rot and Fresh Leaf received a small number of false-positive predictions. This pattern is plausible because cucumber diseases can share similar surface discoloration, necrotic texture, and tissue deterioration patterns, especially when symptoms are mild or partially overlapping. Even so, the current interpretation is based on the confusion matrix rather than expert inspection of misclassified images. Therefore, the findings should be viewed as strong within-dataset evidence, while external validation with field-acquired images is still needed to assess robustness under natural agricultural conditions.

5. Limitations and Future Work

The main limitation of this study is its reliance on a single public dataset. Although the dataset is nearly balanced, it may not represent the full variability of field conditions. In practical agricultural settings, images may include strong illumination changes, shadows, occlusion, overlapping leaves, different cameras, background clutter, and disease symptoms at different stages. Therefore, the reported results should be interpreted as within-dataset performance rather than direct evidence of field-level generalization.

Second, the study does not report duplicate or near-duplicate image screening, repeated training with different random seeds, confidence intervals, or statistical significance testing. These analyses are important because the reported accuracies are very high and the performance gap between DeiT Base and Inception v4 is small. Future studies should include repeated runs, mean ± standard deviation reporting, and statistical testing to determine whether the observed differences between models are stable and meaningful.

Third, computational efficiency was evaluated using parameter count and GFLOPs, but these indicators do not fully describe deployment performance. Actual inference speed, memory use, throughput, and energy consumption can change depending on the target hardware and software backend. Future work should therefore evaluate the models on independent field-acquired images and report device-level latency, model size, memory consumption, and energy use. Model compression methods such as pruning, quantization, and knowledge distillation may also be investigated for real-time agricultural use.

6. Conclusion

This study compared DenseNet201, Inception v4, ConvNeXt v2 Base, and DeiT Base for eight-class cucumber disease classification using a public image dataset. Under the adopted experimental protocol, DeiT Base achieved the highest test performance with an accuracy, precision, recall, and F1-score of 0.9957. Inception v4 produced a very similar result with an accuracy of 0.9948, while ConvNeXt v2 Base reached 0.9913. DenseNet201 achieved 0.9846 accuracy and had the lowest computational cost among the evaluated models. The results show that high classification accuracy can be obtained with both convolutional and Transformer-based architectures on this dataset. However, accuracy alone is not sufficient for model selection. DeiT Base may be preferred when maximum predictive performance is required, whereas DenseNet201 is more suitable when computational cost is the main constraint. Inception v4 appears to offer a useful balance between accuracy and complexity. Since the study is limited to a single public dataset and does not include external validation or device-level testing, the findings should be viewed as a controlled benchmark rather than proof of deployment readiness.

Declarations

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The authors received no specific funding for this study.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability

The dataset used in this study is publicly available from the Kaggle repository under the title Cucumber Disease Recognition Dataset. The dataset contains cucumber disease and healthy-category images used for the eight-class classification experiments.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, AI-assisted tools were used only for language editing, grammar correction, and improving the clarity of academic expression. These tools were not used to generate the scientific methodology, experimental results, data analysis, model outputs, figures, or conclusions. All content was reviewed, verified, and approved by the authors, who take full responsibility for the accuracy and integrity of the manuscript.

References

Asha Rani, K. P., & Gowrishankar, S. (2024). State-of-the-Art Deep Learning Architectures for Identifying Diseases in Cucumber and Black Gram Plants. *IEEE International Conference on Data Engineering and Communication Systems, ICDECS 2024*. https://doi.org/10.1109/ICDECS59733.2023.10503021

Bilal, A., Khan, J. A., Alzahrani, A., Almohammadi, K., Alamri, M., & Liu, X. (2025). Fuzzy deep learning architecture for cucumber plant disease detection and classification. *Journal of Big Data*, *12*(1). https://doi.org/10.1186/s40537-025-01156-z

Cakmak, Y. (2025). Machine Learning Approaches for Enhanced Diagnosis of Hematological Disorders. *Computational Systems and Artificial Intelligence*, *1*(1), 8–14. https://doi.org/10.69882/ADBA.CSAI.2025072

Cakmak, Y., & Maman, A. (2025). Deep Learning for Early Diagnosis of Lung Cancer. *Computational Systems and Artificial Intelligence*, *1*(1), 20–25. https://doi.org/10.69882/ADBA.CSAI.2025074

Cakmak, Y., & Pacal, N. (2025). Deep Learning for Automated Breast Cancer Detection in Ultrasound: A Comparative Study of Four CNN Architectures. *Artificial Intelligence in Applied Sciences*, *1*(1), 13–19. https://doi.org/10.69882/ADBA.AI.2025073

Cakmak, Y., & Zeynalov, J. (2025). A Comparative Analysis of Convolutional Neural Network Architectures for Breast Cancer Classification from Mammograms. *Artificial Intelligence in Applied Sciences*, *1*(1), 28–34. https://doi.org/10.69882/ADBA.AI.2025075

Cao, Y., Sun, G., Yuan, Y., & Chen, L. (2025). Small-sample cucumber disease identification based on multimodal self-supervised learning. *Crop Protection*, *188*. https://doi.org/10.1016/j.cropro.2024.107006

Cucumber Disease Recognition Dataset. Retrieved October 10, 2025, from https://www.kaggle.com/datasets/sujaykapadnis/cucumber-disease-recognition-dataset

Emin Sahin, M., Özkaya, U., Arisoy, C., Coşar, H. İ., & Ulutaş, H. (2025). CucuNetCNNs: Application of novel ensemble deep neural networks for classification of cucumber leaf disease. *Ain Shams Engineering Journal*, *16*(5). https://doi.org/10.1016/j.asej.2025.103380

Huang, G., Liu, Z., Van Der Maaten, L., & Weinberger, K. Q. 2016. *Densely Connected Convolutional Networks*. Retrieved July 23, 2025, from https://github.com/liuzhuang13/DenseNet.

Iqbal, A. (2025). PlantHealthNet: Transformer-Enhanced Hybrid Models for Disease Diagnosis and Severity Estimation in Agriculture. *IEEE Access*, *13*, 101160–101176. https://doi.org/10.1109/ACCESS.2025.3576990

Jain, P., Gupta, V. K., Sharma, G., Dhiman, G., Meena, J., & Singh, M. K. (2024). Detection of Cucumber Diseases using Deep Learning models. *2024 5th IEEE Global Conference for*

Advancement in Technology, GCAT 2024. https://doi.org/10.1109/GCAT62922.2024.10924118

Kumar, R. R., Jain, A. K., Sharma, V., Midha, M., & Das, P. (2024). Enhancing Cucumber Leaf Disease Severity Prediction through Convolutional Neural Networks and Random Forest Integration. *2024 5th International Conference for Emerging Technology, INCET 2024*. https://doi.org/10.1109/INCET61516.2024.10593479

Kunduracioglu, I., & Pacal, I. (2024). Advancements in deep learning for accurate classification of grape leaves and diagnosis of grape diseases. *Journal of Plant Diseases and Protection*, *131*(3), 1061–1080. https://doi.org/10.1007/S41348-024-00896-Z/TABLES/7

Li, R., Su, X., Zhang, H., Zhang, X., Yao, Y., Zhou, S., Zhang, B., Ye, M., & Lv, C. (2024). Integration of Diffusion Transformer and Knowledge Graph for Efficient Cucumber Disease Detection in Agriculture. *Plants*, *13*(17). https://doi.org/10.3390/plants13172435

Liu, Y., Lan, Y., & Chen, X. (2025). Partial convolutional biformer: A transformer architecture for diagnosing crop diseases under complex backgrounds. *Crop Protection*, *193*. https://doi.org/10.1016/j.cropro.2024.107007

Mumuni, A., Mumuni, F., & Gerrar, N. K. (2024). A Survey of Synthetic Data Augmentation Methods in Machine Vision. *Machine Intelligence Research 2024 21:5*, *21*(5), 831–869. https://doi.org/10.1007/S11633-022-1411-7

Pacal, I. (2024). Enhancing crop productivity and sustainability through disease identification in maize leaves: Exploiting a large dataset with an advanced vision transformer model. *Expert Systems with Applications*, *238*, 122099. https://doi.org/10.1016/J.ESWA.2023.122099

Pacal, I., Kunduracioglu, I., Alma, M. H., Deveci, M., Kadry, S., Nedoma, J., Slany, V., & Martinek, R. (2024). A systematic review of deep learning techniques for plant diseases. *Artificial Intelligence Review 2024 57:11*, *57*(11), 1–39. https://doi.org/10.1007/S10462-024-10944-7

Pacal, I., & Işık, G. (2024). Utilizing convolutional neural networks and vision transformers for precise corn leaf disease identification. *Neural Computing and Applications*, *37*(4), 2479–2496. https://doi.org/10.1007/S00521-024-10769-Z/TABLES/5

Pradhan, G., Sharma, R. T., Shah, A. K., & Kukreja, V. (2024). Deep Learning for Cucumber Agriculture: A Hybrid CNN-SVM System for Disease Identification. *2024 International Conference on Automation and Computation, AUTOCOM 2024*, 57–61. https://doi.org/10.1109/AUTOCOM60220.2024.10486173

Rahman, M. S., Ahamed, A., Pranto, M. N., Islam, M. A., Al Masum, A., Al-Sakib, A., Rahman, S. M. A., Haque, R., & Rahman, S. (2024). Effective Disease Recognition in Cucumbers: A Web-Based Application Using Transfer Learning Models. *2024 IEEE 3rd International Conference on Robotics, Automation, Artificial-Intelligence and Internet-of-Things, RAAICON 2024 - Proceedings*, 59–64. https://doi.org/10.1109/RAAICON64172.2024.10928353

Shrestha, T. E., Aurnob, A. R., Tanim, S. A., Islam, M., & Nur, K. (2024). Revolutionizing Cucumber Agriculture: AI for Precision Classification of Leaf Diseases. *Proceedings - 6th International Conference on Electrical Engineering and Information and Communication Technology, ICEEICT 2024*, 776–781. https://doi.org/10.1109/ICEEICT62016.2024.10534530

Singh, A. K., Rao, A., Chattopadhyay, P., Maurya, R., & Singh, L. (2024). Effective plant disease diagnosis using Vision Transformer trained with leafy-generative adversarial network-generated images. *Expert Systems with Applications*, *254*. https://doi.org/10.1016/j.eswa.2024.124387

Szegedy, C., Ioffe, S., Vanhoucke, V., & Alemi, A. A. 2016. *Inception-v4, Inception-ResNet and the Impact of Residual Connections on Learning*. Retrieved July 23, 2025, from www.aaai.org

Touvron, H., Cord, M., Douze, M., Massa, F., Sablayrolles, A., Jégou, H., & Ai, F. (2020). *Training data-efficient image transformers & distillation through attention*.

Wang, F., Wang, Y., Liu, M., Chen, W., Wang, Y., & Xi, Y. (2024). Vegetable Disease Identification Algorithm Based on Improved Swin Transformer. *Proceedings of 2024 8th Asian Conference*

on Artificial Intelligence Technology, ACAIT 2024, 1841–1845. https://doi.org/10.1109/ACAIT63902.2024.11022041

Wang Xuewei, & Liu Jun. (2024). *Detection of small targets in cucumber disease images through global information perception and feature fusion _ Enhanced Reader*.

Wang, Y., Li, T., Chen, T., Zhang, X., Taha, M. F., Yang, N., Mao, H., & Shi, Q. (2024). Cucumber Downy Mildew Disease Prediction Using a CNN-LSTM Approach. *Agriculture (Switzerland)*, *14*(7). https://doi.org/10.3390/agriculture14071155

Wang, Z., Wang, P., Liu, K., Wang, P., Fu, Y., Lu, C.-T., Aggarwal, C. C., Pei, J., & Zhou, Y. (2024). *A Comprehensive Survey on Data Augmentation*. https://arxiv.org/abs/2405.09591v3

Woo, S., Debnath, S., Hu, R., Chen, X., Liu, Z., Kweon, I. S., & Xie, S. (2023). ConvNeXt V2: Co-designing and Scaling ConvNets with Masked Autoencoders. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, *2023-June*, 16133–16142. https://doi.org/10.1109/CVPR52729.2023.01548

Yang, B., Li, M., Li, F., Wang, Y., Liang, Q., Zhao, R., Li, C., & Wang, J. (2024). A novel plant type, leaf disease and severity identification framework using CNN and transformer with multi-label method. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-62452-x

Zeng, Z., Mahmood, T., Wang, Y., Rehman, A., & Mujahid, M. A. (2025). AI-driven smart agriculture using hybrid transformer-CNN for real time disease detection in sustainable farming. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-025-10537-6

Zeynalov, J., Çakmak, Y., & Paçal, İ. (2025). Automated Apple Leaf Disease Classification Using Deep Convolutional Neural Networks: A Comparative Study on the Plant Village Dataset. *Journal of Computer Science and Digital Technologies*, *1*(1), 5–17. https://doi.org/10.61640/jcsdt.2025.0601

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TEXNİKA ELMLƏRİ

TECHNICAL SCIENCES

Real-Time traffic Management Using Big Data and IoT Technologies

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Abstract. *The rapid growth of urbanization and vehicle ownership has intensified traffic congestion and reduced the efficiency of conventional traffic management systems. Traditional approaches, which rely on static data and predefined control strategies, are insufficient to handle the dynamic nature of modern urban traffic networks. In this context, Big Data and Internet of Things (IoT) technologies provide new opportunities for real-time traffic monitoring, analysis, and control. This study proposes a real-time traffic management framework based on the integration of Big Data analytics and IoT technologies. Real-time traffic data are collected from multiple IoT-based sources, including traffic sensors, cameras, and GPS-enabled vehicles. The collected data are processed using scalable Big Data platforms to support real-time traffic state estimation, congestion detection, and adaptive traffic control. Key traffic performance indicators such as average speed, traffic flow, travel delay, and congestion index are used to evaluate system effectiveness. The results demonstrate that the proposed real-time traffic management approach significantly improves traffic performance. Average vehicle speed and traffic flow increase, while travel delay and congestion levels decrease noticeably compared to conventional traffic management strategies. Visualization techniques, including line and column charts, further enhance situational awareness and support timely decision-making. The findings confirm that Big Data and IoT-based real-time traffic management systems play a crucial role in improving traffic efficiency, road safety, and sustainable urban mobility.*

Keywords: *real-time traffic management, big data analytics, internet of things, intelligent transportation systems, traffic congestion, smart cities*

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Böyük məlumat və IoT texnologiyalarından istifadə etməklə real vaxt rejimində nəqliyyat axınının idarə edilməsi

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Xülasə. *Urbanizasiyanın və nəqliyyat vasitələrinin sayının sürətlə artması yol hərəkətində sıxlığın yüksəlməsinə və ənənəvi nəqliyyat idarəetmə sistemlərinin səmərəliliyinin azalmasına səbəb olmuşdur. Statik məlumatlara və əvvəlcədən müəyyən edilmiş idarəetmə strategiyalarına əsaslanan ənənəvi yanaşmalar müasir şəhər nəqliyyat şəbəkələrinin dinamik xarakterini effektiv şəkildə idarə*

etmək üçün kifayət etmir. Bu baxımdan, böyük məlumat (Big Data) və əşyaların interneti (Internet of Things – IoT) texnologiyaları yol hərəkətinin real vaxt rejimində monitorinqi, təhlili və idarə olunması üçün yeni imkanlar yaradır. Bu tədqiqat böyük məlumat analitikası və IoT texnologiyalarının inteqrasiyasına əsaslanan real vaxt rejimində nəqliyyat axınının idarə edilməsi çərçivəsini təklif edir. Real vaxt trafik məlumatları yol hərəkəti sensorları, videomüşahidə kameraları və GPS ilə təchiz edilmiş nəqliyyat vasitələri daxil olmaqla müxtəlif IoT əsaslı mənbələrdən toplanır. Toplanmış məlumatlar real vaxt rejimində yol hərəkətinin vəziyyətinin qiymətləndirilməsi, sıxlığın aşkarlanması və adaptiv nəqliyyat idarəetməsinin həyata keçirilməsi məqsədilə miqyaslana bilən böyük məlumat platformalarında emal olunur. Sistemin effektivliyinin qiymətləndirilməsi üçün orta hərəkət sürəti, nəqliyyat axınının intensivliyi, səyahət gecikməsi və tıxac indeksi kimi əsas yol hərəkəti göstəricilərindən istifadə edilir. Nəticələr göstərir ki, təklif olunan real vaxt nəqliyyat idarəetmə yanaşması yol hərəkətinin göstəricilərini əhəmiyyətli dərəcədə yaxşılaşdırır. Ənənəvi nəqliyyat idarəetmə strategiyaları ilə müqayisədə nəqliyyat vasitələrinin orta sürəti və nəqliyyat axınının intensivliyi artır, səyahət gecikmələri və tıxac səviyyəsi isə nəzərəçarpacaq dərəcədə azalır. Xətti və sütun diaqramları kimi vizuallaşdırma üsulları situasiya məlumatlılığını artırır və operativ qərar qəbulunu dəstəkləyir. Əldə olunan nəticələr təsdiq edir ki, böyük məlumat və IoT texnologiyalarına əsaslanan real vaxt nəqliyyat idarəetmə sistemləri nəqliyyatın səmərəliliyinin yüksəldilməsində, yol təhlükəsizliyinin artırılmasında və dayanıqlı şəhər mobilliyinin təmin edilməsində mühüm rol oynayır.

Açar sözlər: *real vaxt rejimində nəqliyyatın idarə edilməsi, böyük məlumat analitikası, əşyaların interneti (IoT), intellektual nəqliyyat sistemləri, yol hərəkəti sıxlığı, ağıllı şəhərlər*

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Introduction

Rapid urbanization and the continuous increase in vehicle ownership have become major challenges for transportation systems in cities around the world. As urban populations grow, existing road infrastructures are often unable to accommodate increasing traffic demand, leading to severe congestion, longer travel times, higher fuel consumption, and increased air pollution. These issues not only reduce the efficiency of urban mobility but also negatively affect economic productivity, environmental sustainability, and the overall quality of life in urban areas (Zhang et al., 2011).

Conventional traffic management systems are primarily based on static data, historical traffic patterns, and predefined control strategies. Traffic signal timings, route planning, and congestion mitigation measures are typically designed offline and updated infrequently. While such approaches may perform adequately under stable traffic conditions, they are largely ineffective in handling the highly dynamic and unpredictable nature of modern urban traffic (Vlahogianni et al., 2004). Traffic demand fluctuates significantly due to factors such as peak-hour variations, accidents, roadworks, weather conditions, and special events. As a result, traditional traffic control systems often fail to respond promptly to real-time changes, leading to inefficient traffic operations and increased congestion.

The rapid development of Internet of Things (IoT) technologies has fundamentally transformed traffic data collection processes. IoT-enabled devices, including traffic cameras, inductive loop detectors, GPS-equipped vehicles, mobile sensors, and connected infrastructure, are capable of continuously generating large volumes of real-time traffic data. These data provide detailed information on vehicle

speed, traffic flow, density, road occupancy, and incidents across different spatial and temporal scales. However, the massive volume, high velocity, and heterogeneity of such data pose significant challenges for conventional data processing and analysis techniques (Chen et al., 2014).

Big Data analytics offers powerful tools and platforms to address these challenges by enabling scalable storage, high-speed processing, and real-time analysis of large and complex traffic datasets. By integrating Big Data analytics with IoT-based sensing technologies, traffic management systems can achieve real-time traffic state estimation, congestion detection, and predictive analysis (Lv et al., 2015). This integration enables traffic authorities to move from reactive traffic control toward proactive and adaptive traffic management strategies, allowing timely interventions before congestion becomes severe.

Real-time traffic management systems supported by Big Data and IoT technologies provide several advantages over traditional approaches. They enable dynamic traffic signal control, real-time route guidance, and rapid incident response, which collectively contribute to improved traffic flow and reduced travel delays. Moreover, by optimizing traffic operations, such systems help reduce fuel consumption and greenhouse gas emissions, supporting the goals of sustainable urban development and smart city initiatives (Zanella et al., 2014). The increasing adoption of connected and autonomous vehicles further amplifies the importance of real-time, data-driven traffic management frameworks.

Despite the significant progress in this domain, several challenges remain unresolved. Traffic data are often collected from heterogeneous sources using different standards and communication protocols, resulting in interoperability issues. Ensuring low-latency data transmission and real-time processing requires robust communication networks and high-performance computing infrastructure. In addition, concerns related to data privacy, security, and system reliability present critical barriers to large-scale deployment of real-time traffic management systems.

Motivated by these challenges and opportunities, this study focuses on real-time traffic management using the integration of Big Data analytics and IoT technologies. The main objective of this research is to investigate how real-time data collection and analytics can enhance traffic efficiency and management performance. This study proposes a structured real-time traffic management framework and evaluates its effectiveness using key traffic performance indicators. By addressing both technical and operational aspects, this research aims to contribute to the development of intelligent transportation systems that support efficient, safe, and sustainable urban mobility (Aliyev et al., 2025, p. 147).

Research

Literature review. Recent advancements in intelligent transportation systems (ITS) have led to a growing body of research focusing on real-time traffic management supported by Big Data and Internet of Things (IoT) technologies. Previous studies emphasize that the integration of real-time data sources with advanced analytics significantly enhances traffic monitoring, prediction, and control capabilities compared to traditional traffic management approaches (Xu et al., 2018).

