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Reimagining Economics Education Through Artificial Intelligence: Opportunities, Challenges, and Human-Centered Innovation

Madina Allahverdiyeva 

Abstract. *The growing use of Artificial Intelligence (AI) is increasingly influencing the development of contemporary education. The application of AI technologies in teaching and learning offers new opportunities to improve the quality of education, promote greater student engagement, and provide more individualized learning experiences. In economics education, where analytical reasoning, data interpretation, and problem-solving abilities are essential, AI can provide innovative methods to support educators and facilitate students' learning processes. This paper explores the role of Artificial Intelligence in transforming economics education by examining its potential applications, emerging opportunities, and associated challenges. The study discusses how AI-based tools can contribute to adaptive learning, intelligent tutoring, automated feedback, economic data analysis, and interactive learning environments. At the same time, the paper highlights important concerns related to academic integrity, ethical use of technology, data privacy, digital inequality, and the changing role of educators. The paper argues that the successful integration of AI into economics education requires a human-centered approach where technology functions as a complementary instrument rather than a substitute for educators. By combining technological innovation with effective pedagogical strategies, AI can contribute to the development of more flexible, inclusive, and future-oriented economics education systems.*

Keywords: *artificial intelligence, economics education, educational technology, digital transformation, personalized learning, human-centered innovation, AI ethics*

Introduction

The rapid development of digital technologies has significantly transformed the structure, objectives, and practices of contemporary education. Among these technologies, Artificial Intelligence (AI) has emerged as a particularly influential tool with the potential to reshape traditional approaches to teaching and learning. The increasing availability of AI-based systems has created new opportunities for personalized instruction, automated feedback, data-driven learning, and more flexible educational environments. In higher education, AI applications are increasingly being explored as instruments for supporting both educators and students and for improving the efficiency and quality of educational processes (Zawacki-Richter et al., 2019; Bond et al., 2024; Castillo-Martínez et al., 2024).

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Economics education is particularly relevant to the integration of AI because the discipline requires students to develop analytical thinking, data interpretation, quantitative reasoning, forecasting, and problem-solving skills. Economics students increasingly need to work with large datasets, interpret economic indicators, evaluate alternative scenarios, and make evidence-based decisions. In this context, AI-based technologies can provide opportunities for students to engage with economic data, explore complex relationships between variables, and apply theoretical concepts to practical situations. Intelligent tutoring systems, generative AI tools, adaptive learning platforms, and interactive simulations can therefore complement conventional approaches to economics education (Holmes & Tuomi, 2022; Kasneci et al., 2023).

Previous research on AI in higher education has emphasized its potential to personalize learning, improve student support, facilitate feedback, and assist educators with routine academic tasks. At the same time, the literature identifies significant challenges related to academic integrity, ethical responsibility, data privacy, technological dependence, and unequal access to digital resources. (Kasneci et al., 2023; Miao & Holmes, 2023; Bond et al., 2024). These challenges suggest that the educational value of AI cannot be determined solely by its technological capabilities. Rather, its effectiveness depends on the pedagogical context in which it is implemented and on the ability of institutions and educators to use AI responsibly.

Despite the growing body of research on AI in higher education, further attention is needed to the specific implications of AI for economics education. Economics has distinctive characteristics because of its strong reliance on quantitative analysis, economic modeling, forecasting, data interpretation, and evidence-based decision-making. Consequently, the opportunities provided by AI in economics education may extend beyond general personalization and automated support to include new forms of analytical and simulation-based learning. At the same time, the increasing use of AI raises questions about how students can develop independent analytical judgment while using technologies capable of generating information, analyses, and solutions. (Kasneci et al., 2023; Miao & Holmes, 2023; Bond et al., 2024).

This issue creates an important pedagogical challenge. AI should not simply be introduced as a technological replacement for existing educational practices. Instead, its integration should be guided by a human-centered approach that preserves the essential role of educators in developing students' critical thinking, creativity, ethical awareness, and independent judgment. In this perspective, AI functions as a supportive instrument that can expand educational opportunities while human expertise remains central to interpretation, guidance, evaluation, and meaningful interaction. (Holmes & Tuomi, 2022; Miao & Holmes, 2023). Against this background, this study aims to examine the opportunities and challenges arising from the integration of Artificial Intelligence into economics education and to explore the implications of a human-centered approach to AI-supported teaching and learning. The study focuses on three interconnected dimensions: the educational applications of AI, the potential benefits and risks of its integration, and the changing role of educators in AI-supported economics education.