Several researchers have highlighted the role of IoT-based sensing technologies in real-time traffic data collection. Traffic cameras, loop detectors, RFID systems, GPS-enabled vehicles, and mobile sensors are widely used to capture real-time information related to traffic volume, speed, density, and incidents. These data sources provide continuous and high-resolution insights into traffic conditions, enabling timely detection of congestion and abnormal events. However, the large-scale deployment of IoT devices also introduces challenges related to data reliability, communication latency, and sensor maintenance.

Big Data analytics has been extensively applied to process and analyze the massive volume, velocity, and variety of traffic data generated by IoT devices. Existing studies demonstrate that Big Data platforms such as distributed computing frameworks and cloud-based architectures are effective in handling real-time traffic data streams. Machine learning and data mining techniques have been employed for traffic flow prediction, congestion classification, and incident detection. These methods have shown promising results in improving prediction accuracy and decision-making efficiency, particularly in complex urban traffic networks.

Real-time traffic signal control is another key research area addressed in the literature. Adaptive signal control systems using real-time data have been shown to outperform fixed-time and actuated signal control strategies. By dynamically adjusting signal timings based on real-time traffic conditions, these systems help reduce delays, queue lengths, and travel times. Some studies have further incorporated artificial intelligence and reinforcement learning algorithms to enhance the adaptability and robustness of traffic control strategies (Li et al., 2016).

Despite these advancements, the literature also identifies several limitations and research gaps (Wang, 2010). Data heterogeneity and interoperability issues remain significant obstacles, as traffic data are often collected from diverse sources using different formats and standards. Additionally, real-time processing requirements impose high computational and communication demands on traffic management systems. Privacy and security concerns related to the collection and storage of large-scale mobility data are also increasingly emphasized in recent studies.

Overall, the existing literature confirms the potential of Big Data and IoT technologies to revolutionize real-time traffic management. However, there is a need for integrated frameworks that address technical challenges while ensuring scalability, reliability, and sustainability. This study builds upon previous research by focusing on a comprehensive real-time traffic management approach that leverages Big Data analytics and IoT technologies to improve traffic efficiency and system performance (Gubbi et al., 2013).

Methodology and system architecture. This study adopts a data-driven methodology for real-time traffic management by integrating Big Data analytics with IoT-based sensing technologies. The proposed approach consists of four main stages: data collection, data processing, real-time analytics, and traffic management decision-making. The overall system architecture is designed to support continuous data flow, low-latency processing, and adaptive traffic control (Bellemans et al., 2006).

System architecture. The proposed real-time traffic management system is based on a layered architecture, as illustrated in Figure 1.

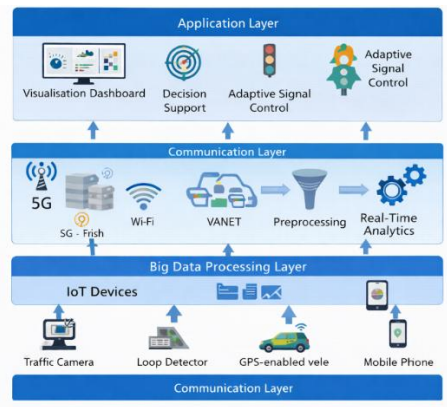

Figure 1

Architecture of the real-time traffic management system based on Big Data and IoT technologies

The architecture consists of the following layers:

1. Data Sensing Layer**:**

This layer includes IoT devices such as traffic cameras, inductive loop detectors, GPS-equipped vehicles, and mobile sensors. These devices continuously collect real-time traffic data including vehicle speed, traffic volume, road occupancy, and incident information.

2. Communication Layer**:**

Collected data are transmitted through wireless communication technologies such as 5G, Wi-Fi, and vehicular ad hoc networks (VANETs). This layer ensures reliable and low-latency data transfer.

3. Big Data Processing Layer**:**

This layer is responsible for data storage, preprocessing, and real-time analytics. Distributed computing frameworks enable scalable processing of high-volume traffic data streams.

4. Application Layer**:**

The application layer provides traffic visualization dashboards, decision support systems, and adaptive traffic signal control mechanisms.

Data collection and variables. Traffic data are collected in real time from multiple sources (Haziyev et al., 2025). The main traffic variables used in this study are summarized in Table 1**.**

Table 1
Description of real-time traffic data variables

Variable	Description	Unit
V	Average vehicle speed	km/h
Q	Traffic flow (vehicles per unit time)	veh/h
K	Traffic density	veh/km
t_d	Average travel delay	seconds
O	Road occupancy rate	%

These variables are collected at fixed time intervals (Δt) to support real-time monitoring and analysis.

Traffic flow modeling. To evaluate traffic conditions, the fundamental relationship between traffic flow, speed, and density is applied:

$$q=k\cdot v \qquad (1)$$

where
q - represents traffic flow,
k - denotes traffic density, and
v - indicates average vehicle speed.

Traffic congestion levels are classified based on threshold values of speed and density. A congestion index CI is calculated as follows:

$$CI = \frac{v_{free} - v_{current}}{v_{free}} \qquad (2)$$

where
v_{free} - is the free-flow speed, and
$v_{current}$ - is the real-time measured speed.
A higher CI value indicates more severe congestion.
Real-Time Analytics and Visualization. Real-time traffic data are analyzed using streaming analytics techniques. Time-series analysis is applied to detect traffic trends and anomalies. Visualization tools present traffic conditions using line charts and column charts**:**

- **Line charts** are used to illustrate changes in traffic speed and flow over time.
- **Column charts** are applied to compare traffic volume across different road segments or intersections.

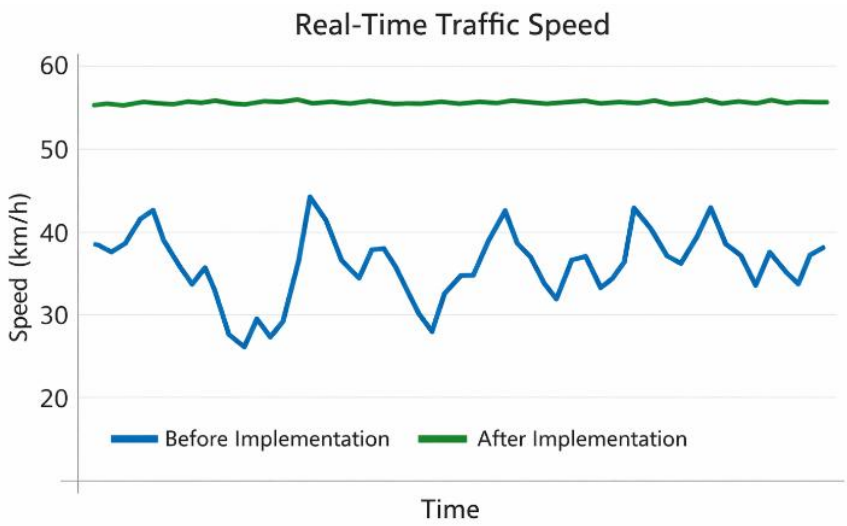

Figure 2
Example of real-time traffic speed variation illustrated using a line chart

These visualizations assist traffic operators in quickly identifying congestion hotspots and abnormal traffic patterns.

Decision-making and traffic control. Based on real-time analytics results, adaptive traffic control strategies are implemented. Traffic signal timing plans are dynamically adjusted according to current traffic demand. The signal green time G for each approach is optimized using the following formulation:

$$G_i = \frac{q_i}{\sum_{j=1}^{n} q_j} \cdot C \qquad (3)$$

where
G_i - is the green time allocated to approach i, (seconds);

q_i - is the traffic flow of approach i (vehicles per hour);

$\sum_{j=1}^{n} q_j$ - is the total traffic flow of all approaches at the intersection;

n - is the number of traffic approaches considered;

C - is the total signal cycle length (seconds).

This adaptive strategy helps reduce queue lengths, travel delays, and overall congestion.

Results and Discussion

This section presents a comprehensive analysis of the results obtained from the implementation of the proposed real-time traffic management framework based on Big Data analytics and IoT technologies. The system performance is evaluated using multiple traffic performance indicators, including average vehicle speed, traffic flow, average travel delay, and congestion index. The obtained results are compared with those of conventional traffic management approaches to assess the effectiveness of real-time, data-driven traffic control strategies.

Traffic performance evaluation. Real-time traffic data were continuously collected from IoT-based sensing devices and processed through the proposed Big Data analytics platform. The evaluation focuses on traffic conditions before and after the deployment of the real-time traffic management system. Table 2 summarizes the comparative results of key traffic performance indicators.

Table 2
Comparison of traffic performance indicators

Indicator	Before implementation	After implementation	Improvement (%)
Average speed (km/h)	32.5	41.8	+28.6
Traffic flow (veh/h)	1450	1680	+15.9
Average delay (s)	78.4	52.1	−33.5
Congestion index	0.42	0.27	−35.7

The results clearly indicate a notable improvement in overall traffic efficiency after the implementation of the proposed framework. The average vehicle speed increased significantly, reflecting smoother traffic flow and reduced stop-and-go conditions. This improvement can be attributed to real-time monitoring and adaptive traffic signal control, which enable timely responses to fluctuations in traffic demand.

Traffic flow also showed a measurable increase, suggesting that the road network was able to accommodate a higher number of vehicles per hour without causing severe congestion. This outcome demonstrates that the proposed system enhances road utilization efficiency by dynamically adjusting control strategies based on real-time traffic conditions (Aliyev, 2024, p. 30).

Furthermore, the average travel delay was substantially reduced, highlighting the effectiveness of adaptive signal timing and congestion mitigation strategies. A lower delay indicates shorter waiting times at intersections and improved travel time reliability for road users. Similarly, the congestion index decreased considerably, confirming a reduction in congestion severity across the monitored road segments.

Overall, these results validate the capability of Big Data and IoT-enabled traffic management systems to outperform traditional static control methods by providing adaptive and responsive traffic control solutions.

Time-series analysis of traffic speed. To further examine the impact of real-time traffic management, a time-series analysis of average traffic speed was conducted. Figure 3 illustrates the variation in traffic speed over time using a line chart representation.

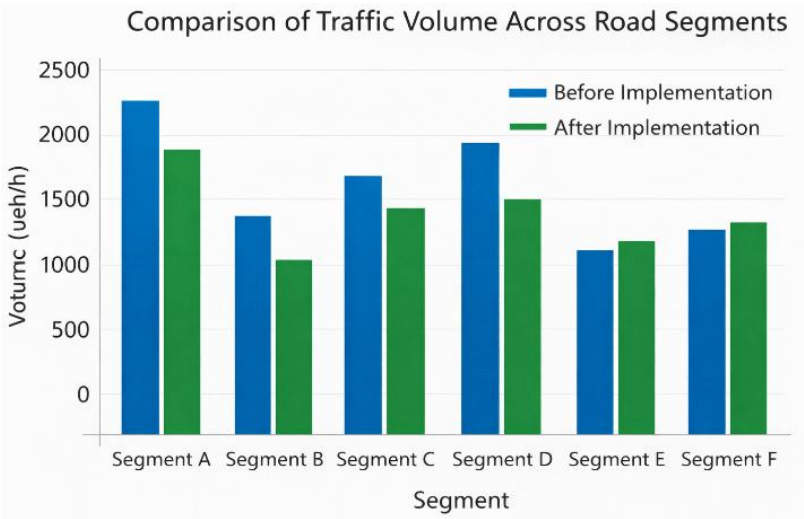

Figure 3
Real-time variation of average traffic speed illustrated using a line chart

The analysis reveals that, prior to system implementation, traffic speed exhibited frequent and sharp fluctuations, often associated with congestion, signal inefficiencies, or unexpected traffic disturbances. After deploying the proposed system, speed variations became more stable, indicating improved traffic flow consistency.

Notably, sudden drops in speed were detected earlier through real-time analytics and promptly addressed using adaptive control measures. This proactive response capability significantly reduced the duration and impact of congestion events. The smoother speed profile observed in the line chart emphasizes the importance of continuous data monitoring and real-time decision-making in modern traffic management systems.

Spatial analysis of traffic volume. In addition to temporal analysis, a spatial evaluation of traffic volume across different road segments was performed. Figure 4 presents a column chart comparing traffic flow levels on selected road segments during peak traffic periods.

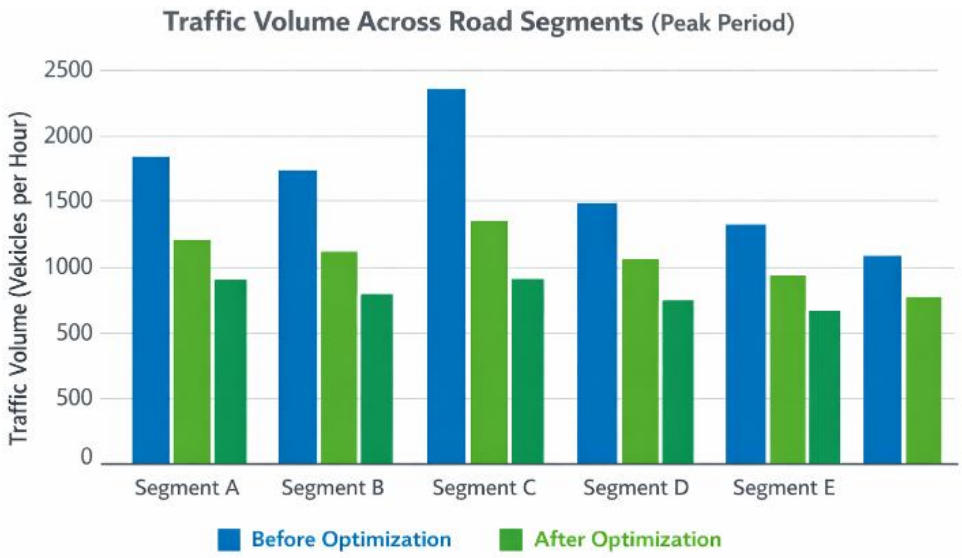

Figure 4
Comparison of traffic volume across road segments using a column chart

The results demonstrate a more balanced distribution of traffic across the network after the application of real-time traffic management strategies. Road segments that previously experienced high congestion levels showed a noticeable reduction in traffic volume. This improvement can be attributed to dynamic route guidance, traffic redistribution strategies, and optimized signal coordination.

By alleviating excessive demand on critical road segments, the proposed system enhances network-wide traffic efficiency and reduces the likelihood of localized congestion. These findings highlight the effectiveness of integrating real-time analytics with network-level traffic management decisions (Aliyev et al., 2024b, p. 257*).*

Discussion. The results obtained from this study confirm that the integration of Big Data analytics and IoT technologies significantly improves real-time traffic management performance. The observed improvements in average speed, traffic flow, and congestion levels are primarily driven by accurate real-time data acquisition, efficient data processing, and adaptive traffic control mechanisms.

Compared to conventional traffic management systems, which rely on historical data and fixed control strategies, the proposed framework offers greater flexibility and responsiveness to real-time traffic dynamics. The ability to detect congestion early and adjust control strategies accordingly plays a crucial role in reducing travel delays and improving overall traffic conditions.

However, the findings also underline several practical challenges. The large volume and high velocity of traffic data require robust and scalable computational infrastructure to ensure low-latency processing. Additionally, the reliability of IoT sensors and communication networks directly affects data accuracy and system performance. Addressing these challenges is essential for the successful deployment of real-time traffic management systems in large-scale urban environments (Aliyev et al., 2024a, p. 22).

In summary, the results demonstrate that Big Data and IoT-based real-time traffic management systems provide a promising solution for enhancing traffic efficiency, reducing congestion, and supporting sustainable urban transportation (Aliyev et al., 2024b, p. 11). *These*outcomes align with previous research findings and further emphasize the potential of intelligent transportation systems in smart city applications (Aliyev et al., 2025, p. 29).

Conclusion

This study examined the role of Big Data analytics and Internet of Things (IoT) technologies in enhancing real-time traffic management and proposed an integrated framework for real-time traffic monitoring, analysis, and adaptive control. By leveraging continuous data streams collected from heterogeneous IoT-based sources and processing them through scalable Big Data platforms, the proposed system enables timely traffic state estimation, congestion detection, and intelligent decision-making.

The experimental results demonstrate that the proposed real-time traffic management approach significantly outperforms conventional traffic control systems that rely on static data and predefined strategies. Noticeable improvements were observed across key traffic performance indicators, including increased average vehicle speed and traffic flow, as well as reduced travel delay and congestion index. These improvements indicate smoother traffic operations, better utilization of road infrastructure, and enhanced travel time reliability for road users.

One of the major strengths of the proposed framework lies in its ability to respond dynamically to rapidly changing traffic conditions. Real-time analytics and visualization tools provide traffic operators with improved situational awareness, enabling early detection of congestion and abnormal

traffic patterns. Adaptive traffic signal control based on real-time demand further contributes to congestion mitigation and network-wide traffic efficiency. As a result, the system supports not only operational efficiency but also broader objectives such as road safety improvement and reduction of fuel consumption and vehicle emissions.

From a practical perspective, the findings confirm that the integration of Big Data and IoT technologies is a key enabler for intelligent transportation systems and smart city applications. The proposed framework offers a flexible and scalable solution that can be adapted to different urban traffic environments. However, the study also highlights several challenges that must be addressed for large-scale real-world deployment. These include data heterogeneity, the need for high-performance computational infrastructure, communication reliability, and concerns related to data privacy and security.

Future research directions may focus on incorporating advanced artificial intelligence techniques, such as deep learning and reinforcement learning, to further enhance traffic prediction accuracy and control optimization. Additionally, the proposed framework can be extended to support multi-modal transportation systems, including public transport, pedestrians, and non-motorized traffic. Validation of the system in large-scale urban networks and long-term operational scenarios would also provide valuable insights into its robustness and sustainability.

In conclusion, this research contributes to the growing body of knowledge on real-time traffic management by demonstrating the effectiveness of Big Data and IoT-based solutions in improving traffic efficiency and supporting sustainable urban mobility. The proposed framework provides a solid foundation for future developments in intelligent transportation systems and offers practical guidance for traffic authorities and urban planners seeking to build smarter and more resilient transportation infrastructures.

References

Aliyev, A. (2024). Advanced methods of organization of cargo transportation. *Scientific Work, 18*(1), 27–34. https://doi.org/10.36719/2663-4619/98/27-34

Aliyev, A., Haziyev, Y., Valiyev, S., & Aliyev, S. (2024a). Transport and environmental problems. *Scientific Work, 18*(5), 20–26. https://doi.org/10.36719/2663-4619/102/20-26

Aliyev, A., Haziyev, Y., Valiyev, S., & Aliyev, S. (2024b). Transport corridors and transit potential of Azerbaijan. *Scientific Work, 18*(12), 9–13. https://doi.org/10.36719/2663-4619/109/9-13

Aliyev, A., Haziyev, Y., Valiyev, S., & Aliyev, S. (2025). The role of the transport factor in Azerbaijan's defense potential. *Scientific Work, 19*(2), 27–32. https://doi.org/10.36719/2663-4619/111/27-32

Aliyev, A., Valiyev, S., Aliyev, S., Haziyev, Y., & Orujov, T. (2024). The role of transportation and forwarding systems in the implementation of logistics operations. *Scientific Work, 18*(3), 254–260. https://doi.org/10.36719/2663-4619/100/254-260

Aliyev, A. A., Nurubeyli, T. K., Haziyev, Y. H., Valiyev, S. M., Najafov, E. T., & Mammadov, F. I. (2025). Innovative noise mitigation techniques in transportation systems: Towards sustainable urban mobility. *International Journal on Technical and Physical Problems of Engineering, 17*(2), 142–151.

Bellemans, T., De Schutter, B., & De Moor, B. (2006). Model predictive control for ramp metering of motorway traffic: A case study. *Control Engineering Practice, 14*(7), 757–767. https://doi.org/10.1016/j.conengprac.2005.03.010

Chen, M., Mao, S., & Liu, Y. (2014). Big data: A survey. *Mobile Networks and Applications, 19*(2), 171–209. https://doi.org/10.1007/s11036-013-0489-0

Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems, 29*(7), 1645–1660. https://doi.org/10.1016/j.future.2013.01.010

Haziyev, Y. H., Aliyev, A. A., Seyidova, M. M., Najafov, E. T., Orujov, T. Z., Mammadov, F. I., & Zeynalova, S. J. (2025). Predicting failures and maintenance in transportation systems using AI and data analytics. *International Journal on Technical and Physical Problems of Engineering, 17*(3), 264–274.

Li, L., Lv, Y., & Wang, F.-Y. (2016). Traffic signal timing via deep reinforcement learning. *IEEE/CAA Journal of Automatica Sinica, 3*(3), 247–254. https://doi.org/10.1109/JAS.2016.7508798

Lv, Y., Duan, Y., Kang, W., Li, Z., & Wang, F.-Y. (2015). Traffic flow prediction with big data: A deep learning approach. *IEEE Transactions on Intelligent Transportation Systems, 16*(2), 865–873. https://doi.org/10.1109/TITS.2014.2345663

Vlahogianni, E. I., Karlaftis, M. G., & Golias, J. C. (2004). Short-term traffic forecasting: Overview of objectives and methods. *Transport Reviews, 24*(5), 533–557. https://doi.org/10.1080/0144164042000195072

Wang, F.-Y. (2010). Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications. *IEEE Transactions on Intelligent Transportation Systems, 11*(3), 630–638. https://doi.org/10.1109/TITS.2010.2060218

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for smart cities. *IEEE Internet of Things Journal, 1*(1), 22–32. https://doi.org/10.1109/JIOT.2014.2306328

Zhang, J., Wang, F.-Y., Wang, K., Lin, W.-H., Xu, X., & Chen, C. (2011). Data-driven intelligent transportation systems: A survey. *IEEE Transactions on Intelligent Transportation Systems, 12*(4), 1624–1639. https://doi.org/10.1109/TITS.2011.2158001

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Multi-UAV Search Strategies for Anomaly Monitoring

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Abstract. *Teams of unmanned aerial vehicles with onboard vision are used to locate events of interest inside a bounded area, such as disaster victims, wildfire ignition points, and industrial leaks. The choice of search strategy is usually made without a formal basis. This study asks when a detection-driven adaptive strategy outperforms systematic geometric coverage. The spatial clustering of events is treated as a controlled variable generated by a Thomas cluster process. Lawnmower, spiral, and Hilbert-curve sweeps are compared against an adaptive strategy that adds bounded detection-triggered detours to a Hilbert sweep. In a 400 m arena the adaptive strategy found 23 percent more events than the best sweep under tight clustering. The advantage crossed to a deficit near a cluster scale of about 47 m. A frame-level analysis shows that this gain is not simply an artifact of the camera footprint. Co-detectability is nonetheless collinear with the clustering variable, so a second experiment separates the two effects through a minimum event separation of 90 m that exceeds the footprint diagonal. The advantage then moves from event count to detection timing. Clustered events were found 34 s earlier on average, and at the tightest clustering level half of the events were reached after 275 s rather than 483 s. Under uniform placement the detours became a bounded cost and the sweeps performed better.*

Keywords: *multi-UAV search, coverage path planning, adaptive search, spatial clustering, event detection, co-detection*

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Anomaliyaların monitorinqi üçün çoxsaylı PUA-larla axtarış strategiyaları

İlham Mirzəyev[1*], İsmayıl İsmayılov[2], Emil Sadıqov[1], Fərid Quliyev[1]

Xülasə. *Görüntü emalı sistemləri ilə təchiz olunmuş pilotsuz uçuş aparatlarından ibarət qruplardan bir çox hadisələrin, məsələn, fəlakət qurbanlarının, meşə yanğınlarının başlanğıc nöqtələrinin və sənaye sızmalarının aşkarlanması üçün istifadə olunur. Bu əməliyyatlarda axtarış strategiyasının seçimi adətən formal əsaslandırma olmadan həyata keçirilir. Bu tədqiqatda aşkarlamaya əsaslanan adaptiv strategiyanın hansı hallarda sistematik metodlardan daha yaxşı nəticə verdiyi araşdırılmışdır. Hadisələrin məkan üzrə qruplaşması Thomas klaster prosesi vasitəsilə idarə olunan dəyişən kimi modelləşdirilmişdir. Lawnmower, Spiral və Hilbert əyrisi üzrə axtarış strategiyaları Hilbert marşrutunun genişləndirilmiş adaptiv variantı ilə müqayisə edilmişdir. 400 m-lik sınaq ərazisində sıx qruplaşma şəraitində adaptiv strategiya ən yaxşı sistematik axtarış strategiyasından 23 faiz daha çox hadisə aşkar etmişdir. Klaster miqyası təxminən 47 m olduqda bu üstünlük əksinə çevrilərək çatışmazlığa keçmişdir.*

Tək bir kamera görüntüsündən aşkarlanmış hadisələr ilə bağlı analizlər göstərir ki, bu üstünlük sadəcə kameranın əhatə sahəsinin nəticəsi deyil. Bununla belə, birgə aşkarlanma qruplaşma dəyişəni ilə xətti əlaqədə olduğundan, ikinci eksperimentdə hadisələr arasında kameranın əhatə sahəsinin diaqonalını aşan 90 m-lik minimum məsafə tətbiq edilərək bu iki təsir bir-birindən ayrılmışdır. Bu halda üstünlük aşkar edilmiş hadisələrin sayından onların aşkarlanma vaxtına keçmişdir. Sıx qruplaşmış hadisələr orta hesabla 34 saniyə daha tez aşkar edilmiş və ən sıx qruplaşma səviyyəsində hadisələrin yarısına 483 saniyə əvəzinə 275 saniyədə çatılmışdır. Hadisələrin ərazi üzrə bərabər paylandığı halda isə adaptiv yanaşmadakı əlavə dövrlər xərcə çevrilmiş və sistematik axtarış strategiyaları daha yaxşı nəticə göstərmişdir.

Açar sözlər: *çox-PUA-lı axtarış, əhatəetmə marşrutunun planlaşdırılması, adaptiv axtarış, anomaliya klasterləşməsi, hadisələrin aşkar olunması, birgə aşkar olunma*

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Introduction

Large and complex areas often require frequent monitoring to detect anomalies before they lead to serious consequences. Examples include disaster victims in search-and-rescue operations, wildfire ignition points, industrial leaks, and other events of interest that may be difficult to locate quickly over a wide area. Conventional monitoring methods can be costly or limited by coverage area, weather, resolution, or revisit time. Cooperative multi-UAV teams equipped with real-time computer vision offer a flexible alternative that can be deployed on demand to search large areas and locate anomalies more rapidly.

A central question in cooperative aerial monitoring is which search strategy to use. Systematic geometric sweeps, such as lawnmower patterns and space-filling curves, guarantee complete and uniform coverage of the survey area. Detection-driven adaptive search takes a different approach and uses real-time detections to redirect UAVs toward neighboring regions. Adaptive search relies on the assumption that shared causal factors make anomalies spatially clustered. This assumption is often reasonable in industrial settings, but it is not always satisfied.

The physical basis of clustering differs across anomaly types and monitoring scenarios. In disaster response, for example, people and damaged infrastructure may occur in groups because they are affected by the same event. During wildfire monitoring, ignition points and fire-related anomalies can be spatially concentrated within areas where environmental conditions favor ignition. In industrial monitoring, leaks, equipment failures, and other faults may cluster around particular facilities, pipeline sections, or production areas. Environmental monitoring can also produce clustered observations when multiple anomalies arise from the same local source or environmental condition. In contrast, some anomalies may occur independently across the monitored area. Isolated manufacturing defects, sporadic infrastructure damage, or individual security events are examples where detecting one anomaly provides little information about the location of another. The degree of spatial clustering therefore varies across anomaly types and operating conditions, making it an important factor in deciding whether detection-driven adaptive search can provide a useful advantage over systematic coverage.

This work makes five contributions. First, it establishes a controlled evaluation framework that parameterizes anomaly clustering with a Thomas process and drives a cooperative multi-UAV search with vision-in-the-loop detections. Second, it uses a paired-seed design in a first set of experiments to compare three standard coverage geometries against a minimal and interpretable adaptive strategy. Third, it separates theoretical geometric co-detectability from realized co-detection through a frame-level analysis, which shows that the realized artifact is small, lower for the adaptive method than for the Hilbert baseline, and collinear with the clustering treatment. Fourth, it resolves this collinearity with a separation-controlled redesign in a second set of experiments, where a hard one-footprint minimum target separation moves the adaptive advantage from target count to detection latency. Fifth, it isolates the underlying search mechanism through ablation in both experiments. These contributions apply directly to offshore spill surveillance, pipeline monitoring, and facility inspection.

1.1. UAV-based monitoring

Aerial monitoring under a hard time limit is established across several application domains. A survey of civil applications lists search and rescue, remote sensing, and civil infrastructure inspection among the mature uses of unmanned aircraft (Shakhatreh et al., 2019). Search and rescue has received its own review, covering platform types, sensor payloads from thermal and RGB imaging to LiDAR, target detection methods, and the assignment of tasks across a team (Lyu et al., 2023). The breadth of that treatment shows how much of the field concerns perception and platform design rather than the order in which ground is examined. Wildfire monitoring places the same problem under a moving deadline, and one system plans fixed-wing trajectories with a variable neighborhood search metaheuristic so that a fleet can track a spreading front (Bailon-Ruiz et al., 2022). Its planner couples models of terrain, wind, and fire propagation in order to predict where the fire will be, which is the opposite regime from the static targets studied here. The oil and gas value chain presents the same structure, and UAVs are now applied across it. A recent survey of UAV-based remote sensing for the petroleum industry identifies six application areas: offshore oil spill detection, oil leakage detection, pipeline monitoring, gas-emission sensing, remote facility inspection, and environmental monitoring (Asadzadeh et al., 2022). The same survey reviews the platforms and sensor payloads commonly used in each area. Operational experience with the technology predates these surveys, and early use of unmanned aircraft for oil spill surveillance established the concept in practice (Allen & Walsh, 2008). These studies fix the operational scenario adopted here. A team of UAVs performs a time-limited patrol over a large area in which the locations of anomalies are unknown before the mission. Depending on the application, the surveyed area may include a disaster zone, a forest affected by wildfire, an industrial facility, an infrastructure corridor, or another monitored region. Anomaly detection is performed during the mission so that confirmed detections can immediately influence the search trajectory rather than being processed only after the survey is completed. This setting also motivates a modular detector interface. Any perception system that can provide confirmed anomaly positions in real time can be substituted without changing the search layer evaluated in this paper.

1.2. Coverage path planning and systematic search geometries

Coverage path planning computes a path that passes a sensor over every point of a region. An early survey of the field groups the published methods by how each one decomposes the region before a path is planned (Choset, 2001). A later survey extends that grouping and adds the methods introduced in the intervening decade (Galceran & Carreras, 2013). The version written for unmanned aircraft catalogs the simple flight patterns, including back-and-forth and spiral paths, and reports energy consumption as the main optimization criterion under the limited endurance of the platform (Cabreira et al., 2019). None of the three treats the spatial distribution of the targets as an input to the choice of pattern.

Two constructions from this literature serve as baselines here. The first is the boustrophedon decomposition, in which each cell of an exact decomposition is covered by back-and-forth motions

(Choset & Pignon, 1998). The same decomposition underpins the standard treatment of complete coverage in known spaces, where covering every cell by back-and-forth motions is reported to be provably complete (Choset, 2000). A multi-robot extension divides the cells among a team so that repeated coverage is minimized (Rekleitis et al., 2008). That partition-then-cover structure is adopted directly in this study, with one sub-region assigned to each aircraft.

The second construction is the space-filling curve. A traversal of such a curve maps two-dimensional coverage onto a locality-preserving one-dimensional ordering with minimal backtracking. The reported method minimizes the robot-to-robot communication needed to organize the movements, and it guarantees coverage in a finite time that decreases as the reciprocal of the number of robots sharing the task (Spires & Goldsmith, 1998). Later work adapts the same curve to regions that contain obstacles (Joshi et al., 2019). Locality preservation is not only an efficiency property. A Hilbert traversal visits spatially adjacent cells consecutively, so a vehicle can leave the curve for a local excursion and resume it at the saved index without stranding distant unswept pockets. The adaptive strategy proposed here depends on exactly this property, and the Hilbert curve therefore serves both as a systematic baseline and as the exploration layer of the adaptive method.

Energy is the usual objective when a spiral is preferred. An energy-aware spiral planner for UAV photogrammetry achieved energy savings over back-and-forth coverage in reported experiments (Cabreira et al., 2018). Operational search and rescue doctrine takes a different route and standardizes a small set of patterns, including the parallel sweep, creeping line, expanding square, and sector search, together with the effective sweep-width concept (International Civil Aviation Organization & International Maritime Organization, 2006). Sweep width is the quantity that converts a sensor specification into a lane spacing, and the same reasoning fixes the lane spacing of all four methods compared here.

Across this literature, pattern selection is generally made by convention or by single-objective optimization of energy, time, or path length. There is no principled guidance for choosing a pattern from the expected spatial distribution of the targets, and there is no reporting convention for target spacing relative to the sensor footprint.

1.3. Adaptive and detection-driven search

Adaptive search updates the plan from observations instead of fixing it in advance. In the Bayesian formulation of coordinated search for a lost target, each platform maintains a probability density over the target location and acts on it (Bourgault et al., 2003). The density is updated by both detections and non-detections, so a sweep that finds nothing still changes where the team will look next. Search has also been treated as a sequence of decisions, with the policy chosen to minimize the expected time until the searcher locates the target or declares it absent (Chung & Burdick, 2012).

A third approach defines coverage with respect to an expected information density. The reported objective encodes both exploration and exploitation, and it trades between them in a single objective function whether the information is diffuse or localized (Miller et al., 2016). What these three formulations share is continuous replanning against a global utility, and none of them bounds how much systematic coverage is surrendered for a single exploitation decision. That bound is the design question addressed in this study.

Industrial deployments show the same unbounded convergence. A team driven by distributed consensus converges on a detected gas source (Facinelli et al., 2019). The proposed strategy differs in that it limits how many aircraft can leave the main search area to investigate a detected target. This allows the rest of the group to continue searching the area while some of the aircraft investigate the discovery. Reinforcement learning has been applied to the same cooperative search problem within a

digital-twin training framework (Shen et al., 2023). A multi-agent formulation of swarm target search follows the same direction (Hou et al., 2024).

The closest prior study evaluates a context-aware deep Q-network on discrete uniform and clustered target layouts (Mohanty et al., 2020). The study found that missions finished faster when targets were clustered together. It explained this by saying that several targets within the same cluster could be dealt with at the same time. However, that study only compared two levels of clustering. In this study, clustering is varied gradually across many levels. More importantly, the effect of dealing with several targets at the same time is directly controlled in the experiment instead of simply being used as an explanation for the results.

1.4. Search theory and the role of target spatial distribution

The prediction that motivates the experiments is based on classical search theory. The main idea is that search effort should be allocated according to where the target is most likely to be found (Koopman, 1957). This idea was later developed into a general theory of optimal search (Stone, 1975). This theory leads to two important cases. When targets are uniformly distributed, uniform coverage is optimal because every location has the same probability of containing a target. It leaves little for an adaptive strategy to exploit. In contrast, when targets are spatially clustered, some regions are more likely to contain targets than others. Concentrating search effort in these regions can be more efficient than maintaining uniform coverage. However, this difference matters mainly when search resources are limited. If a UAV has unlimited endurance and enough time to complete a full sweep, both strategies can eventually find all static targets. Therefore, the expected advantage of adaptive search is not that it can find targets that uniform search cannot reach, but that it can use limited flight time or energy more efficiently when targets are clustered.

Foraging theory also shows that the effectiveness of a search strategy depends on how targets are distributed. When targets are sparse and locations can be revisited, an inverse-square power-law distribution of flight lengths has been reported to provide an efficient search strategy (Viswanathan et al., 1999). As the conditions of the search change, a transition between different search regimes has been observed. In particular, the efficient movement pattern can shift from superdiffusive movement, which includes occasional long movements, to more direct ballistic movement (Santos et al., 2004). However, a wide-ranging search strategy that is effective for sparse targets is not necessarily optimal for all types of blind search (Palyulin et al., 2014). Together, these findings suggest that the spatial distribution of targets can determine which search strategy is most effective. This leads to the prediction that a similar transition may occur in geometric multi-UAV search as the level of target clustering changes. Identifying this transition is the main objective of this study.

1.5. Modeling clustered spatial distributions

Spatial point-process theory provides a systematic way to vary target clustering. Spatially independent targets are modeled using a homogeneous Poisson point process, which provides a baseline with no spatial clustering. Clustered target fields are modeled using Neyman–Scott Poisson cluster processes, with the Thomas process used as the specific model (Thomas, 1949). The properties of this process family are described in the standard reference on stochastic geometry (Chiu et al., 2013). In the Thomas process, offspring points are distributed around randomly placed parent points according to a Gaussian kernel. The spread of these offspring points is controlled by the parameter σ, allowing the level of clustering to be varied continuously. This parameter also provides a measure of the characteristic spatial scale of the target clusters and can therefore be related to the physical correlation lengths of the anomalies. To account for differences between the specified and resulting target distributions, the realized clustering statistic is reported together with the nominal σ. This is

important since the removal of overlapping targets and the treatment of targets near the search-area boundaries can change the final cluster size.

1.6. Position of this study

This study brings together several research directions that are usually considered separately. Systematic coverage path planning, adaptive search based on detection feedback, and controlled spatial clustering are evaluated within the same mission framework and under a common detection model. The study examines how the relative performance of these search strategies changes as the level of target clustering increases. This change is evaluated for specific geometric search patterns under a fixed time budget, while the sensor's ability to detect multiple nearby targets is explicitly controlled. The effect of simultaneous target detection is first measured, bounded, and then removedby construction. As a result, the observed transition between search strategies can be attributed primarily to the spatial distribution of targets rather than to differences in sensor geometry. The clustering-dependent crossover is therefore treated as the main object of measurement in the study.

2. Methodology

2.1. Problem statement

A bounded planar survey region (A) represents a monitored industrial area containing (N) anomalies at positions $x_1, \dots, x_N$. The anomalies represent events such as disaster victims, wildfire ignition points, industrial leaks, infrastructure damage, and equipment failures, and their spatial distribution can range from approximately independent to strongly clustered. A team of (K=3) identical UAVs operates within (A) at a fixed altitude. Each UAV flies at a constant cruise speed of approximately $v \approx 5$ m/s and carries a sensor with a 71.1 m × 53.3 m footprint, giving a diagonal of approximately 89 m. A target is considered detected when it is first covered by the sensor footprint. Each trial is limited by a fixed mission time budget (T), which is shorter than the time T_{sweep} required to complete a full systematic sweep of the survey region. The ratio T/T_{sweep} is reported to express the available search time relative to the time required for complete coverage, allowing the results to be compared across different UAV platforms and operating conditions.

The cumulative number of detected targets at time t is denoted by $D(t)$. Two timing metrics are used to describe the speed of detection: T_{50}, the time required to detect 50% of the targets, and T_{90}, the time required to detect 90% of the targets. When a detection threshold is not reached before the end of the mission, the corresponding time is treated as censored at T.

Two sets of experiments are conducted. The first uses the total number of detected targets at the end of the mission, $D(T)$, as the primary performance metric. The second focuses on detection speed using T_{50} and T_{90}. These experiments are used to compare systematic coverage and adaptive search across different levels of spatial target clustering. The main objective is to identify the clustering level at which the relative performance of the two strategies changes. This performance crossover can then provide a practical rule for selecting a search strategy: systematic coverage is expected to be more suitable for dispersed anomalies, while adaptive search is expected to become more effective as anomalies become increasingly clustered.

2.2. Proximity assumption

An adaptive search strategy is useful only when detecting one anomaly provides information about the likely locations of other anomalies. In particular, the detection of one anomaly should increase the probability that additional targets are located nearby. This spatial proximity is represented by the

cluster scale σ, which controls the strength and spatial extent of target clustering. By varying σ continuously, different levels of spatial dependence can be represented within the same model. Small values of σ produce tightly clustered targets, so detecting one target provides strong information about nearby targets. As σ increases, the targets become more widely dispersed and the spatial relationship between them becomes weaker. At sufficiently large values of σ, the target distribution approaches spatial independence, where detecting one target provides little information about the locations of others (Figure 1).

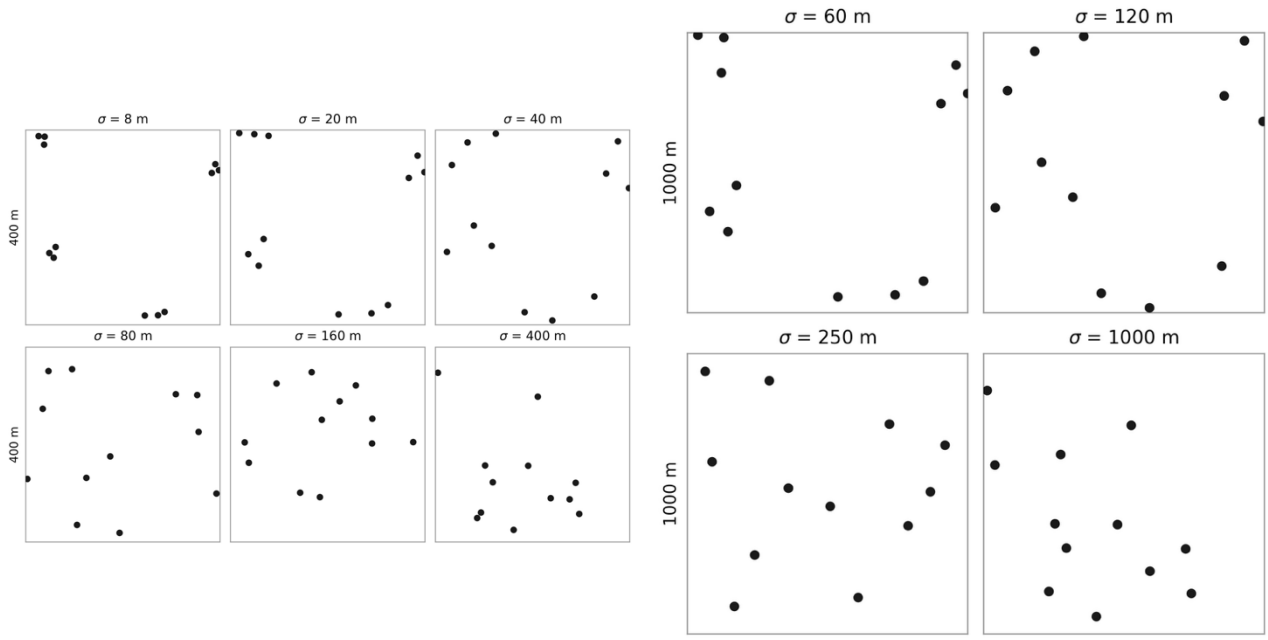

Figure 1
Example target layouts generated by the Thomas cluster process for Experiment 1 and Experiment 2 (left to right)

2.3. Modeling anomaly spatial distribution

Parent placement. Target fields are generated using a Thomas cluster process (Thomas, 1949). First, $N_p = 4$ parent points are placed inside the square $[-h, h]^2$, where the half-span is $h = 0.4L$ and L is the side length of the arena. The first parent is placed at a uniformly random location within this square. To place each of the remaining parents, 128 candidate locations are generated uniformly, and the candidate that is farthest from the nearest already-placed parent is selected. This farthest-point sampling procedure keeps the four parent points separated and prevents the cluster centers from being placed too close to one another.