The study addresses the following research questions:

1. What are the main opportunities for applying Artificial Intelligence in economics education?
2. What pedagogical, ethical, and technological challenges are associated with the integration of AI into economics education?
3. How can a human-centered approach contribute to the effective and responsible use of AI in economics education?

By addressing these questions, the study contributes to the discussion of AI in education by focusing specifically on economics education and by emphasizing the need to balance technological innovation

with pedagogical principles and human expertise. Economics students increasingly need to work with large datasets, interpret economic indicators, evaluate alternative scenarios, and make evidence-based decisions (Aliyeva et al., 2026).

Methods

Research Design

This study employs a qualitative thematic review of the existing literature to critically examine the opportunities, challenges, and broader implications of Artificial Intelligence (AI) in economics education. This methodological approach is appropriate because the study seeks to synthesize and interpret insights from existing academic and institutional literature rather than collect and statistically analyze primary data. The thematic approach facilitates the identification of recurring patterns, emerging perspectives, and key areas of scholarly discussion concerning the application of AI in economics education, including its potential benefits, associated risks and challenges, and the evolving role of educators in AI-supported learning environments.

Literature Selection

The literature examined in this study consists of peer-reviewed academic publications, literature and systematic reviews, and relevant reports published by recognized international organizations. The selected sources address AI in education and higher education, with particular attention to its relevance to economics education. Sources were considered relevant when they addressed one or more of the following areas: personalized learning, intelligent tutoring systems, generative AI, automated feedback, data-driven learning, simulation-based education, academic integrity, AI ethics, data privacy, digital inequality, and the changing role of educators. Priority was given to recent publications reflecting the rapid development of AI and generative AI in educational contexts. Earlier influential studies were also included when they provided important conceptual or theoretical foundations for understanding AI applications in education. The selection of sources was guided primarily by their relevance to the research questions and their contribution to the study objectives.

Data Analysis

The selected literature was analyzed using thematic analysis. The analysis involved three main stages. First, the selected sources were reviewed to identify their main arguments, findings, and areas of focus. Second, recurring concepts and issues were identified and grouped into related categories. Third, these categories were organized into broader themes corresponding to the research questions of the study. The thematic analysis identified four interconnected areas. The first focused on the opportunities offered by AI within economics education, particularly personalized learning and intelligent tutoring systems. The second examined AI-supported analytical and practical learning, including data-driven learning approaches and simulation-based activities. The third explored the pedagogical, ethical, and technological challenges associated with integrating AI into economics education, with particular attention to academic integrity, data privacy, digital inequality, and the reliability of AI-generated information. The fourth considered the evolving role of educators and emphasized the importance of maintaining a human-centered approach to AI-supported economics education.

Methodological Scope and Limitations

This study is based exclusively on secondary sources and does not involve primary data collection from students, educators, or educational institutions. Therefore, the findings represent a thematic synthesis and interpretation of the existing literature rather than empirical evidence of the effectiveness of specific AI tools in economics education. The qualitative nature of the review also means that the interpretation of the literature involves a degree of researcher judgment. Nevertheless, organizing the reviewed literature according to clearly defined thematic areas and research questions

provides a structured basis for identifying major opportunities, challenges, and implications of AI integration into economics education. The limitations of the literature-based approach are considered when interpreting the findings and formulating directions for future empirical research.

Statement on the Use of Artificial Intelligence

Artificial Intelligence tools were used during the preparation of this manuscript for language editing, grammatical improvement, structural organization, and refinement of academic expression. The author independently reviewed and verified the AI-assisted content and remains fully responsible for the accuracy, originality, interpretation, and final version of the manuscript. All AI-assisted content was critically evaluated and revised by the author to ensure its academic integrity and alignment with the objectives of the study.

Results

The thematic analysis of the selected literature identified four major areas concerning the integration of Artificial Intelligence into economics education: personalized and adaptive learning, AI-supported analytical and practical learning, pedagogical and ethical challenges, and the changing role of educators. These themes correspond to the research questions of the study and demonstrate that AI creates both new educational opportunities and significant implementation challenges. (Zawacki-Richter et al., 2019; Bond et al., 2024).