Offspring assignment. A total of $N = 12$ target points are generated, with exactly three targets assigned to each of the four parents. The assignment is made using $i \bmod N_p$, which means that the first target is assigned to the first parent, the second to the second parent, and so on. After all four parents have received one target, the assignment starts again from the first parent. This process continues until all 12 targets have been assigned. The assignment is therefore deterministic and balanced, ensuring that every parent produces exactly three offspring.

Offspring scatter. After each target has been assigned to a parent, its position is generated by adding a random two-dimensional offset to the parent location c. The offset is drawn from an isotropic Gaussian distribution with a standard deviation of σ along both coordinate axes. Thus, targets tend to remain close to their assigned parent, while the value of σ controls how widely they are spread around

it. A small σ produces tight clusters, whereas a larger σ produces more dispersed clusters. The resulting probability density of an offspring around its parent is given in Equation 1.

$$f(x \mid c) = \frac{1}{2\pi\sigma^2} e^{\left(-\frac{\|x-c\|^2}{2\sigma^2}\right)} \qquad (1)$$

Boundary constraint. If an offspring is generated outside the box, it is rejected and a new position is drawn. The point is not moved, or clamped, to the nearest boundary. Clamping would cause offspring generated with large σ values to accumulate along the boundary and would therefore distort the intended spatial distribution. Rejection instead produces a Gaussian distribution conditioned on the offspring remaining inside the box. As σ increases, this conditioned distribution approaches a uniform distribution within the box.

Minimum separation constraint. An optional minimum pairwise distance $s_{\min}$ can be imposed between all targets. If a Gaussian draw produces a point that violates this minimum distance, the point is rejected and another draw is attempted. If the minimum separation cannot be satisfied after 400 attempts, a ring-search fallback is used. In this fallback, the point is placed on a circle centered on its parent, and the radius of the circle is gradually increased until a position is found that is both inside the box and sufficiently separated from all existing targets. A final check is then performed to verify that the required minimum separation has been satisfied. If the constraint is still violated, an error is raised and the invalid layout is not accepted.

The ring fallback is important when interpreting the effect of σ. When σ is small and $s_{\min}$ is large, the minimum-separation constraint can prevent targets from occupying their original Gaussian positions. Instead, the fallback moves them onto concentric rings around the parent. Thus, a hard minimum separation places a lower limit on the range of $s_{\min}$ values that can represent the intended Gaussian clustering without being strongly affected by the separation constraint. The two experiments use different minimum-separation values. Experiment 1 uses $s_{\min} = 12$ m, which still allows sensor-footprint overlap. Experiment 2 uses $s_{\min} = 90$ m, which is greater than the 89 m sensor-footprint diagonal and therefore removes single-frame co-detection.

Pairwise-distance law. The Gaussian scatter also provides a direct relationship between the clustering parameter σ and the distance between targets within the same cluster. Two offspring from the same parent are generated using independent Gaussian offsets. Therefore, the difference between their positions is also Gaussian, with a variance of $2\sigma^2$ along each coordinate axis. The distance d between the two offspring consequently follows a Rayleigh distribution with scale $\sigma\sqrt{2}$,. The probability that two offspring from the same parent are located within a distance r of each other is therefore given by Equation 2.

$$P(d \leq r) = 1 - e^{\left(-\frac{r^2}{4\sigma^2}\right)} \qquad (2)$$

Equation 2 quantifies the proximity between targets within the same cluster. For a given distance r, a smaller σ produces a higher probability that two targets are close to each other, while a larger σ produces a lower probability. This provides a quantitative representation of the proximity assumption used by the adaptive search strategy: detecting one target is more informative about the location of other targets when σ is small. The same relationship also shows how the clustering scale interacts with the hard minimum-separation constraint, since sufficiently small values of σ become difficult to realize when targets are required to remain at least $s_{\min}$ apart.

2.4. Search strategies

All strategies operate within the same multi-UAV framework. The survey region is divided into K sub-regions, with one sub-region assigned to each UAV. This decomposes the multi-UAV coverage problem into independent single-UAV coverage tasks (Rekleitis et al., 2008). Each UAV then follows the coverage pattern assigned to its sub-region independently. The sensing, target confirmation, flight control, and data logging modules are kept identical across all strategies. The only component that differs is the sequence of waypoints used to determine each UAV's trajectory. This ensures that differences in performance are caused by the search strategy rather than by differences in the underlying UAV or sensing systems.

2.4.1. Systematic geometric baselines

Three systematic coverage patterns are used as baselines. The lawnmower, or boustrophedon, pattern consists of parallel back-and-forth sweeps with lane spacing determined by the sensor swath, providing systematic and uniform coverage of the assigned sub-region (Figure 2). It serves as the primary baseline because of its widespread use in coverage path planning. The spiral pattern follows an inward or outward spiral trajectory within each sub-region and provides a systematic alternative for environments where targets may be concentrated toward the center. The Hilbert space-filling curve provides another systematic traversal pattern that preserves spatial locality while covering the assigned area. All three baselines use the same lane spacing, which is determined by the sensor footprint and the reliable-detection fraction. Therefore, the baselines have the same coverage density and differ only in the order in which the area is traversed.

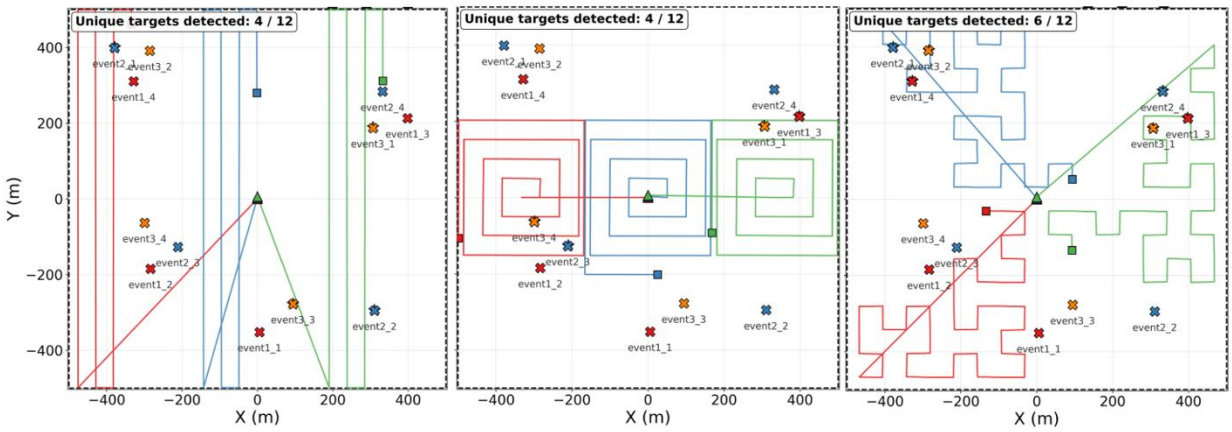

Figure 2

Systematic coverage algorithms: lawnmower, spiral, and Hilbert traversal (left to right)

2.4.2. Detection-driven adaptive strategy

The proposed strategy uses the systematic Hilbert path as its main coverage plan and adds a local search response when a target is detected. Each UAV follows its assigned Hilbert trajectory in the same way as in the baseline, and all confirmed detections are stored in a shared registry. When a target is confirmed, the nearest available UAV temporarily leaves its planned trajectory and searches the area around the detected target. This local search is bounded so that the UAV does not move indefinitely away from its assigned path. After completing the local search, the UAV returns to the point where it left the Hilbert trajectory and continues along the original path. The Hilbert coverage path is therefore not replanned or replaced during the mission. Instead, the adaptive strategy adds short, detection-triggered detours to the existing systematic path. If additional targets are located near the confirmed target, the detour can result in additional detections. If no additional targets are present,

the UAV returns after only a limited additional flight distance, keeping its behavior close to that of the original Hilbert strategy. The following paragraphs describe the detection, detour, and return mechanisms in detail.

Exploration layer. A single Hilbert space-filling curve is first generated over the entire survey region, with the lane spacing determined by the sensor footprint. The resulting sequence of waypoints is then divided into K contiguous segments, with one segment assigned to each UAV. During normal exploration, each UAV follows the waypoints in its assigned segment in sequence. A waypoint is considered reached when the UAV comes within 5 m of its location. This exploration procedure is identical to that used by the systematic Hilbert baseline and is not changed by the adaptive strategy. Therefore, when no exploitation detours are active, the proposed strategy follows exactly the same waypoint sequence as the Hilbert baseline.

Exploitation layer. A confirmed target can trigger at most one local detour. Let c denote the position of the confirmed target. When a detour is triggered, the UAV closest to c is selected from the UAVs that are not already performing another detour. The selected UAV therefore does not have to be the UAV that detected the target. It temporarily leaves its assigned Hilbert path and performs one complete lap around the detected target. The lap consists of K_h waypoints placed on a circle with radius R_{halo} centered at c. If the target is close to the boundary of the survey region, the ring waypoints are clamped to remain inside the region so that the resulting path remains flyable. After completing the lap, the UAV returns to its original exploration path and continues from the exact waypoint index at which the detour began.

Fold rule. When a new target is confirmed, its position is compared with the centers of detours that have already been registered. If the new confirmation is within the specified fold radius of an existing detour center, no new detour is created. Instead, the new target is treated as another target belonging to the same local cluster, since the existing detour is already intended to search that area. A detour center is registered immediately when its confirmation passes the fold check, even if the corresponding detour has not yet started and is still waiting in the queue. As a result, later targets detected near a queued or active detour are folded into that existing detour rather than creating additional rings. The fold rule is applied only when new confirmations arrive; it does not remove or cancel a detour that has already been queued.

Effort bounds. The adaptive strategy also ensures that at least one UAV that is still performing its assigned sweep remains on the exploration path at all times. A UAV that has already completed its assigned segment is not counted toward this requirement. If a confirmed target cannot be serviced immediately because no suitable UAV is available, the corresponding detour is placed in a queue. The queued detour is dispatched when a UAV becomes available, unless a later confirmation near the same detour center is folded into the existing detour. These rules limit the amount of flight time that can be redirected from systematic exploration to local exploitation.

Halo radius. The radius of the local detour is chosen so that the UAV searches the region where additional targets from the same cluster are most likely to be found. The choice of R_{halo}differs between the two experiments. In Experiment 1, the halo radius is linked to the assumed cluster scale and is set to $R_{\text{halo}} = 30$ m. This radius is smaller than the effective sensor footprint radius, so one complete lap around the detected target provides coverage of the entire disc around the detection, including its center. In Experiment 2, the halo radius is determined by the geometry of the detection and separation constraints rather than by the cluster scale. The hard minimum separation is $s_{\min} = 90$ m, which means that no other target can be located within 90 m of a confirmed target. A target closer than this distance would have been detected in the same sensor frame, and such target configurations are excluded by the generator. Therefore, any undetected target from the same cluster must be located at a distance $r \geq s_{\min}$from the confirmed target. The sensor reliably detects targets

within a band of approximately $w = 27$ m on either side of the UAV's flight path. To search for targets beginning at the 90 m exclusion boundary, the inner edge of this detection band is placed on that boundary. This geometric relationship gives Equation 3.

$$R_{\text{halo}} = s_{\min} + w = 90 + 27 = 117m \tag{3}$$

- One complete lap therefore searches the first region outside the 90 m exclusion zone where another undetected target could be located. No flight time is spent searching the inner region because it is guaranteed to contain no additional target.

- **Detour cost.** The flight cost of each detour is bounded and can be calculated before the mission begins. Each detour consists of one complete lap around the confirmed target. The circular halo is represented by a regular K_h-gon, where K_h equally spaced waypoints are placed on the halo circle and connected by straight flight segments. The lap therefore follows the perimeter of the inscribed K_h-gon rather than the circumference of the circle. Its length is given by Equation 4.

$$L_{\text{ring}} = 2K_h R_{\text{halo}} \sin\left(\frac{\pi}{K_h}\right) \tag{4}$$

The distance required for the UAV to leave its original sweep and reach the nearest waypoint of the K_h-gon is added to the polygon perimeter, together with the distance required to return to the sweep after completing the lap. Including these entry and exit legs, the total detour distance is approximately 176 m per lap in Experiment 1 and approximately 716 m per lap in Experiment 2. At a constant speed of $v = 5$ m/s, these distances correspond to approximately 35 s and 143 s, respectively. The cost of each detour is therefore fixed by the predefined K_h-gon geometry and does not depend on how many additional targets are found during the lap. This bounded cost allows the adaptive strategy to investigate detected targets without allowing a single detection to generate unlimited additional search effort. When targets are clustered, one K_h-gon lap can detect nearby targets before the systematic sweep reaches the same region again. When a detected target is isolated, the detour still incurs only its predefined cost, keeping the adaptive strategy relatively close to the systematic Hilbert baseline in dispersed environments.

2.5. Detection model

Search strategy and target perception are treated as separate components of the experimental framework. The purpose of the study is to evaluate how different search strategies respond to the spatial distribution of targets, rather than to compare the performance of specific deep-learning detectors. Therefore, a lightweight detector based on hue–saturation–value (HSV) color segmentation is used. In the simulation, ground anomalies are represented by flat-colored markers with predefined and distinct HSV characteristics. A detection is registered when the number of pixels matching the target color within the camera footprint exceeds a predefined threshold. This produces detection events that depend on the UAV's position and sensor overflight while avoiding the need to train a deep-learning model. The detected image pixels are then projected into world coordinates using attitude-corrected ray casting, and the resulting detections are matched to the corresponding simulation timestamps. This deterministic perception pipeline provides a controlled proxy for the target detections that would be produced by a real-time computer-vision system in an operational deployment.

2.6. Metrics and statistical design

All performance metrics are computed from the same shared pose and detection log streams for all four strategies, ensuring that every strategy is evaluated using the same data and scoring procedure. Temporal performance is evaluated using three measures.

- **Per-target latency (L).** The time from mission start until each target is first detected is recorded as its latency. When a target is not detected before the mission ends, its latency is censored at the mission time limit. The resulting per-target latencies are reported together with their trial mean.
- **Milestone attainment (T_{50}, T_{90}).** These measures represent the time required to detect 50% and 90% of all targets, respectively. If a milestone is not reached before the mission time limit, its attainment time is censored at the budget limit. Each milestone is reported both as a censored mean time and as an attainment rate, defined as the fraction of trials in which the corresponding detection threshold is reached.
- **Cumulative detection curves ($D(t)$).** These curves show how the number of detected targets changes throughout the mission. They capture the complete detection progression and therefore distinguish strategies that achieve the same final number of detections but reach those detections at different rates.

Total fleet distance traveled is reported alongside the performance metrics to determine whether any advantage of the adaptive strategy is associated with increased travel. The crossover analysis relates strategy performance to the realized clustering statistics, including per-layout dispersion and nearest-neighbor distances. This allows the change in relative strategy performance to be examined as the actual spatial distribution of targets changes.

2.7. Experimental Setup

Three UAVs operate at an altitude of 30 m and a cruise speed of approximately 5 m/s. The onboard camera has a horizontal field of view of 1.74 rad, producing a ground footprint of 71.1 m × 53.3 m with an 89 m diagonal. Computer vision processing is restricted to the central 75% of the image to improve detection reliability, giving a reliable cross-track half-width of approximately $w \approx 27$ m. All four search strategies use the same sweep lane spacing, derived using a 0.95 overlap factor. Each target field contains 12 anomalies generated by a Thomas cluster process with four parent locations and three offspring per parent.

2.7.1. Experiment 1 (400 m arena)

Performance was evaluated using a full-factorial stochastic simulation study that varied six clustering levels, $\sigma \in \{8, 20, 40, 80, 160, 400\}$ m, four search strategies, and ten pseudo-random seeds. The static arena measured 400 m × 400 m, and each trial was limited to a 120 s flight budget, corresponding to approximately $0.55\,T_{\text{sweep}}$. A minimum target separation of 12 m was imposed, which still allowed multiple targets to fall within the sensor footprint and be detected in the same frame. The primary performance metric was the cumulative number of detected targets $D(T)$ (Table 1).

Three structural limitations motivated the scale-up to a second experiment. First, the 89 m sensor-footprint diagonal at 30 m altitude was large relative to the spatial scale of the tighter clusters. As a result, clustering levels with $\sigma \leq 40$ m frequently produced frame-level co-detections. This introduced a sensor-dependent effect that could not be cleanly separated from the effect of spatial clustering itself. Increasing the minimum target separation to 90 m would have removed this co-detection effect, but this constraint could not be imposed reliably within the 400 m arena without substantially restricting the range of achievable clustered layouts. The resulting layouts would become more dispersed and would weaken the intended clustering variation. Second, the 120 s flight budget allowed the UAVs to complete only approximately 1.5 legs of the spiral pattern, making this baseline poorly represented under the chosen time budget. Third, ten-seed replication became unnecessarily redundant once the statistical analysis was based on pooled regime-level comparisons.

2.7.2. Experiment 2 (1000 m separation-controlled arena)

Experiment 2 expanded the arena to 1000 m × 1000 m to address the geometric limitations identified in Experiment 1, while keeping the sensor, platform, and fleet parameters unchanged. The larger arena allowed a hard minimum target separation of $s_{\min} = 90$ m to be imposed. Because this separation exceeds the 89 m sensor-footprint diagonal, frame-level co-detection was eliminated. The clustering range was adjusted to $\sigma \in \{60, 120, 250, 1000\}$ m. Here, $\sigma = 60$ m represents the tightest clustering level that can be generated under the 90 m separation constraint, while $\sigma = 1000$ m provides the approximately uniform control condition. The flight budget was increased to 800 s, corresponding to approximately $0.54\, T_{\text{sweep}}$ for the larger arena. This preserved a similar level of resource scarcity to Experiment 1 while allowing the spiral baseline to complete approximately four full rings, avoiding the structural limitation observed in the smaller arena. The adaptive detour geometry was also rescaled to account for the increased target separation. Replication was reduced to five paired seeds per experimental cell, and the primary metric focus was shifted from cumulative detection count to paired detection latency (Table 1).With frame-level co-detection removed, fixed-budget detection counts provided fewer distinct outcome levels, reducing their statistical resolution. Paired latency differences provided a more sensitive measure of the relative performance of the strategies under the same experimental conditions.

Table 1
Experiment settings

Parameter	Experiment 1	Experiment 2
Area	400 m × 400 m	1000 m × 1000 m
Min target separation	12 m	90 m
Mission budget	120 s	800 s
σ levels	8 / 20 / 40 / 80 / 160 / 400 m	60 / 120 / 250 / 1000 m
Seeds per cell	10	5
Trials	240	80
Primary metric	fraction found within budget	time-to-detection (latency, T50/T90, curves)
Adaptive detour geometry	$R_{halo} = 30m$, $K_h = 5$, fold 45 m	$R_{halo} = 117m$, $K_h = 8$, fold 60 m

3. Results

3.1. Scope of the evaluation

Four search strategies were evaluated. Three are fixed systematic coverage strategies: lawnmower, spiral, and a Hilbert space-filling curve. The fourth is the proposed adaptive strategy, which follows the Hilbert sweep and adds detection-triggered halo-ring detours. Target locations were generated using a Thomas cluster process, with the cluster scale σ serving as the single controlled variable. Small values of σ produce tightly clustered targets, whereas large values produce increasingly dispersed layouts that approach a uniform distribution. The same target layout was used for all four strategies within each seed, so the methods were evaluated on paired and directly comparable conditions.

The two experiments were conducted at different spatial scales. Experiment 1 used a 400 m × 400 m arena with three UAVs, a 120 s mission budget, and a 12 m minimum target separation. It evaluated six clustering levels with ten paired seeds per level and strategy, resulting in 240 trials. Experiment 2 used a 1000 m × 1000 m arena with an 800 s mission budget and a 90 m minimum target separation. It evaluated four clustering levels with five paired seeds per level and strategy, resulting in 80 trials.

The primary metric in Experiment 1 was the fraction of the 12 targets detected within the mission budget. Detection time was used as a secondary metric and summarized using the censored mean detection time and T_{50}. Detection time was the primary metric in Experiment 2. The T_{90} milestone was not reached in any trial: 0 of 10 trials in every Experiment 1 cell and 0 of 5 trials in every Experiment 2 cell reached 90% detection. Thus, no strategy detected 90% of the targets within the available mission time, confirming that both experiments operated within the intended resource-limited regime.

3.2. Experiment 1: detection yield and the clustering crossover

Table 2 reports the fraction of targets detected within the 120 s mission budget. The paired difference is calculated as the adaptive strategy score minus the Hilbert strategy score for each seed and is reported in targets per seed, together with a bootstrap 95% confidence interval and the corresponding win/tie/loss counts.

Table 2
Fraction of targets found within budget, Experiment 1

Cell (σ, m)	Lawnmower	Spiral	Hilbert	Adaptive (proposed)	Paired Δ targets [95% CI] (W/T/L)	Wilcoxon p
C1 (8)	0.433 ± 0.192	0.158 ± 0.114	0.550 ± 0.119	0.675 ± 0.121	+1.50 [+0.80, +2.20] (7/3/0)	0.016
C2 (20)	0.450 ± 0.177	0.200 ± 0.098	0.567 ± 0.135	0.658 ± 0.154	+1.10 [+0.20, +2.10] (5/4/1)	0.094
C3 (40)	0.483 ± 0.123	0.217 ± 0.090	0.508 ± 0.133	0.550 ± 0.153	+0.50 [−0.40, +1.40] (4/4/2)	0.438
C4 (80)	0.442 ± 0.125	0.300 ± 0.081	0.533 ± 0.137	0.400 ± 0.086	−1.60 [−2.40, −0.80] (1/1/8)	0.012
C5 (160)	0.475 ± 0.104	0.300 ± 0.148	0.533 ± 0.172	0.400 ± 0.110	−1.60 [−2.40, −0.70] (1/2/7)	0.016
C6 (400)	0.475 ± 0.176	0.275 ± 0.111	0.450 ± 0.131	0.350 ± 0.141	−1.20 [−2.10, −0.40] (1/3/6)	0.047

At the tightest clustering level, $\sigma = 8$ m, the adaptive strategy achieved the highest detection rate. It detected a mean of 0.675 of the available targets, corresponding to 8.1 of the 12 targets per trial. The best systematic baseline was the Hilbert strategy, with a mean detection fraction of 0.550, or 6.6 targets per trial *Figure 3*. Thus, the adaptive strategy detected approximately 23% more targets than Hilbert at this clustering level. Because the layouts were paired across strategies, the per-seed comparison provides a more direct measure of the difference. The adaptive strategy outperformed Hilbert on 7 of 10 seeds and tied on the remaining 3, with no losses. The mean paired advantage was +1.50 targets, meaning that the adaptive strategy found, on average, 1.5 more targets than Hilbert on the same layouts. The bootstrap 95% confidence interval for this advantage was [+0.80, +2.20] targets, indicating that the estimated improvement remained positive across the reported interval. A Wilcoxon signed-rank test on the paired differences gave $p = 0.016$, providing evidence that the observed advantage was not likely to arise from random variation alone under the test's null hypothesis of no systematic paired difference.

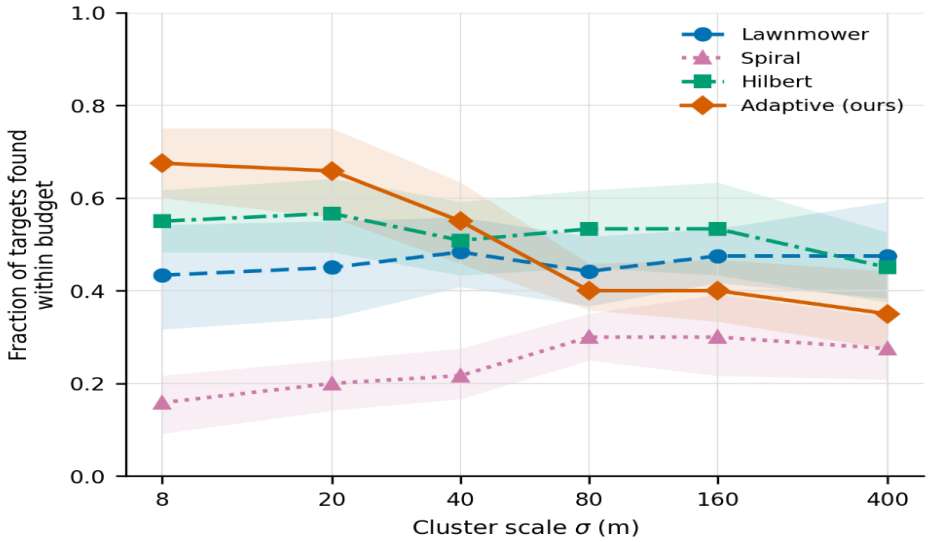

Figure 3
Adaptive sweep advantage in found target ratio

The adaptive advantage did not decrease smoothly to zero as the clusters became more dispersed. Instead, performance changed from a positive to a negative advantage near the scale of the camera footprint. The advantage remained clear at σ = 20 m, where the adaptive strategy achieved a mean detection fraction of 0.658 compared with 0.567 for Hilbert, with a paired advantage of +1.10 targets. At σ = 40 m, the difference was smaller, with a paired advantage of +0.50 targets, but this difference was not statistically significant. From σ = 80 m onward, the adaptive strategy performed worse than Hilbert, with significant paired deficits of −1.60 targets at C4, −1.60 targets at C5, and −1.20 targets at C6. Thus, the paired advantage changes sign between C3 and C4. Interpolation on the logarithmic σ scale places the crossover at approximately σ = 47 m. With a sensor footprint radius of 36 m at 30 m altitude, this corresponds to a cluster-to-footprint ratio of approximately 1.3.

Total fleet distance traveled was nearly identical for the adaptive and Hilbert strategies across all clustering levels, with differences of only a few meters. This indicates that the observed performance difference was not caused by substantially greater overall flight distance, but by how the two strategies allocated that flight effort between systematic coverage and detection-triggered detours.

3.3. Experiment 2: separating the search mechanism from frame-level co-detection

The co-detection confound in Experiment 1 - The target-count advantage observed in Experiment 1 is partly confounded by the sensor geometry. As target clustering becomes stronger, the probability that multiple targets fall within the same camera footprint increases. When two targets are separated by less than the 89 m footprint diagonal, an overflight can detect both targets within the same frame. This means that a higher detection count may partly reflect the ability of the sensor to detect multiple nearby targets simultaneously, rather than the ability of the search strategy to exploit spatial clustering. This effect was therefore measured directly. Table 3 reports three quantities for each strategy and clustering level: the proportion of target pairs separated by less than the 89 m footprint diagonal, the percentage of targets with at least one co-detectable neighbor, and the percentage of detected targets that were co-detected with at least one neighbor.

Table 3 shows frame-level co-detectability and realized co-detection in Experiment 1. The four right-hand columns report the percentage of found targets that arrived through a co-detection event.

Table 3
Realized co-detection in Experiment 1

Cell (σ, m)	Pairs < 89 m (%)	Targets w/ neighbor (%)	Lawnmower	Spiral	Hilbert	Adaptive (proposed)
C1 (8)	18.2	100.0	33.4	19.0	42.1	31.1
C2 (20)	18.0	100.0	18.7	14.8	15.6	11.1
C3 (40)	15.0	95.0	13.2	0.0	9.6	5.8
C4 (80)	10.5	79.2	8.3	0.0	2.9	3.3
C5 (160)	12.4	70.8	0.0	2.9	4.0	0.0
C6 (400)	9.8	68.3	2.0	5.0	0.0	0.0

The proportion of target pairs separated by less than the 89 m footprint diagonal decreases from 18.2% at C1 to 9.8% at C6, although the decrease is not strictly monotonic. In particular, C5 has a higher proportion than C4, at 12.4% compared with 10.5%. The proportion of targets with at least one co-detectable neighbor provides a more stable measure of co-detectability and decreases monotonically from 100.0% at C1 to 68.3% at C6. Across the 60 seed layouts, this measure is strongly negatively correlated with log σ, with a Pearson correlation of $r=-0.77$ ($p < 0.001$). This indicates that increasing spatial dispersion reduces the likelihood of co-detectable neighbors and confirms that σ systematically controls the extent of the co-detection effect.

The realized co-detection rates are substantially lower than the geometric availability would suggest. At C1, 19.0% to 42.1% of detected targets were obtained through a co-detection event, whereas at C6 the highest observed rate was only 5.0%. The effect therefore reflects the spatial structure of the tighter layouts rather than a systematic preference of one search strategy. In particular, the adaptive strategy did not produce more co-detections than Hilbert. Its realized co-detection rate was lower at C1, at 31.1% compared with 42.1%, and was also lower at C2, C3, and C5. It was marginally higher only at C4, where the rates were 3.3% for the adaptive strategy and 2.9% for Hilbert. At C6, both strategies had a co-detection rate of 0.0%.

The confounding effect nevertheless remains in another form. Across the 60 paired seeds, layout co-detectability is positively correlated with the paired advantage in detected targets, defined as adaptive minus Hilbert, with a Pearson correlation of $r=+0.60$ ($p<0.001$). Thus, layouts with greater co-detectability also tend to be layouts in which the adaptive strategy achieves a larger detection advantage. However, this relationship is largely explained by differences between clustering levels. After removing the mean effect of σ within each cell, the correlation decreases to ($r=+0.14$) and is no longer significant ($p = 0.29$). Therefore, most of the observed ($r=+0.60$) relationship comes from the between-cell variation in σ, rather than from differences between layouts at the same clustering level. Since increasing σ simultaneously changes both the spatial opportunity for halo-based exploitation and the probability of co-detection, Experiment 1 cannot cleanly separate these two effects. Experiment 2 was therefore designed to remove the co-detection effect while retaining variation in the spatial clustering of targets.

Elimination of co-detection by construction. Experiment 2 imposes a minimum target separation of 90 m, which is greater than the 89 m camera-footprint diagonal. Consequently, no two targets can occur within the same camera footprint, and simultaneous detection of multiple targets is excluded by construction. The co-detection audit confirms this result, with every experimental cell reporting 0.0% of detected targets as co-detection events. Any performance difference observed in Experiment 2 therefore cannot be attributed to the ability of the sensor to detect multiple nearby targets in the same frame.

Detection counts - Table 4 reports the target-count results for Experiment 2. The difference between the adaptive and Hilbert strategies is substantially smaller than in Experiment 1 and does not reach statistical significance.

Table 4
Fraction of targets found within budget in Experiment 2

Cell (σ, m)	Lawnmower	Spiral	Hilbert	Adaptive (proposed)	Paired Δ [95% CI]	W/T/L	Wilcoxon p
C1 (60)	0.450 ± 0.075	0.217 ± 0.126	0.550 ± 0.075	0.633 ± 0.095	+1.00 [+0.20, +1.80]	3/2/0	0.250
C2 (120)	0.483 ± 0.091	0.417 ± 0.118	0.517 ± 0.124	0.533 ± 0.095	+0.20 [+0.00, +0.60]	1/4/0	1.000
C3 (250)	0.550 ± 0.126	0.533 ± 0.151	0.567 ± 0.124	0.583 ± 0.102	+0.20 [−1.20, +1.40]	3/0/2	1.000
C4 (1000)	0.567 ± 0.109	0.700 ± 0.075	0.467 ± 0.075	0.433 ± 0.124	−0.40 [−1.00, +0.40]	1/1/3	0.625

Pooled across the two clustered conditions, C1 and C2, the adaptive strategy detected an average of 0.60 more targets than Hilbert on the same target layouts (Figure 4). The 95% confidence interval for the paired difference was [+0.10, +1.10] targets, so the estimated advantage remained positive across the reported interval. However, the Wilcoxon signed-rank test gave $p = 0.0625$, which is above the conventional 0.05 significance threshold. The clustered conditions therefore show a positive trend in favor of adaptive search, but the evidence is insufficient to establish a statistically significant advantage at the 5% level. At the approximately uniform extreme, C4 with $\sigma = 1000$ m, the spiral strategy achieved the highest mean detection fraction at 0.700. The adaptive strategy detected 0.40 fewer targets than Hilbert on average, although this difference was not statistically significant. Thus, the count results suggest a shift from a possible adaptive advantage in clustered environments toward no clear advantage, and potentially a disadvantage, as the target distribution becomes approximately uniform.

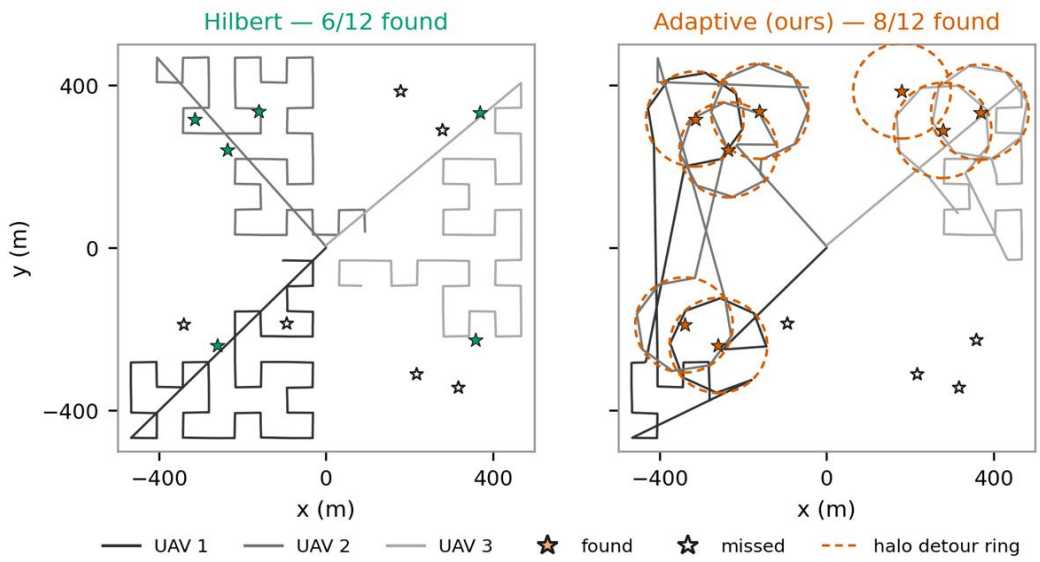

Figure 4
Detection count advantage of adaptive strategy in Experiment 2

Detection timing - Table 5 reports the censored mean detection time and the T50 milestone for Experiment 2.

Table 5
Detection timing in Experiment 2

Cell (σ, m)	Method	Censored mean detect (s)	T50 attained	T50 mean (s)	Paired Δ vs Hilbert (s)
C1 (60)	Hilbert	496 ± 33	5/5	482.8	—
C1 (60)	Adaptive	447 ± 49	5/5	275.3	−48 [−79, −27]
C2 (120)	Hilbert	515 ± 109	4/5	493.4	—
C2 (120)	Adaptive	495 ± 65	4/5	397.0	−20 [−57, +33]
C3 (250)	Hilbert	561 ± 67	4/5	623.7	—
C3 (250)	Adaptive	515 ± 58	4/5	498.6	−46 [−96, +4]
C4 (1000)	Hilbert	572 ± 76	4/5	544.5	—
C4 (1000)	Adaptive	588 ± 76	2/5	536.4	+16 [−0, +40]

Pooled across the clustered cells, the adaptive strategy reduced the censored mean detection time by 34.19 s compared with Hilbert. The 95% confidence interval for the paired difference was [−59.45, −3.66] s, with the entire interval below zero, indicating a consistent reduction in detection time across the reported uncertainty range. A Wilcoxon signed-rank test gave p=0.0322, providing evidence of a statistically significant reduction at the conventional 5% level. The paired per-seed comparison also shows a clear pattern: the adaptive strategy was faster on 9 of the 10 seeds, tied on none, and was slower on only 1 seed. The improvement is also visible in the T_{50} milestone. At C1, the adaptive strategy reached 50% target detection in a mean of 275.3 s, compared with 482.8 s for Hilbert, while both strategies reached the T_{50} milestone in all five seeds. This shows that the adaptive strategy did not merely increase the final number of detected targets; under clustered conditions, it also reached the same intermediate detection level substantially earlier.

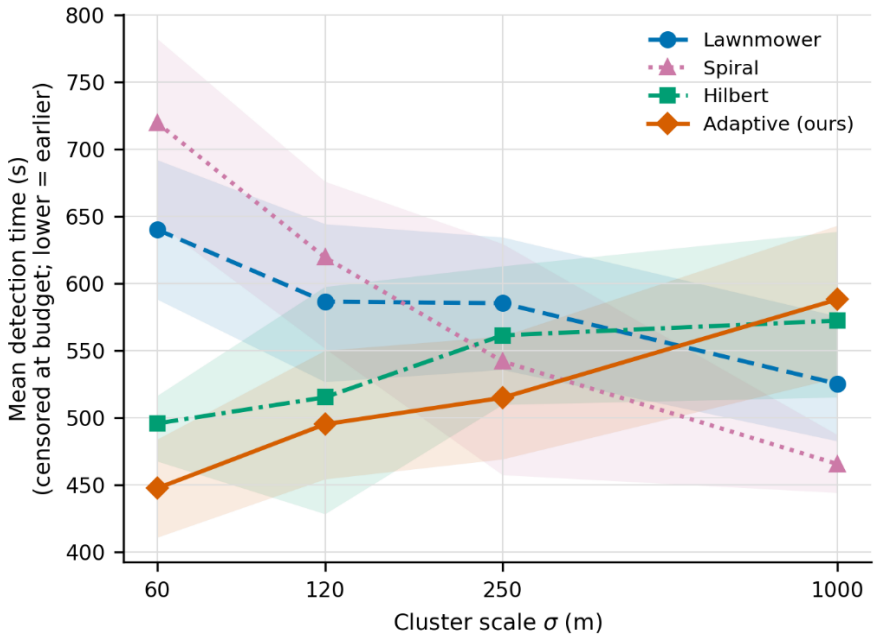

Figure 5
Mean detection time to target comparison in Experiment 2

At the approximately uniform extreme, the timing advantage of the adaptive strategy disappears, consistent with the detection-count results. At C4, the adaptive strategy reached the T_{50} milestone in only 2 of 5 seeds, compared with 4 of 5 seeds for Hilbert. Its censored mean T_{50} was also 16 s longer than that of Hilbert, indicating that the adaptive detours provided no timing benefit when targets were approximately uniformly distributed (Figure 5).

3.4. Ablation

With detours disabled, the adaptive planner reduces to the Hilbert sweep by construction. On the shared test seed at σ = 8 m in Experiment 1, the ablated planner produced exactly the same result as the Hilbert baseline, detecting 6 of 12 targets. A separate mechanism-identity check in the 1000 m arena recorded zero halo-ring detours when the maximum detour count was set to zero. These checks confirm that the exploration layers are identical and that any performance difference between the full adaptive strategy and Hilbert is attributable to the detection-triggered detour mechanism.

4. Discussion

4.1. A crossover set by the sensor, not by the strategy

The most informative feature of the Experiment 1 results is not the magnitude of the gain, but the location of the sign change. The adaptive advantage does not decrease gradually to zero as the clusters become more dispersed. Instead, it changes from positive to negative at a cluster scale close to the reliable sensor-footprint radius, with a cluster-to-footprint ratio of approximately 1.3. This suggests that the sensor geometry plays an important role in determining the boundary between the two search regimes. When the cluster scale is small relative to the region that can be resolved by the sensor, detecting one target provides useful information about the likely location of other targets. A bounded halo lap can then use this information to detect nearby targets before the systematic sweep reaches the same area again. As the cluster scale becomes larger than the footprint, a detection provides less useful information within the spatial range that the detour can cover, and the same lap is more likely to become an unproductive excursion. The crossover should therefore depend on the relationship between the target-cluster scale and the sensor's effective search scale. Changes in altitude, field of view, or lane spacing could consequently shift the crossover, rather than the crossover being determined only by the specific detour heuristic. This interpretation is consistent with regime crossovers reported in random-search studies, where the efficient movement pattern changes as the spatial scale of the targets changes relative to the searcher (Santos et al., 2004).

The distance measurements provide further support for this interpretation. The adaptive and Hilbert strategies traveled nearly identical total fleet distances at every clustering level, so the poorer performance of the adaptive strategy in dispersed layouts cannot be explained by substantially greater travel. Instead, the adaptive strategy used part of the same available flight effort for detours around detected targets, including targets that did not provide useful information about nearby anomalies. Under the fixed mission-time budget, this represents an allocation of limited search effort rather than a reduction in total travel capacity. The result is consistent with classical search theory, where concentrating search effort is beneficial when the target-location prior is concentrated, but provides less benefit when the prior approaches a uniform distribution (Koopman, 1957).

4.2. Why the advantage moves from count to time

The two experiments examine the same adaptive mechanism under different constraints, and the difference in their results is informative. In Experiment 1, a substantial part of the observed signal came from targets that could be detected within the same camera footprint. This effect was recorded mainly through an integer detection count under a short mission budget. Experiment 2 removed this channel by imposing a 90 m minimum separation between targets. The remaining effect was the ability of the adaptive detour to visit the region around a detected target before the systematic sweep would reach it. The systematic sweep eventually reaches the same region, so the detour does not necessarily increase the final number of detected targets when sufficient mission time is available. Its main effect is to change the order in which targets are detected.