Personalized and Adaptive Learning

The reviewed literature indicates that one of the most significant opportunities associated with AI in education is the development of personalized and adaptive learning environments. AI-based systems can analyze students' learning progress, identify areas of difficulty, and provide individualized learning materials and feedback. Such systems may allow students to receive additional explanations or practice activities according to their learning needs and progress. For economics education, personalized learning is particularly relevant because students may differ considerably in their levels of mathematical, statistical, and analytical preparation. AI-supported systems can provide differentiated learning activities and assist students in working with economic concepts at different levels of complexity. The literature therefore suggests that AI can contribute to a more flexible learning environment in which students receive support according to their individual learning requirements (Crompton & Burke, 2023; Holmes & Tuomi, 2022). AI-based systems can support personalized learning by adapting educational content, learning activities, and feedback according to individual learning requirements (Crompton & Burke, 2023; Holmes & Tuomi, 2022; Teymurova, 2026).

AI-Supported Analytical and Practical Learning

A second major finding concerns the use of AI to strengthen analytical and practical learning. Economics education requires students to interpret quantitative information, analyze economic indicators, understand relationships between variables, and apply theoretical concepts to practical situations. AI-based technologies can support these activities by assisting learners with data analysis, pattern recognition, forecasting exercises, and scenario-based learning (Holmes & Tuomi, 2022). The reviewed literature also indicates that interactive simulations and AI-supported learning environments can help students connect theoretical knowledge with practical applications. Economic scenarios can be explored through digital environments in which students examine alternative conditions and observe potential outcomes. Such approaches may strengthen students' ability to interpret economic information and apply theoretical knowledge to practical problems (Kasneci et al., 2023).

Generative AI tools can additionally provide explanations, examples, and immediate responses to students' questions. However, the literature emphasizes that AI-generated information should be

critically evaluated because such systems may produce inaccurate, incomplete, or misleading information (Kasneci et al., 2023). Consequently, AI-supported analytical learning requires students to develop skills in verification, interpretation, and critical evaluation.

Pedagogical, Ethical, and Technological Challenges

The thematic analysis identified several challenges that may limit the effective integration of AI into economics education. Academic integrity represents one of the most frequently discussed concerns, particularly following the rapid development of generative AI systems. Students may use AI-generated content in assignments without adequately demonstrating their own analytical abilities, creating challenges for traditional assessment practices (Kasneci et al., 2023; McDonald et al., 2024). Another important challenge concerns data privacy and security. AI-supported educational systems may require the collection and processing of information about students' learning activities and performance. This creates a need for transparency, informed use of data, and appropriate institutional safeguards (Miao & Holmes, 2023; Bond et al., 2024).

The literature also identifies unequal access to digital technologies and differences in digital competence as important barriers to effective AI adoption. Students and educational institutions may have different levels of access to reliable digital infrastructure, AI tools, and the knowledge required to use them effectively. Therefore, the implementation of AI may potentially reinforce existing educational inequalities if access and digital literacy are not addressed (Williamson & Eynon, 2020; Castillo-Martínez et al., 2024).

Changing Role of Educators and Human-Centered Integration

The fourth major finding concerns the changing role of educators. The literature does not support the view that AI should simply replace teachers. Instead, AI is increasingly described as a tool that can complement educators by supporting routine activities, providing learning assistance, and facilitating feedback (Zawacki-Richter et al., 2019; Bond et al., 2024; Tuomi et al., 2022). At the same time, educators remain essential for developing students' critical thinking, independent judgment, ethical awareness, and ability to interpret information. Human-centered approaches to AI in education emphasize the importance of maintaining human agency, meaningful interaction, transparency, and educator involvement in AI-supported learning environments (Alfredo et al., 2024; Bond et al., 2024). For economics education, this finding is particularly important because economic learning involves not only technical analysis but also interpretation, judgment, and evaluation of economic and policy-related consequences. AI can support the processing of information and exploration of scenarios, while educators continue to provide intellectual guidance and contextual interpretation.

Summary of the Results

Overall, the results indicate that AI integration into economics education can be organized around two complementary dimensions. The first is the educational potential of AI, including personalized learning, analytical support, interactive learning, and automated feedback. The second is the conditions required for responsible implementation, including academic integrity, ethical use, data protection, equitable access, digital competence, and continued human involvement. These findings provide the basis for the subsequent discussion of how AI can be integrated into economics education while maintaining a balance between technological innovation and human-centered pedagogy.

Discussion

The findings of this study indicate that Artificial Intelligence has considerable potential to transform economics education, particularly through personalized learning, intelligent tutoring, automated feedback, data-driven learning, and interactive learning environments. However, the findings also demonstrate that the educational value of AI depends on the conditions under which it is

implemented. This supports the broader literature on AI in higher education, which emphasizes that technological capabilities alone do not guarantee improved educational outcomes (Zawacki-Richter et al., 2019; Bond et al., 2024; Castillo-Martínez et al., 2024).