This difference explains why the detection-count advantage in Experiment 2 is small and does not reach statistical significance, whereas the latency advantage does. The adaptive mechanism primarily changes when targets are detected rather than how many are eventually detected. Final detection counts under a fixed time budget therefore provide a relatively low-resolution measure of this effect, while paired detection latency captures the timing improvement directly. The paired latency results are also consistent across seeds: the adaptive strategy was faster on 9 of the 10 clustered pairs and slower on only one. This consistency provides evidence that the observed timing advantage reflects the search mechanism rather than a particularly favorable target layout.

4.3. Operational implications

The results can be translated into a decision rule that can be applied before a mission begins. The key quantity is the expected spatial correlation length of the anomalies relative to the reliable ground footprint of the sensor at the planned flight altitude. When the expected correlation length is smaller than or comparable to the footprint scale, a detected anomaly provides useful information about the likely location of nearby anomalies, and bounded detours can improve search performance. Examples include connected oil-slick spills and spatially extended corrosion zones. When anomalies are more isolated and their correlation length is large relative to the footprint, a detection provides less information about nearby targets, and a systematic sweep is more appropriate. Sporadic third-party damage and isolated manufacturing defects are examples of this regime.

The mission objective is equally important. When the priority is to minimize the time required to provide responders with confirmed anomaly locations, as in emergency spill response or search-and-rescue missions, detection latency is the relevant performance measure. Under clustered target conditions, the results support using the adaptive strategy in this setting. When the objective is instead to maximize the total number of anomalies detected during a routine patrol with a longer time budget, the benefit of adaptation is smaller because the systematic sweep eventually reaches regions explored by the detours. In this case, adaptation may provide little additional benefit and can introduce a small time cost. The bounded detour design also limits the cost of using adaptation when the target distribution is uncertain. A concurrency cap, a fixed lap count, and a minimum sweeper floor restrict the amount of flight effort that can be diverted from systematic coverage. Thus, an incorrect assumption about target clustering results in a known and bounded cost rather than an uncontrolled loss of coverage.

4.4. Limitations

Several limitations should be considered when interpreting these results. First, all targets are static and present from the beginning of the mission. The findings therefore do not directly extend to moving targets, such as drifting oil slicks, or to anomalies that emerge during the patrol. Second, target detection is modeled using a deterministic color segmenter. This provides controlled and repeatable detections but does not reproduce the false positives and missed detections that can occur with a learned computer-vision model. A noisier detector could trigger detours from false confirmations and could therefore reduce the measured benefit of the adaptive strategy. Third, the clustering generator uses a fixed structure of four parent locations with three offspring per parent. Consequently, the number of clusters and the number of targets within each cluster are not varied independently of σ. Fourth, the number of independent seeds is modest, with ten seeds per cell in Experiment 1 and five in Experiment 2. This limits statistical power and contributes to the wide confidence intervals and non-significant p-values observed in several Experiment 2 cells, even when the per-seed differences show a consistent direction. Finally, both experiments use square survey regions and a fleet of three UAVs. The results therefore do not establish how the detour allocation mechanism behaves with larger fleets or under different region geometries, where the interaction between adaptive detours and spatial partitioning may change.

5. Conclusion

This study investigated the level of spatial clustering at which detection-driven adaptive multi-UAV search begins to outperform systematic geometric coverage under a fixed time budget. Spatial clustering was treated as a controlled experimental variable rather than as an uncontrolled property of the target layouts. Three systematic sweep geometries were compared with a minimal adaptive strategy using identical target layouts. The adaptive strategy used the Hilbert sweep as its exploration layer and differed from it only through bounded detours triggered by confirmed detections. The comparison revealed a crossover between search regimes rather than a single strategy that was consistently superior. Under the tightest clustering condition in the 400 m arena, the adaptive strategy detected an average of 8.1 of 12 targets, compared with 6.6 for the best systematic sweep, corresponding to a 23% improvement. It outperformed Hilbert on 7 of 10 paired layouts and did not lose on any layout. The advantage decreased as the clusters became more dispersed, with the paired difference approaching parity at $\sigma = 40$ m and becoming negative at larger clustering scales, reaching deficits of 1.20 to 1.60 targets. Fleet distance remained nearly identical across the strategies at every clustering level, indicating that the reversal was caused by how the available flight time was allocated rather than by a difference in total travel. Interpolation placed the crossover at approximately $\sigma = 47$ m, or about 1.3 times the reliable cross-track sensing distance of the camera. Because this criterion is expressed as a ratio between the spatial scale of the target distribution and the effective sensing scale, it can be adapted to different flight altitudes and sensor configurations.

The second experiment imposed a minimum target separation greater than the sensor footprint diagonal. As a result, a single camera frame could no longer detect two targets simultaneously, removing the co-detection ambiguity present in the smaller arena. Under this constraint, the effect of adaptation was expressed more clearly through detection timing than through final target count. The pooled count advantage narrowed to 0.60 targets and did not reach statistical significance, whereas the censored mean detection time was reduced by 34.19 s, with a Wilcoxon test ($p = 0.0322$). The adaptive strategy was faster on 9 of the 10 paired layouts and slower on only one. At the tightest clustering level, the adaptive strategy reached 50% target detection in a mean of 275.3 s, compared with 482.8 s for Hilbert, and both strategies reached this milestone on all five layouts. These results indicate that the main benefit of exploitation is earlier detection rather than a consistent increase in the final number of targets detected. This distinction is particularly important in applications where the value of a detection decreases with time. Under approximately uniform placement, the timing advantage disappeared and the bounded detour became a cost, making systematic coverage preferable. Finally, the ablation test reproduced the Hilbert detection count exactly when detours were disabled, confirming that the observed difference between the two methods is attributable to the detection-triggered detour layer.

Three practical rules follow from these results.

- **Deployment.** Enable adaptive detours when the operational objective is to provide responders with confirmed anomaly locations as quickly as possible, particularly when the anomalies are expected to be spatially clustered.
- **Dispersion.** Prefer systematic coverage when anomalies are expected to be distributed over spatial scales larger than the reliable sensor footprint. If adaptive detours are retained under uncertain conditions, their maximum effort should be explicitly bounded so that the cost of an incorrect assumption about clustering remains limited.
- **Reporting.** Report target spacing relative to the effective sensor footprint. Without controlling or reporting this relationship, an observed advantage of an adaptive planner may be partly attributable to frame-level co-detection rather than to the planner itself.

More broadly, the choice between systematic and adaptive search should not be viewed simply as a choice between two planner families. The results indicate that it depends on a measurable relationship

between the spatial scale of the target distribution and the effective sensing scale of the UAV. Both quantities can be estimated before deployment, allowing the search strategy to be selected according to the expected operating regime. Whether the same relationship remains valid when targets move or appear during the mission is not established by the present experiments and provides a natural direction for future work. These scenarios will place greater emphasis on real-time detection latency, which is the setting in which adaptive coordination is expected to provide the greatest benefit. The strategies will also be tested in non-square and obstructed survey regions to determine whether the observed crossover depends on the geometry of the survey area. The framework will be scaled to larger and heterogeneous UAV swarms to examine how localized detour allocation interacts with spatial partitioning as the fleet size and platform capabilities increase. Finally, the deterministic color segmenter will be replaced with a learned detector that produces realistic false positives and missed detections. This will allow the sensitivity of the adaptive detour mechanism to detection quality to be evaluated under more realistic perception conditions.

References

Allen, J., & Walsh, B. (2008). Enhanced oil spill surveillance, detection and monitoring through the applied technology of unmanned air systems. *International Oil Spill Conference Proceedings, 2008*(1), 113–120. https://doi.org/10.7901/2169-3358-2008-1-113

Asadzadeh, S., de Oliveira, W. J., & de Souza Filho, C. R. (2022). UAV-based remote sensing for the petroleum industry and environmental monitoring: State-of-the-art and perspectives. *Journal of Petroleum Science and Engineering*, *208*, Article 109633. https://doi.org/10.1016/j.petrol.2021.109633

Bailon-Ruiz, R., Bit-Monnot, A., & Lacroix, S. (2022). Real-time wildfire monitoring with a fleet of UAVs. *Robotics and Autonomous Systems*, *152*, Article 104071. https://doi.org/10.1016/j.robot.2022.104071

Bourgault, F., Furukawa, T., & Durrant-Whyte, H. F. (2003). Coordinated decentralized search for a lost target in a Bayesian world. In *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)* (Vol. 1, pp. 48–53). IEEE. https://doi.org/10.1109/IROS.2003.1250604

Cabreira, T. M., Di Franco, C., Ferreira, P. R., Jr., & Buttazzo, G. C. (2018). Energy-aware spiral coverage path planning for UAV photogrammetric applications. *IEEE Robotics and Automation Letters, 3*(4), 3662–3668. https://doi.org/10.1109/LRA.2018.2854967

Cabreira, T. M., Brisolara, L. B., & Ferreira, P. R., Jr. (2019). Survey on coverage path planning with unmanned aerial vehicles. *Drones*, *3*(1), Article 4. https://doi.org/10.3390/drones3010004

Chiu, S. N., Stoyan, D., Kendall, W. S., & Mecke, J. (2013). *Stochastic geometry and its applications* (3rd ed.). Wiley. https://doi.org/10.1002/9781118658222

Choset, H. (2000). Coverage of known spaces: The boustrophedon cellular decomposition. *Autonomous Robots*, *9*(3), 247–253. https://doi.org/10.1023/A:1008958800904

Choset, H. (2001). Coverage for robotics – a survey of recent results. *Annals of Mathematics and Artificial Intelligence*, *31*(1), 113–126. https://doi.org/10.1023/A:1016639210559

Choset, H., & Pignon, P. (1998). Coverage path planning: The boustrophedon cellular decomposition. In A. Zelinsky (Ed.), *Field and service robotics* (pp. 203–209). Springer. https://doi.org/10.1007/978-1-4471-1273-0_32

Chung, T. H., & Burdick, J. W. (2012). Analysis of search decision making using probabilistic search strategies. *IEEE Transactions on Robotics*, *28*(1), 132–144. https://doi.org/10.1109/TRO.2011.2170333

Facinelli, D., Larcher, M., Brunelli, D., & Fontanelli, D. (2019). Cooperative UAVs gas monitoring using distributed consensus. In *2019 IEEE 43rd Annual Computer Software and Applications Conference (COMPSAC)* (pp. 463–468). IEEE. https://doi.org/10.1109/COMPSAC.2019.00072

Galceran, E., & Carreras, M. (2013). A survey on coverage path planning for robotics. *Robotics and Autonomous Systems*, *61*(12), 1258–1276. https://doi.org/10.1016/j.robot.2013.09.004

Hou, Y., Zhao, J., Zhang, R., Cheng, X., & Yang, L. (2024). UAV swarm cooperative target search: A multi-agent reinforcement learning approach. *IEEE Transactions on Intelligent Vehicles*, *9*(1), 568–578. https://doi.org/10.1109/TIV.2023.3316196

International Civil Aviation Organization, & International Maritime Organization. (2006). *International aeronautical and maritime search and rescue manual: Volume I. Organization and management* (5th ed.).

Joshi, A. A., Bhatt, M. C., & Sinha, A. (2019). Modification of Hilbert's space-filling curve to avoid obstacles: A robotic path-planning strategy. In *2019 Sixth Indian Control Conference (ICC)* (pp. 338–343). IEEE. https://doi.org/10.1109/ICC47138.2019.9123166

Koopman, B. O. (1957). The theory of search: III. The optimum distribution of searching effort. *Operations Research*, *5*(5), 613–626. https://doi.org/10.1287/opre.5.5.613

Lyu, M., Zhao, Y., Huang, C., & Huang, H. (2023). Unmanned aerial vehicles for search and rescue: A survey. *Remote Sensing*, *15*(13), Article 3266. https://doi.org/10.3390/rs15133266

Miller, L. M., Silverman, Y., MacIver, M. A., & Murphey, T. D. (2016). Ergodic exploration of distributed information. *IEEE Transactions on Robotics*, *32*(1), 36–52. https://doi.org/10.1109/TRO.2015.2500441

Mohanty, N., Gadde, M. S., Sundaram, S., Sundararajan, N., & Sujit, P. B. (2020). *Context-aware deep Q-network for decentralized cooperative reconnaissance by a robotic swarm* [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2001.11710

Palyulin, V. V., Chechkin, A. V., & Metzler, R. (2014). Lévy flights do not always optimize random blind search for sparse targets. *Proceedings of the National Academy of Sciences*, *111*(8), 2931–2936. https://doi.org/10.1073/pnas.1320424111

Rekleitis, I., New, A. P., Rankin, E. S., & Choset, H. (2008). Efficient boustrophedon multi-robot coverage: An algorithmic approach. *Annals of Mathematics and Artificial Intelligence*, *52*(2–4), 109–142. https://doi.org/10.1007/s10472-009-9120-2

Santos, M. C., Raposo, E. P., Viswanathan, G. M., & da Luz, M. G. E. (2004). Optimal random searches of revisitable targets: Crossover from superdiffusive to ballistic random walks. *Europhysics Letters (EPL)*, *67*(5), 734–740. https://doi.org/10.1209/epl/i2004-10114-9

Shakhatreh, H., Sawalmeh, A. H., Al-Fuqaha, A., Dou, Z., Almaita, E., Khalil, I., Othman, N. S., Khreishah, A., & Guizani, M. (2019). Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges. *IEEE Access*, *7*, 48572–48634. https://doi.org/10.1109/ACCESS.2019.2909530

Shen, G., Lei, L., Zhang, X., Li, Z., Cai, S., & Zhang, L. (2023). Multi-UAV cooperative search based on reinforcement learning with a digital twin driven training framework. *IEEE Transactions on Vehicular Technology*, *72*(7), 8354–8368. https://doi.org/10.1109/TVT.2023.3245120

Spires, S. V., & Goldsmith, S. Y. (1998). Exhaustive geographic search with mobile robots along space-filling curves. In A. Drogoul, M. Tambe, & T. Fukuda (Eds.), *Collective robotics* (pp. 1–12). Springer. https://doi.org/10.1007/BFb0033369

Stone, L. D. (1975). *Theory of optimal search*. Academic Press.

Thomas, M. (1949). A generalization of Poisson's binomial limit for use in ecology. *Biometrika*, *36*(1–2), 18–25. https://doi.org/10.1093/biomet/36.1-2.18

Viswanathan, G. M., Buldyrev, S. V., Havlin, S., da Luz, M. G. E., Raposo, E. P., & Stanley, H. E. (1999). Optimizing the success of random searches. *Nature*, *401*(6756), 911–914. https://doi.org/10.1038/44831

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Application of Renewable Energy Sources in the Mining Industry: Assessment of Ecological and Economic Potential

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Abstract. *This article comprehensively assesses the ecological and economic potential of applying renewable energy sources in the mining industry. The primary objective of the study is to determine the feasibility of reducing dependence on conventional energy sources and integrating alternative energy solutions into industrial processes. The article analyzes the application prospects of solar, wind, hydro, and other renewable energy sources in the mining sector, examining their impact on production processes and their contributions to energy efficiency. Furthermore, the issues of reducing carbon dioxide emissions, environmental protection, and ensuring ecological sustainability as outcomes of implementing these technologies are elaborated upon in detail. Within the framework of the study, the experiences of various countries are comparatively analyzed, and the economic effectiveness of contemporary energy models applied in the mining industry is evaluated. The advantages of alternative energy sources are identified in terms of capital investment, operational costs, and long-term economic benefits. The findings indicate that the application of renewable energy sources in the mining industry represents an approach that is not only ecologically sound but also economically viable. This, in turn, holds considerable significance for ensuring energy security and achieving the sustainable development of the industry in the future.*

Keywords: *renewable energy, mining industry, renewable energy sources, ecological sustainability, economic effectiveness, energy efficiency*

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Dağ-mədən sənayesində bərpa olunan enerji mənbələrinin tətbiqi: Ekoloji və iqtisadi potensialın qiymətləndirilməsi

Zeynal Abasov

Xülasə. *Bu məqalədə mədən sənayesində bərpa olunan enerji mənbələrinin tətbiqinin ekoloji və iqtisadi potensialı kompleks şəkildə qiymətləndirilmişdir. Tədqiqatın əsas məqsədi ənənəvi enerji mənbələrindən asılılığın azaldılması və alternativ enerji həllərinin sənaye proseslərinə inteqrasiyasının səmərəliliyini müəyyən etməkdən ibarətdir. Məqalədə günəş, külək, hidro və digər bərpa olunan enerji mənbələrinin mədən sektorunda tətbiq imkanları təhlil edilmiş, onların istehsal proseslərinə təsiri və enerji səmərəliliyinə verdiyi töhfələr araşdırılmışdır. Eyni zamanda, bu texnologiyaların tətbiqi nəticəsində karbon qazı emissiyalarının azaldılması, ətraf mühitin qorunması və ekoloji dayanıqlığın təmin olunması məsələləri geniş şəkildə nəzərdən keçirilmişdir. Tədqiqat çərçivəsində müxtəlif ölkələrin təcrübələri müqayisəli şəkildə təhlil edilmiş, mədən sənayesində tətbiq olunan müasir enerji modellərinin iqtisadi effektivliyi qiymətləndirilmişdir.*

Kapital qoyuluşu, əməliyyat xərcləri və uzunmüddətli iqtisadi faydalar baxımından alternativ enerji mənbələrinin üstünlükləri müəyyən edilmişdir. Nəticələr göstərir ki, bərpa olunan enerji mənbələrinin mədən sənayesində tətbiqi yalnız ekoloji baxımdan deyil, həm də iqtisadi cəhətdən səmərəli yanaşma kimi çıxış edir. Bu isə gələcəkdə enerji təhlükəsizliyinin təmin olunması və sənayenin dayanıqlı inkişafı üçün mühüm əhəmiyyət kəsb edir.

Açar sözlər: *davamlı enerji, mədən sənayesi, bərpa olunan enerji mənbələri, ekoloji dayanıqlıq, iqtisadi effektivlik, enerji səmərəliliyi*

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Introduction

The development dynamics of the global economic system in the modern era are accompanied by a continuous increase in demand for energy resources. Concurrently, global challenges such as climate change, rising carbon emissions, and environmental degradation have necessitated a reassessment of operational models across industrial sectors. In this context, conventional approaches to energy production and consumption are gradually undergoing transformation, being replaced by more sustainable and ecologically responsible models. This transformation process is particularly pronounced in sectors characterized by high energy intensity.

The mining industry, while serving as one of the fundamental pillars of the global economy, plays a significant role in ensuring industrial production and facilitating the energy transition. This sector forms the essential raw material base required for the development of both the conventional energy sector and next-generation technologies. At the same time, the mining industry is characterized by high energy consumption and carbon emissions, rendering it one of the critical sectors in terms of environmental impact. In this regard, the optimization of energy use and the application of alternative energy sources in the mining sector constitute not merely an economic necessity, but an ecological imperative as well (Abdullayev, 2020).

Conventionally, energy supply in the mining industry has been primarily ensured through fossil fuels. This leads to increased carbon emissions, air and soil pollution, as well as the disruption of ecosystems. Furthermore, the fact that the majority of mining sites are located in remote regions with underdeveloped infrastructure further complicates energy supply and generates additional logistical costs. Under these conditions, the application of renewable energy sources is regarded as a promising solution both for enhancing the stability of energy supply and for optimizing operational costs.

In recent years, the rapid advancement of renewable energy technologies, particularly solar and wind energy, has expanded their applicability across industrial sectors. The declining cost of technologies and the increasing accessibility of energy production have notably stimulated investment interest in this field. Moreover, advancements in energy storage technologies are creating conditions for overcoming the instability problems posed by intermittent energy sources. These factors render the application of renewable energy sources in the mining industry increasingly feasible and economically justified.

International experience demonstrates that the application of renewable energy sources in the mining industry is not limited solely to reducing environmental impacts. This approach simultaneously enables the reduction of long-term energy costs, the enhancement of energy security, and the

minimization of dependence on energy price volatility. Furthermore, such approaches positively influence the improvement of companies' ESG (Environmental, Social, and Governance) indicators and the enhancement of their investment attractiveness. This, in turn, creates additional advantages for companies operating in global capital markets (Aghaei & Alizadeh, 2013).

Nevertheless, the application of renewable energy sources in the mining industry cannot be regarded as a universally straightforward and unproblematic process. A number of technical, economic, and institutional constraints exist in this domain. High initial capital investment costs, the intermittent nature of energy production, technological compatibility challenges, and the inadequate development of the regulatory framework constitute the principal difficulties of this process. For this reason, the application of renewable energy sources must be evaluated with due consideration of the specific characteristics of each individual mining project.

Although the application of renewable energy sources across various industrial sectors has been extensively investigated in the existing scholarly literature, the comprehensive assessment of the ecological and economic potential of such applications in the mining industry — that is, on the basis of an integrated approach — has not been presented in a sufficiently systematic manner. The majority of studies focus either on technological aspects or on individual economic indicators, which limits a holistic analysis of the subject. At the same time, the investigation of regional specificities and the applicability for developing countries also remains at a limited level.

In this regard, the present study aims to comprehensively assess the ecological and economic potential of applying renewable energy sources in the mining industry, to conduct a comparative analysis of international experience, and to identify application prospects for Azerbaijan on the basis of the findings obtained. This approach ensures that the subject is investigated in a direction that allows for more systematic and practically significant conclusions to be drawn.