The first major implication concerns personalized and adaptive learning. AI-based systems can provide learners with individualized support based on their learning progress and identified knowledge gaps. For economics education, this opportunity is particularly relevant because students may have different levels of mathematical, statistical, and analytical preparation. AI-supported learning environments may therefore provide additional explanations, examples, and practice opportunities according to individual needs. At the same time, personalization should not result in excessive automation of the learning process. Students still need opportunities to formulate questions, evaluate evidence, and develop independent economic reasoning (Crompton & Burke, 2023; Holmes & Tuomi, 2022).

The findings also highlight the importance of AI for data-driven and practice-oriented economics education. Economics increasingly depends on the analysis and interpretation of large amounts of quantitative information. AI can support students in identifying patterns, examining economic scenarios, and interpreting data. This can strengthen the connection between theoretical concepts and practical economic problems. However, the use of AI-generated analysis also creates a need for stronger verification and critical evaluation skills. Students should not treat AI-generated explanations or interpretations as inherently accurate. Instead, AI-supported analysis should be accompanied by source verification, comparison of alternative explanations, and critical examination of assumptions (Kasneci et al., 2023; Holmes & Tuomi, 2022).

The findings concerning academic integrity are consistent with the wider literature on generative AI in education. The increasing accessibility of AI-generated text and solutions challenges traditional approaches to assessment and raises questions about whether submitted work accurately reflects students' own knowledge and abilities (Kasneci et al., 2023; McDonald et al., 2024). For economics education, this issue is particularly important because assignments frequently require analytical reasoning, interpretation of economic evidence, and problem-solving. Consequently, assessment practices may need to place greater emphasis on students' reasoning processes, application of concepts, oral explanation, and reflection on how conclusions were reached rather than relying exclusively on final written outputs.

Another important implication concerns data privacy, transparency, and responsible use of AI. The collection and processing of student data can support personalization and learning analytics, but it can also create risks related to privacy, security, and user autonomy. Research on human-centered AI in education emphasizes the importance of balancing automation with human control, involving educational stakeholders in system design, and ensuring safety, reliability, and trustworthiness (Alfredo et al., 2024; Bond et al., 2024). Similarly, international guidance on generative AI in education emphasizes human agency, responsible use, and appropriate safeguards (Miao & Holmes, 2023; UNESCO, 2024).

The findings further suggest that digital inequality should be considered an important part of AI adoption strategies. Although AI can potentially expand access to educational support, unequal access to reliable internet connections, appropriate devices, digital skills, and AI-enabled educational services may produce new forms of inequality. Therefore, institutions should consider infrastructure and digital literacy alongside the introduction of AI-based educational technologies. AI integration should be accompanied by measures that ensure students have meaningful and equitable opportunities to use these technologies (Williamson & Eynon, 2020; Bond et al., 2024).

The changing role of educators is another central issue identified by this study. AI can reduce some routine tasks and provide students with additional learning support, but it does not eliminate the need for educators. Instead, the teacher's role may increasingly involve facilitating critical thinking, evaluating AI-generated information, designing meaningful learning activities, providing ethical guidance, and supporting students' intellectual development. Recent research on AI in education similarly emphasizes the importance of maintaining human agency and meaningful involvement of educators and students in AI-supported educational systems (Alfredo et al., 2024; Tuomi et al., 2022).

For economics education specifically, this human-centered perspective is particularly significant. Economics involves not only technical analysis but also interpretation, judgment, policy evaluation, and consideration of social and ethical consequences. AI can assist students in processing information and exploring alternative scenarios, but the interpretation of economic evidence and the evaluation of policy implications require human judgment. Therefore, AI should be positioned as a cognitive and educational support tool rather than as an autonomous substitute for the educator or the learner (Holmes & Tuomi, 2022).

The findings also have important implications for institutional policy and teacher development. Universities should provide educators with opportunities to develop AI literacy and pedagogical competencies that enable them to integrate AI into their courses in a responsible and effective manner. Institutional guidelines should clearly address appropriate AI use, academic integrity, data privacy, transparency, and assessment practices. At the same time, students should develop the ability to use AI tools responsibly while also critically questioning, verifying, and evaluating the accuracy and reliability of AI-generated information (Miao & Holmes, 2023; UNESCO, 2024).