The Purpose of the Study

The primary objective of this study is to assess the ecological and economic potential of applying renewable energy sources in the mining industry. Within the framework of the research, the integration of alternative energy sources into industrial processes, their efficiency, and their long-term impacts have been examined (BPS, 2022).

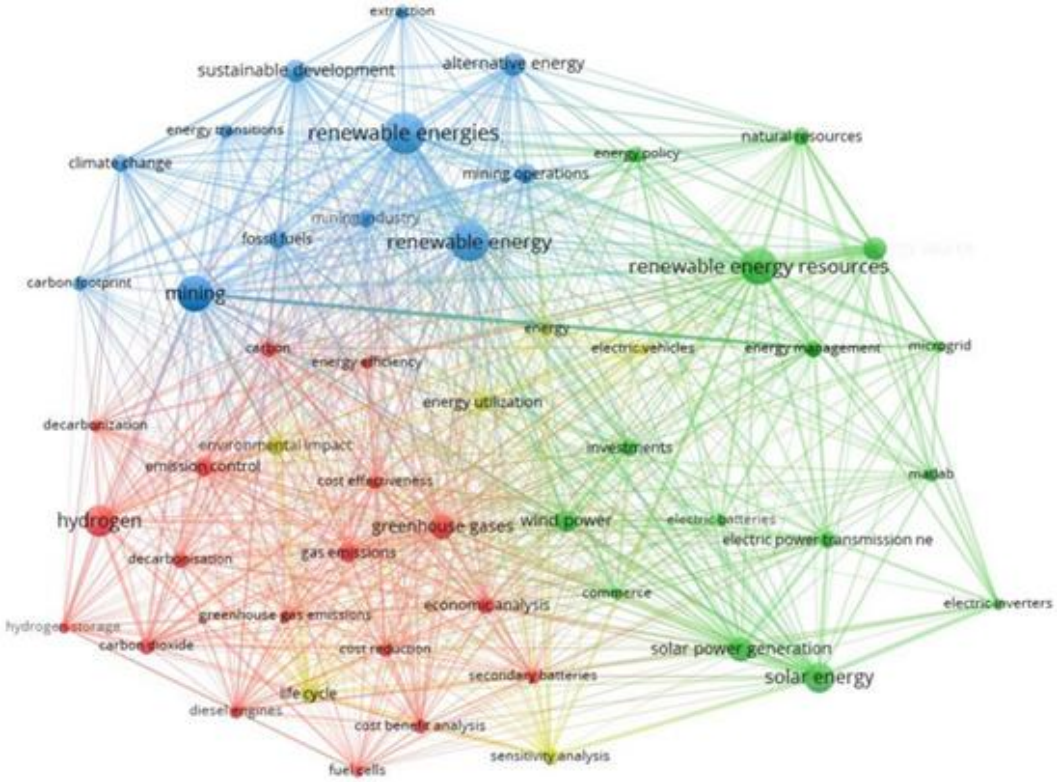
In accordance with the purpose of the study, the following objectives have been identified:

1. To analyze the characteristics and challenges of conventional energy sources used in the mining industry;
2. To examine the application prospects of renewable energy sources (solar, wind, etc.);
3. To assess the ecological impact of these sources;
4. To analyze the economic efficiency of alternative energy technologies;
5. To identify application prospects by examining international experience.

In recent years, scholarly interest in the application of renewable energy sources for the purpose of optimizing energy consumption and reducing environmental impacts in the mining industry has increased considerably. Internationally adopted strategies aimed at combating climate change and reducing carbon emissions have stimulated the formation of new approaches in this field.

The mining industry has conventionally been regarded as one of the most energy-intensive sectors and remains predominantly dependent on fossil fuels. This gives rise to both high operational costs and adverse environmental impacts. A number of studies indicate that energy costs in the mining industry may constitute 15–40% of total operational expenditures. For this reason, the application of

alternative energy sources holds strategic significance from both an economic and an ecological standpoint (Aliyev, 2020).



According to reports by the International Energy Agency (IEA), solar and wind energy have been the most rapidly developing energy sources over the past decade. The application of these energy sources has become particularly widespread at mining sites located in remote areas with inadequate energy infrastructure. This approach not only reduces dependence on diesel generators but also enables the optimization of energy costs.

Figure 1
Visual map of scholarly research directions in renewable energy and the mining industry

The application of solar energy in the mining industry has been extensively investigated in the scholarly literature. Studies indicate that, despite high initial capital investment, solar energy is distinguished by low operational costs over the long-term perspective and is considered economically viable. Wind energy, in turn, serves as an effective alternative particularly in regions situated in open areas with high wind potential (Dincer, 2000).

Some researchers evaluate the application of hybrid energy systems as a more optimal solution. In these systems, the combined use of solar, wind, and diesel generators ensures the continuity of energy supply and mitigates energy-related risks. Concurrently, advancements in energy storage technologies further enhance the effectiveness of such systems.

On the other hand, several authors also note the challenges that exist in the application of renewable energy sources. These include high initial investment costs, technological uncertainties, limited capacities of energy storage systems, and infrastructure deficiencies in certain regions.

From a theoretical standpoint, the principal approach in this field is associated with the concept of sustainable development. This concept envisages the balancing of economic development with ecological and social factors. The application of renewable energy sources in the mining industry serves to ensure this balance and to enhance the long-term sustainability of the sector. The structure and principal directions of scholarly research conducted in the field of renewable energy and the mining industry are of a complex nature. In contemporary approaches, the thematic classification and interrelations of studies carried out in this field are of particular significance (McKinsey, 2022).

In this regard, a visual analysis of the scholarly literature on the subject enables a more precise identification of research directions.

As can be observed from Figure 1, research conducted in the field of renewable energy and the mining industry is grouped along several principal directions. Among these directions, renewable energy sources, energy efficiency, reduction of carbon emissions, and economic analysis emerge as the primary subjects.

The central positioning of concepts such as "renewable energy", "mining", and "sustainable development" in the visual map indicates that these fields constitute the principal direction in scholarly research. At the same time, the close interrelation of concepts such as "carbon emissions", "environmental impact", and "energy efficiency" confirms that ecological challenges represent one of the core components of research conducted in this domain.

Furthermore, the presentation of concepts such as "solar energy", "wind power", and "energy management" as distinct clusters demonstrates that renewable energy technologies occupy a particular place in scholarly research. This, in turn, reaffirms the relevance of applying renewable energy sources in the mining industry (Əliyev, 2019).

Overall, the visual analysis presented indicates that scholarly research conducted on the subject is of a multidisciplinary nature and is shaped on the basis of the interrelation of energy, economic, and ecological aspects.

Methodology

In this study, a comprehensive methodological approach has been employed for the purpose of assessing the ecological and economic potential of applying renewable energy sources in the mining industry. The research is primarily grounded in analytical and comparative analysis methods.

Within the framework of the study, existing scholarly literature, reports of international organizations, and statistical data were systematically analyzed at the initial stage. Through this approach, prevailing theoretical and practical perspectives pertaining to the application of renewable energy sources in the mining industry were synthesized.

Concurrently, the experiences of various countries were examined on a comparative basis. To this end, energy models applied in Canada, Australia, and other countries were analyzed and their effectiveness was evaluated.

Economic analysis methods were also employed in the study. Within this framework, capital investment, operational costs, and long-term economic benefits associated with the application of alternative energy sources were taken into consideration. The optimization of energy costs and investment efficiency served as the principal evaluation criteria.

In the assessment of ecological aspects, the reduction of carbon emissions, the minimization of environmental impact, and the principles of sustainable development were adopted as the foundational basis (Energy Institute, 2024).

The methodological foundation of the study is constituted by a systemic approach. Within the framework of this approach, energy use in the mining industry was assessed in a comprehensive manner — across technical, economic, and ecological dimensions. The systemic approach enabled the consideration of the interplay between various factors and facilitated the attainment of more objective conclusions.

Both qualitative and quantitative analysis methods were employed throughout the research process. Within the framework of qualitative analysis, existing scholarly approaches, theoretical models, and international experience were examined. Quantitative analysis, in turn, was conducted on the basis of a comparison of indicators such as energy costs, emission metrics, and investment efficiency.

Furthermore, the scenario analysis method was employed. Through this approach, possible development scenarios across various energy models — namely conventional and renewable energy-based systems — were examined, and their potential outcomes were evaluated. Scenario analysis facilitated a more substantiated decision-making process under conditions of uncertainty.

A comparative advantages analysis was also conducted in the study. Within this framework, the economic and ecological differences between conventional and renewable energy sources were systematically compared. In particular, energy consumption, operational costs, and carbon emissions were adopted as the principal criteria for comparison.

One of the significant elements of the methodology is risk assessment. Within this framework, technical, financial, and institutional risks that may arise during the application of alternative energy sources were examined. The identification of risks created conditions for a more realistic evaluation of future application prospects.

Finally, for the purpose of ensuring the reliability of the study's findings, a comparative verification of data obtained from various sources was conducted. This approach enhanced the objectivity and scholarly rigor of the conclusions (European Commission, 2022).

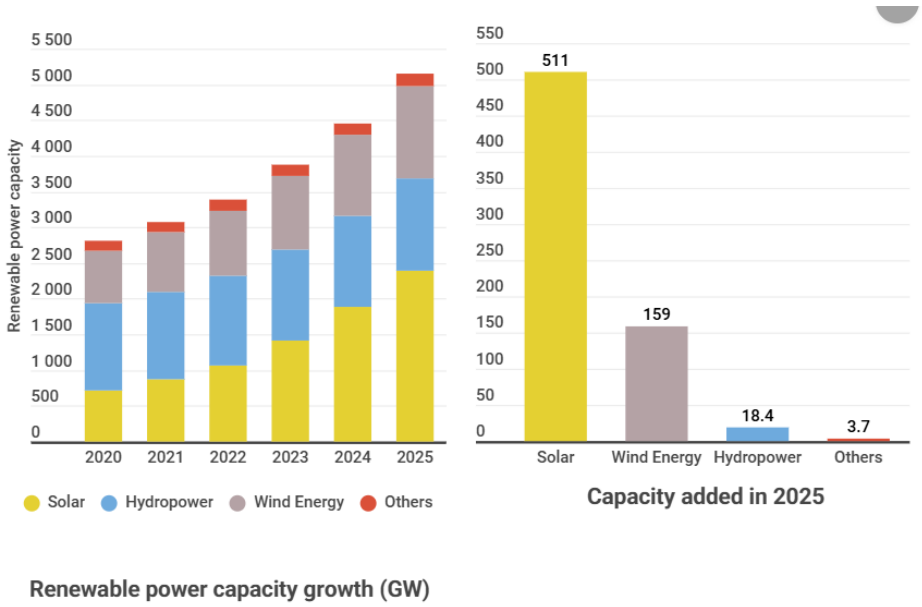
In this study, comparative analysis, literature review, and statistical data analysis methods were employed for the purpose of evaluating the effectiveness of applying renewable energy sources in the mining industry. Within the framework of the research, data were systematized and synthesized on the basis of reports from international organizations, scholarly articles, and national sources.

The mining industry is regarded as one of the most energy-intensive industrial sectors, and the predominant share of energy consumed in this field has conventionally been based on diesel fuel and other fossil energy sources. Diesel generators are extensively utilized as the primary energy source particularly at mining sites located in remote regions with underdeveloped energy infrastructure. This, in turn, creates additional logistical challenges.

Dependence on fossil fuels gives rise to serious challenges not only from an economic standpoint but also from an ecological perspective. Diesel-based energy systems not only cause high levels of carbon emissions but also result in the release of other harmful gases into the atmosphere. This exerts an adverse effect on the acceleration of climate change and the degradation of the environment. These impacts are observed with particular clarity in open-pit mines and large-scale extraction processes. Scholarly research conducted in recent years and reports by international organizations indicate that the application of renewable energy sources in the mining industry can play a significant role in addressing these challenges. Alternative sources such as solar and wind energy create opportunities not only for the reduction of emissions but also for the optimization of energy costs. In particular, the rapid advancement of solar energy technologies and the decline in their costs have rendered their application in this field more favorable.

Analyses conducted indicate that although the initial investment costs of solar and wind energy are high, operational costs are considerably lower over the long-term perspective. Particularly at remote mining sites, where the transportation of diesel fuel generates additional expenditure, renewable energy becomes more cost-effective. This leads to both an increase in economic efficiency and a considerable reduction in carbon emissions. Based on various studies, the application of renewable energy technologies results in a 20–40% reduction in energy costs at mining enterprises. Concurrently, a 30–60% reduction in carbon emissions is observed, which constitutes a significant indicator from the standpoint of ecological sustainability (OECD, 2021).

The particularly rapid advancement of solar energy in recent years is explained by its increasing technological accessibility and greater economic viability. Although wind energy also plays an important role, it lags behind solar energy in terms of growth rate. Hydropower, while representing a more stable source, demonstrates comparatively limited dynamics in terms of new capacity additions.



The figure below presents the growth dynamics of renewable energy capacity in recent years, as well as the structure of newly added energy capacities for the year 2025.

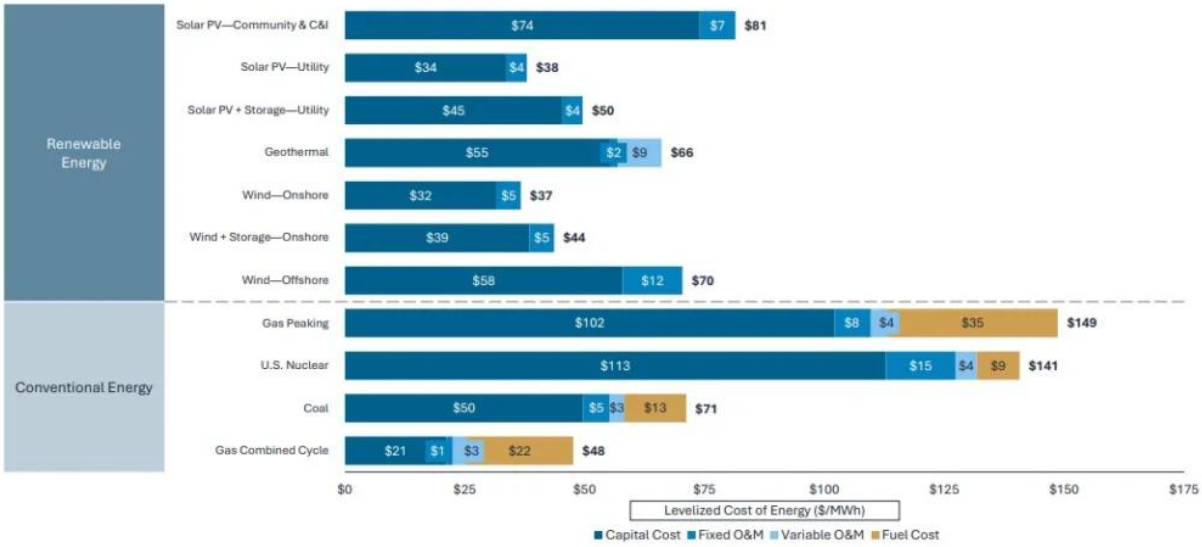
As can be observed from the figure, a sustained increase in renewable energy capacity has been recorded in recent years, with the predominant share of this growth attributable to solar energy. The dominance of solar energy among the newly added energy capacities in 2025 is associated with its technological advancement and economic accessibility.

Figure 2

Growth of renewable energy capacity and the structure of newly added capacities in 2025

This dynamic is also of considerable significance for the mining industry. The rapid development of solar energy and its broad application prospects render it an optimal energy source particularly for remote mining sites. At the same time, wind energy serves as an additional energy source in certain regions, enabling the diversification of energy supply (REN21, 2023).

Contemporary research indicates that the Levelized Cost of Energy (LCOE) indicators for renewable energy sources have decreased considerably in recent years and have, in many instances, become more competitive in comparison with conventional energy sources.



The figure below presents a comparison of LCOE indicators across various energy sources.

As can be observed from the figure, LCOE indicators for renewable energy sources are, in many instances, at a lower level in comparison with conventional energy sources. In particular, onshore wind energy and utility-scale solar energy are distinguished by the lowest energy production costs.

The fact that solar energy falls within the range of 30–40 $/MWh in certain cases indicates that it has become one of the most economically favorable energy sources. Wind energy similarly enables energy production at comparably low costs (Gielen, Boshell, Saygin, Bazilian, Wagner, & Gorini, 2019).

This difference is of particular significance for the mining industry. For mining enterprises that have conventionally relied on diesel and gas-based energy systems, a transition to renewable energy sources may result in a reduction of operational costs over the long-term perspective.

Figure 3

Comparison of the levelized cost of energy (LCOE) across various energy sources

At the same time, as can be observed from the figure, the primary costs associated with renewable energy sources are related to initial capital investment; however, operational costs are comparatively low. This indicates that these technologies are more efficient for long-term mining projects.

In conclusion, the high fuel costs associated with conventional energy sources increase dependence on price volatility, thereby elevating economic risks. Renewable energy sources, in this regard, present a more stable and predictable energy model.

Overall, the LCOE comparison presented demonstrates that the application of renewable energy sources in the mining industry constitutes a direction that is justified and prospective not only from an ecological but also from an economic standpoint.

The mining industry is regarded as one of the most environmentally sensitive and intensive industrial sectors. The energy sources utilized in this field, particularly fossil fuels, give rise to high levels of carbon emissions and other ecological challenges. In this regard, the application of renewable energy

sources serves as a significant instrument for reducing the environmental impacts of the mining industry (Hüseynov, 2021).

Diesel and coal-based technologies employed in conventional energy systems represent one of the primary sources of carbon dioxide emissions. The utilization of these energy sources results in the release of large volumes of carbon dioxide (CO_2), nitrogen oxides (NO_x), and other harmful substances into the atmosphere. This not only accelerates climate change but also leads to the deterioration of air quality and adverse effects on human health.

The application of renewable energy sources creates opportunities for mitigating these adverse impacts. Alternative energy sources such as solar and wind energy are characterized by near-zero emissions during the operational phase. This attribute renders them among the most ecologically suitable energy sources for the mining industry.

International research indicates that, as a result of implementing renewable energy systems at mining sites, a reduction of carbon emissions in the range of 30–70% is achievable. This enables a considerable reduction in the adverse impact of the mining industry on the global carbon balance.

At the same time, the application of renewable energy sources also creates conditions for the improvement of environmental management systems in the mining industry. This enables companies to operate in accordance with international ecological standards and to improve their ESG (Environmental, Social, and Governance) indicators. The improvement of ESG indicators, in turn, plays a significant role in attracting international investment flows (Owusu & Asumadu-Sarkodie, 2016).

Another significant point is the reduction of ecological risks arising during the processes of energy production and consumption. Leakages and accidents that may occur during the transportation and storage of diesel fuel can give rise to serious ecological challenges. The application of renewable energy sources eliminates these risks, thereby forming a safer and more sustainable energy system.

It should be noted, however, that renewable energy sources are not entirely without impact. The production and disposal of solar panels, for instance, may be accompanied by certain ecological effects. Nevertheless, when the overall life cycle is taken into consideration, these impacts are at a considerably lower level in comparison with conventional energy sources.

Overall, the analyses conducted indicate that the application of renewable energy sources in the mining industry presents significant ecological advantages. This approach serves not only the reduction of carbon emissions but also the protection of the environment, the enhancement of ecosystem sustainability, and the ensuring of the long-term ecological safety of the industry.

Energy supply in the mining industry constitutes one of the principal components of operational costs. Particularly at mining enterprises located in remote areas with limited infrastructure, energy costs may account for a significant portion of total production expenditures. In this regard, the assessment of the economic efficiency of energy sources is of considerable importance for the sustainable development of the mining industry (International Energy Agency, 2023).

Discussion

Conventionally, energy supply in the mining industry is primarily ensured through diesel generators. However, the high price of diesel fuel, transportation costs, and price volatility render this energy model economically unstable. In particular, the delivery of fuel to remote areas generates additional logistical costs and increases the overall cost of energy.

In recent years, the advancement of renewable energy technologies and the decline in their costs have created new economic opportunities in this field. Although alternative sources such as solar and wind energy require initial capital investment, their operational costs are comparatively low. This characteristic leads to a reduction in overall energy costs over the long-term perspective.

One of the most widely employed indicators for assessing the economic efficiency of energy sources is the levelized cost of energy.

As can be observed in Figure 4, renewable energy sources — particularly onshore wind and solar energy — possess lower LCOE indicators in comparison with other energy technologies. This demonstrates that they are more competitive from an economic standpoint (Quliyev, 2022).

The relatively low-cost energy production of solar photovoltaic systems and onshore wind energy constitutes one of the primary reasons for their widespread adoption in recent years. In contrast, costs in nuclear energy and gas-based energy technologies remain at a higher level, rendering them less favorable from an economic perspective.

At the same time, the figure indicates that while the primary costs associated with renewable energy technologies are related to initial investment, operational costs are low. This characteristic is of particular significance for long-term mining projects.

The application of renewable energy sources creates opportunities not only for the reduction of energy costs but also for ensuring long-term economic stability. The implementation of such energy projects requires substantial capital expenditure (CAPEX) at the initial stage. However, these costs are compensated over time through lower operational expenditures (OPEX). Over the long-term perspective, this model is considered more efficient, and the return on investment period reaches a satisfactory level.

Another significant economic advantage is the reduction of dependence on energy price volatility. Price fluctuations occurring in fossil fuel markets increase economic risks in the mining industry. Renewable energy sources, in this regard, present a more stable energy model and facilitate long-term planning (International Renewable Energy Agency, 2022).

At the same time, the application of renewable energy technologies creates additional economic opportunities for mining companies. For instance, in certain cases, surplus generated energy may be transmitted to other consumers, thereby serving as an additional source of revenue. Furthermore, the reduction of carbon emissions gives rise to opportunities for participation in carbon credit markets, which provides additional economic benefits.

Nevertheless, certain economic challenges also exist. The high level of initial investment costs and, in certain cases, the requirement for additional infrastructure to implement the technologies are regarded as among the principal obstacles in this field. However, the advancement of technology and the expansion of financial instruments are creating conditions for the gradual resolution of these challenges.

Overall, the analyses conducted indicate that the application of renewable energy sources in the mining industry constitutes an economically justified and efficient approach. This approach serves not only the reduction of costs but also the ensuring of economic stability, the mitigation of risks, and the formation of long-term sustainable development (Saidur, Rahim, Islam, & Solangi, 2011).

Figure 4

Levelized cost of energy (LCOE) across various energy technologies

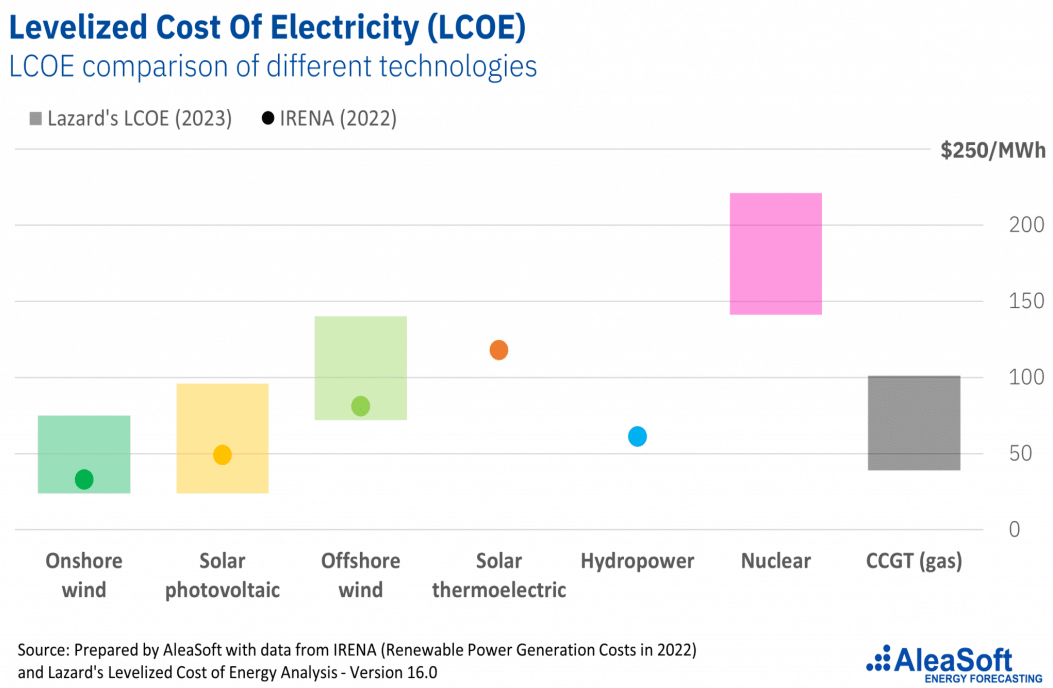
The application of renewable energy sources in the mining industry, while offering significant advantages, is also accompanied by a number of risks and challenges. One of the principal challenges is the high initial investment costs, which particularly complicate the realization of projects at remote mining sites (U.S. Energy Information Administration, 2023).

Furthermore, the intermittency of solar and wind energy poses a risk to the continuity of energy supply. The integration of existing infrastructure with these systems is technically complex and requires additional resources and qualified personnel. The limited capacity of energy storage technologies also constitutes one of the factors that complicates implementation.

Technological and financial risks are also of considerable significance. Uncertainties regarding the long-term effectiveness of equipment, volatility in energy markets, and limited access to financial resources affect the efficiency of projects. The inadequacy of the legal and institutional framework, as well as personnel shortages, further complicate this process.

Overall, the effective management of these risks and proper planning are regarded as the fundamental prerequisites for the successful implementation of renewable energy projects.

As presented in Figure 5, the risks associated with the application of renewable energy sources in the mining industry have been systematized across various categories. Each of these risks exerts a different level of influence on the realization of projects. Their comprehensive assessment is therefore imperative (International Renewable Energy Agency, 2023).



Financial risks are primarily associated with high initial investment costs and market volatility. Technical risks, in turn, are related to the intermittency of energy production and the integration of existing infrastructure. At the same time, institutional and legal challenges constitute one of the significant factors capable of delaying the execution of projects.

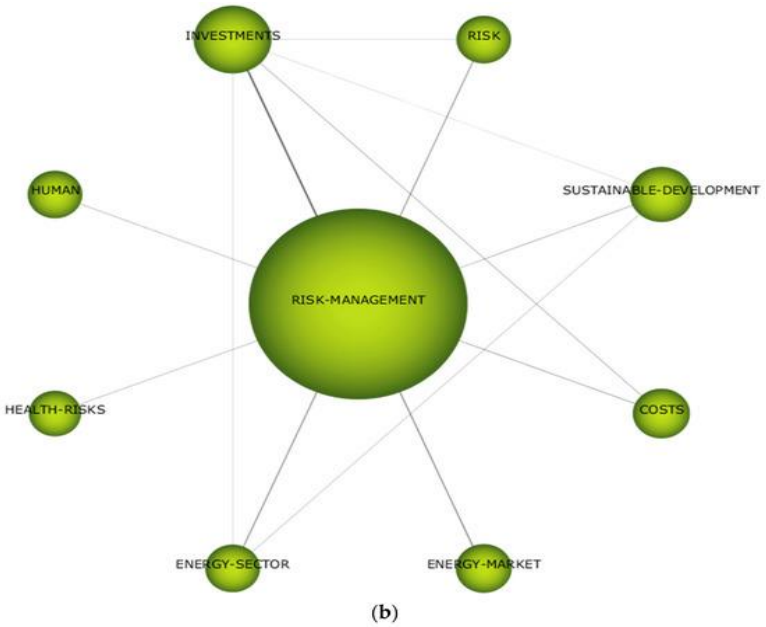


Figure 5
Classification of principal risks in renewable energy projects

In this regard, the application of a comprehensive approach to risk management — encompassing technological advancement, state support, and effective planning — is of considerable importance.

Azerbaijan, while possessing abundant natural resources, has conventionally maintained an economic model based on oil and gas extraction in the energy sector. However, in recent years, global energy transition processes and escalating challenges associated with climate change have necessitated the diversification of the country's energy policy. In this context, the development of renewable energy sources and their application across various industrial sectors, including the mining industry, is of considerable significance.

The geographical and climatic characteristics of Azerbaijan create favorable conditions for the development of renewable energy sources. Solar energy potential is particularly high. The elevated solar radiation across the majority of the country's regions renders the application of solar energy economically attractive. At the same time, wind energy potential along the Caspian Sea coastline and on the Absheron Peninsula is also sufficiently high. This creates broad opportunities for the application of alternative energy sources in the mining industry (Jowitt, et al., 2020).

The application of renewable energy sources in the mining industry is particularly relevant for sites with underdeveloped energy infrastructure or those located off-grid. Since certain mineral deposits in Azerbaijan are situated in mountainous and remote regions, conventional energy supply in these areas presents challenges from both technical and economic perspectives. In this regard, alternative sources such as solar and wind energy can serve as effective means for resolving these challenges.

State policy also plays a significant role in this direction. A number of strategic programs and state documents have been adopted in Azerbaijan for the purpose of developing the renewable energy sector. Within the framework of these documents, increasing the share of alternative sources in energy

production, enhancing energy efficiency, and reducing carbon emissions have been identified as the principal priorities. Incentive mechanisms implemented by the state and international cooperation projects accelerate the development of this sector.

At the same time, reforms being carried out in Azerbaijan in the direction of modernization and digitalization of the industrial sector create favorable conditions for the renewal of energy systems in the mining industry as well. This renders the application of renewable energy technologies more realistic and feasible. The concept of "green energy zones" in particular creates new opportunities in this direction (Kaldellis, 2010).

Furthermore, Azerbaijan's participation in international energy projects and its role in the global energy market provides additional impetus for the development of renewable energy sources. The commitments undertaken by the country within the framework of the Paris Climate Agreement require the reduction of carbon emissions and the enhancement of ecological sustainability. This, in turn, necessitates the application of alternative energy sources in the mining industry as well.

Nevertheless, certain challenges also exist. The limited nature of technological capabilities, the incomplete provision of access to financial resources, and in certain cases the insufficient development of infrastructure affect the pace of development in this field. At the same time, shortages of qualified personnel and limited experience in the implementation of new technologies also create certain obstacles.

Notwithstanding these challenges, given the existing potential and state support, it is clearly evident that broad prospects exist for the application of renewable energy sources in the mining industry in Azerbaijan. Projects to be implemented in this direction can make a significant contribution not only to the enhancement of energy efficiency but also to the resolution of ecological challenges and the ensuring of economic sustainability (Karimov, 2023).

The development of renewable energy sources in Azerbaijan is also one of the priority directions of state policy. In particular, the implementation of solar and wind energy projects is planned within the framework of the "green energy zone" concept in the Karabakh and East Zangezur economic districts.

These initiatives create opportunities for the diversification of the country's energy balance, the reduction of carbon emissions, and the more sustainable operation of industrial sectors, including the mining sector. The future expansion of these projects may accelerate the application of renewable energy technologies in the mining industry.

Overall, the application of renewable energy sources in the mining industry holds strategic significance for Azerbaijan, and the development of this field plays an important role in terms of strengthening the country's energy security, achieving economic diversification, and ensuring ecological sustainability (KPMG, 2021).

The geographical distribution of renewable energy potential in Azerbaijan is illustrated in Figures 6 and 7.

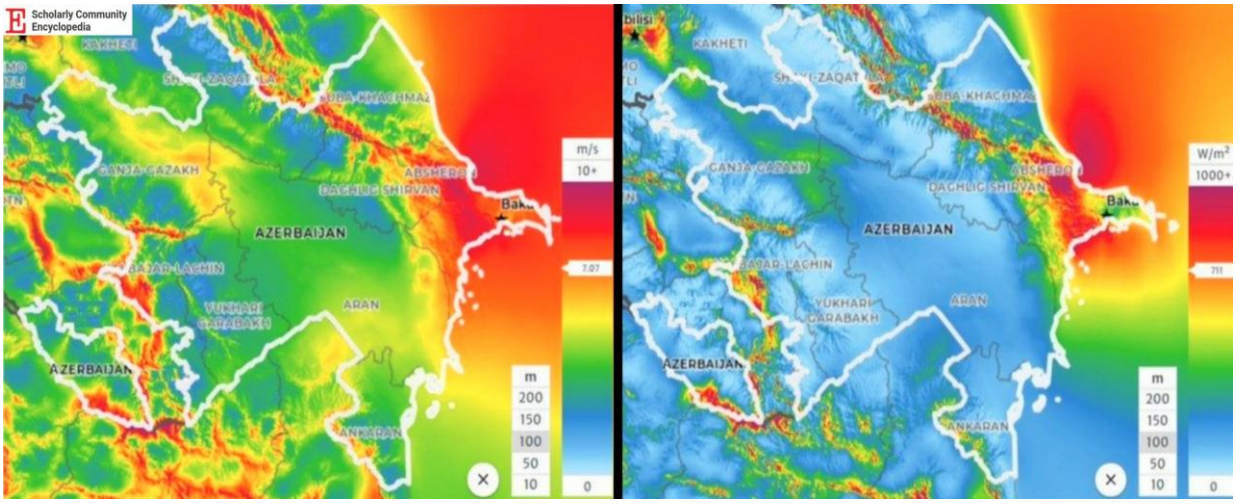


Figure 6
Geographical map of wind energy sources in Azerbaijan

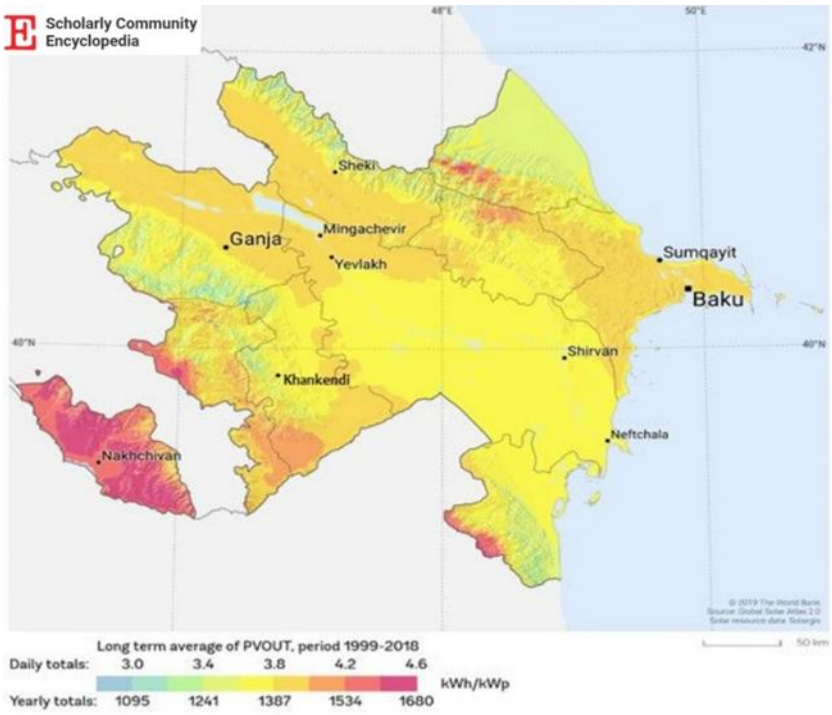


Figure 7
Geographical map of solar photovoltaic energy sources in Azerbaijan

As can be observed from the figures, different regions of Azerbaijan possess varying potential in terms of renewable energy sources. Solar energy potential is particularly sufficient across extensive territories of the country, which demonstrates its broad application prospects.

Wind energy potential, in turn, is predominantly concentrated along the Absheron Peninsula and the Caspian Sea coastline. As these regions are characterized by high wind speeds, they are regarded as more favorable from the standpoint of energy production.

These geographical advantages create broad opportunities for the application of alternative energy sources in the mining industry. Particularly for mining sites located in remote areas with underdeveloped energy infrastructure, the utilization of this potential can serve as an economically and ecologically effective solution.

The findings of the conducted research indicate that the application of renewable energy sources in the mining industry is not merely a technical and economic matter, but rather a complex process that encompasses strategic, institutional, and ecological aspects simultaneously. In this regard, the analysis of the findings obtained in a broader context and their comparison with existing approaches is of considerable importance (Lazard, 2023).

Global experience demonstrates that in developed countries, the application of renewable energy sources in the mining industry is implemented at a more rapid pace.

This is primarily explained by the high level of technological advancement in those countries, the breadth of access to financial resources, and the more stable and incentivizing normative-legal framework. In developing countries, however, this process proceeds at a comparatively slower pace, which is associated with financial constraints, deficiencies in technical knowledge, and institutional challenges.

In this context, Azerbaijan's position merits particular attention. Azerbaijan holds a strong position in the conventional energy sector as a country endowed with abundant hydrocarbon reserves, while simultaneously possessing favorable geographical conditions in terms of renewable energy potential. This creates a unique situation for the country and facilitates the gradual and balanced implementation of the energy transition.

At the same time, the analysis conducted indicates that the application of renewable energy sources in the mining industry is not limited solely to the optimization of energy costs. This approach also plays a significant role in terms of improving the ecological indicators of enterprises, reducing carbon emissions, and aligning with international ecological standards. This, in turn, enhances the investment attractiveness of companies and strengthens their competitiveness in global markets.

On the other hand, certain risks and constraints also exist in this field. In particular, the intermittency of energy production, the high level of initial investment costs, and the insufficient development of technical infrastructure serve as the principal obstacles to this process. It should be noted, however, that the rapid advancement of technology and the widespread application of energy storage systems are creating conditions for the gradual resolution of these challenges (Mammadov, 2021).

Furthermore, institutional and governance aspects are also of particular significance. For the successful implementation of renewable energy projects, it is essential that state policy be supportive, the normative-legal framework be improved, and the investment environment be favorable. Steps taken in Azerbaijan in this direction in recent years indicate that positive trends are being established.

At the same time, the role of human capital should also be specifically noted. The application of renewable energy technologies requires the availability of qualified specialists.

In this regard, one of the principal priorities for Azerbaijan should consist of not only making efficient use of existing energy potential, but also accelerating the development of alternative energy sources and integrating them into various sectors of industry (Shahbaz, et al., 2020).

Conclusions

The conducted research demonstrates that the application of renewable energy sources in the mining industry presents significant advantages from both ecological and economic standpoints. The

reduction of dependence on conventional energy sources contributes to the lowering of carbon emissions and the protection of the environment. At the same time, alternative sources such as solar and wind energy serve as effective and stable energy solutions particularly for mining sites with underdeveloped energy infrastructure.

Nevertheless, challenges such as high initial investment costs, technical constraints, and the intermittency of energy production exist in this field. However, technological advancement and the expansion of financial mechanisms render the resolution of these challenges feasible.

The analysis conducted with respect to Azerbaijan indicates that favorable potential exists in the country for the development of renewable energy sources, and that state policy plays a significant role in accelerating this process.

Based on the findings of the research, the following recommendations are put forward:

- the expansion of financial and fiscal incentives for renewable energy projects;
- the implementation of hybrid energy systems in regions with underdeveloped energy infrastructure;
- the strengthening of qualified personnel training and scientific research activities;
- the enhancement of the application of international experience and innovative technologies.

In conclusion, the application of renewable energy sources in the mining industry is assessed as an ecologically and economically justified and prospective direction.

References

Abdullayev, N. (2020). *Mədən sənayesində enerji istifadəsi*.

Aghaei, J., & Alizadeh, M.-I. (2013). Demand response in smart electricity grids equipped with renewable energy sources: A review. *Renewable and Sustainable Energy Reviews, 18*, 64–72. https://doi.org/10.1016/j.rser.2012.09.019

Aliyev, F. (2020). *Azərbaycanda bərpa olunan enerji mənbələrinin inkişaf perspektivləri*. Elm.

BPS. (2022). Renewable energy in mining operations. *Journal of Cleaner Production, 345*, 131–140.

Dincer, I. (2000). Renewable energy and sustainable development: A crucial review. *Renewable and Sustainable Energy Reviews, 4*(2), 157–175. https://doi.org/10.1016/S1364-0321(99)00011-8

Əliyev, T. (2019). *Azərbaycanda enerji siyasəti*.

Energy Institute. (2024). *Statistical review of world energy 2024*. https://energyinst.org/__data/assets/pdf_file/0004/1810156/Statistical-Review-of-World-Energy-2024.pdf

European Commission. (2022). *Green deal and energy transition policies*.

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews, 24*, 38–50. https://doi.org/10.1016/j.esr.2019.01.006

Hüseynov, E. (2021). *Enerji iqtisadiyyatı*. Bakı.

International Energy Agency. (2023). *World energy outlook 2023*. https://www.iea.org/reports/world-energy-outlook-2023

International Renewable Energy Agency. (2022). *Renewable energy in industry*.

International Renewable Energy Agency. (2023). *Renewable power generation costs in 2022*. https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022

Jowitt, S. et al. (2020). Mining and the environment. *Science, 367*(6473), 379–380.

Kaldellis, J. K. (Ed.). (2010). *Stand-alone and hybrid wind energy systems: technology, energy storage and applications*. Woodhead Publishing.

Karimov, S. (2023). *Dayanıqlı inkişaf və enerji resursları*.

KPMG. (2021). *Energy transition in mining sector*.

Lazard. (2023). *Levelized cost of energy analysis (version 16.0)*. https://www.lazard.com/media/2ozoovyg/lazards-lcoeplus-april-2023.pdf

Mammadov, R. (2021). *Enerji təhlükəsizliyi və dayanıqlı inkişaf*.

McKinsey. (2022). *Decarbonization of mining industry*.

OECD. (2021). *Energy and environment outlook*.

Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering, 3*(1), Article 1167990. https://doi.org/10.1080/23311916.2016.1167990

Quliyev, H. (2022). *Alternativ enerji mənbələri və tətbiqi*.

REN21. (2023). *Renewables 2023 global status report*. https://www.ren21.net/gsr-2023/

Saidur, R., Rahim, N. A., Islam, M. R., & Solangi, K. H. (2011). Environmental impact of wind energy. *Renewable and Sustainable Energy Reviews, 15*(5), 2423–2430. https://doi.org/10.1016/j.rser.2011.02.024

Shahbaz, M. et al. (2020). Renewable energy consumption and growth. *Energy Policy, 140*.

U.S. Energy Information Administration. (2023). *International energy outlook 2023*. https://www.eia.gov/outlooks/ieo/

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