Overall, the discussion suggests that the central issue is not whether AI should be introduced into economics education, but how it should be integrated. A sustainable approach requires alignment between technological capabilities, pedagogical objectives, ethical principles, and human expertise. The human-centered model proposed in this study therefore places educators and learners at the center of AI-supported educational innovation while using AI to expand opportunities for personalization, analytical learning, and practical application.

Conclusion

Artificial Intelligence is increasingly influencing the development of contemporary education and has significant potential to transform economics education. This study examined the main opportunities and challenges associated with the integration of AI into economics education and explored the importance of a human-centered approach to its implementation.

The findings indicate that AI can support personalized learning, intelligent tutoring, automated feedback, data-driven learning, and simulation-based educational activities. These applications can help students engage more effectively with economic concepts, quantitative information, and practical problem-solving tasks. AI can also support educators by reducing certain routine activities and creating additional opportunities for individualized student support.

At the same time, the integration of AI presents important challenges. Academic integrity, ethical responsibility, data privacy, unequal access to digital technologies, and the reliability of AI-generated information require careful consideration. The findings therefore suggest that technological adoption alone cannot ensure meaningful improvements in economics education. Effective implementation requires appropriate pedagogical strategies, institutional support, digital competencies, and clear ethical principles.

The study further emphasizes that educators should remain central to AI-supported economics education. AI should be used as a complementary educational instrument rather than as a substitute for human expertise. Educators play an essential role in developing students' critical thinking, independent judgment, ethical awareness, and ability to evaluate information. A human-centered approach can therefore combine the analytical capabilities of AI with the pedagogical and interpersonal capabilities of educators.

From a practical perspective, higher education institutions should invest in AI literacy, professional development for educators, responsible-use guidelines, and equitable access to digital technologies. Assessment practices should also be adapted to encourage independent reasoning, critical evaluation, and responsible use of AI-generated information.

Finally, this study is based on a thematic analysis of existing literature and therefore does not provide primary empirical evidence concerning the effectiveness of specific AI tools in economics education. Future research should examine AI-supported economics education through empirical studies involving students and educators and should investigate the effects of specific AI applications on learning outcomes, analytical skills, and student engagement.

Overall, the future of economics education should not be determined by whether Artificial Intelligence replaces traditional teaching, but by how effectively it can be integrated into educational practices while preserving human judgment, critical thinking, ethical responsibility, and meaningful interaction. A balanced human-centered approach can enable AI to serve as a strategic instrument for developing more flexible, inclusive, and future-oriented economics education.

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Mathematical Modeling and Analysis of Pid-Based Flight Control Systems for Unmanned Aerial Vehicles

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Abstract. Unmanned aerial vehicles (UAVs) are increasingly used in civilian, industrial, and special-purpose applications due to their mobility, flexibility, and autonomous operating capabilities. One of the main technical challenges in UAV systems is maintaining stable flight performance under changing operating conditions and external disturbances. Flight stability directly affects navigation accuracy, maneuverability, and overall system reliability. Therefore, automatic flight control systems based on proportional-integral-derivative (PID) controllers remain widely applied in modern UAV platforms. This study presents the mathematical modeling and simulation-based analysis of PID-based flight control systems for UAV stabilization. The proposed approach focuses on roll, pitch, and yaw attitude control using a classical PID controller structure. The UAV dynamic model, PID control law, and main performance indicators, including overshoot, settling time, rise time, and steady-state error, are analyzed. Simulation results show that properly selected PID parameters significantly improve the dynamic response of the UAV attitude-control system. Compared with low-gain and medium-gain configurations, the optimized PID controller provides faster stabilization, lower steady-state error, and improved response smoothness. The study also discusses the advantages, limitations, and tuning challenges of PID controllers and indicates the future potential of adaptive and AI-based control methods for UAV stabilization.

Keywords: UAV, PID controller, flight control, stabilization, mathematical modeling, control systems

Introduction

Unmanned aerial vehicles (UAVs) have become one of the most rapidly developing technological platforms in modern engineering. Their application areas include aerial monitoring, mapping, agriculture, logistics, search and rescue operations, environmental observation, and special-purpose missions. The increasing use of UAVs has created a strong need for reliable flight control systems capable of ensuring stable, accurate, and safe operation under different flight conditions.

One of the main technical challenges in UAV operation is flight stabilization. During flight, a UAV is continuously affected by external disturbances such as wind, vibration, payload variation, maneuvering forces, and sensor measurement errors. These factors may cause deviations in roll, pitch, and yaw angles, which directly influence the stability and controllability of the aircraft. Therefore, the development of effective automatic control algorithms is an important requirement for improving UAV flight performance (Mahony et al., 2012; Bouabdallah et al., 2004).

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Among different control methods, the proportional-integral-derivative (PID) controller remains one of the most widely used approaches in UAV flight control systems due to its simple structure, practical implementation, and real-time error compensation capability (Li et al., 2006). In UAV systems, PID controllers are commonly used to regulate attitude angles, altitude, angular velocity, and trajectory tracking parameters (Bouabdallah et al., 2004; Mahony et al., 2012). Correct tuning of the proportional, integral, and derivative coefficients allows the system to achieve faster response, lower overshoot, and improved steady-state accuracy (Li et al., 2006).

Previous studies have shown that UAV control and communication reliability are closely related to the quality of onboard control architecture, flight-controller design, telemetry stability, and signal-processing mechanisms. Research works on UAV telemetry, control channels, signal quality, antenna parameters, and electronic interference have emphasized the importance of reliable system architecture for stable UAV operation (Aghayev et al., 2025; Azizullayev, 2025; Rzayeva et al., 2025a, 2025b; Azizullayev, 2026; Rustamov et al., 2025). In addition, studies related to national flight-card design and UAV telemetry systems show that flight-control hardware and software integration plays an essential role in ensuring autonomous and stable UAV performance (Nematzade & Rzayeva, 2024).

However, despite the wide use of PID controllers in UAV systems, the influence of PID parameters on dynamic response characteristics still requires detailed mathematical analysis. In particular, overshoot, settling time, rise time, and steady-state error are important indicators for evaluating the effectiveness of a UAV stabilization system. Improperly selected PID coefficients may lead to oscillations, slow response, or unstable flight behavior.

The main purpose of this study is to present a mathematical model and simulation-based analysis of PID-based flight control systems for UAV stabilization. The study focuses on the control of roll, pitch, and yaw motion using a classical PID controller. The influence of PID parameters on flight stability and dynamic response is analyzed through mathematical equations and response characteristics. The proposed approach provides a general and open scientific framework for evaluating UAV flight stabilization without depending on any restricted or confidential system data.

Recent studies have also investigated the influence of telemetry reliability, signal protection mechanisms, and communication stability on UAV control efficiency under different operating conditions (Rustamov et al., 2025; Azizullayev, 2026). Reliability improvement of radio-electronic subsystems is also considered an important factor in UAV operational stability (Nematzade et al., 2026).

Methods

This section presents the mathematical model of the UAV flight-control system, the structure of the PID controller, the governing control equations, and the simulation environment used for evaluating the stabilization performance of the UAV.

UAV dynamic model. In this study, the unmanned aerial vehicle is modeled as a rigid-body dynamic system with rotational motion around three principal axes: roll, pitch, and yaw. These rotational movements determine the flight attitude and stability of the UAV during operation. Future development may also include intelligent image-processing methods based on artificial neural networks for automatic recognition and classification of objects in the monitored environment (Nematzade et al., 2026). Distance measurement and sensing methods can also play an important role in the detection and localization of mines, particularly in systems designed to reduce direct human exposure to hazardous areas (Rzayeva et al., 2025b).

In addition, frequency-hopping-based communication approaches can improve the robustness of control and telemetry links in radio-electronic warfare and interference-prone environments (Azizullayev et al., 2026). External disturbances such as aerodynamic forces, environmental effects, and maneuvering conditions may influence these angular motions and reduce flight stability.

The rotational dynamics of the UAV can be mathematically expressed as follows:

$$J_\phi \ddot{\phi}(t) = \tau_\phi(t) \quad (1)$$

$$J_\theta \ddot{\theta}(t) = \tau_\theta(t) \quad (2)$$

$$J_\psi \ddot{\psi}(t) = \tau_\psi(t) \quad (3)$$

where J_ϕ , J_θ , and J_ψ represent the moments of inertia around the roll, pitch, and yaw axes, respectively. The variables $\phi(t)$, $\theta(t)$, and $\psi(t)$ denote the angular positions, while $\tau_\phi(t)$, $\tau_\theta(t)$, and $\tau_\psi(t)$ denote the control torques generated by the propulsion and stabilization system.

For simplified dynamic analysis, the transfer function of the UAV rotational channel can be represented by the following second-order model:

$$G(s) = \frac{1}{Js^2} \quad (4)$$

This transfer function describes the relationship between the applied control torque and the angular response of the UAV.

PID controller structure. The PID controller is used to minimize the difference between the desired reference angle and the measured output angle of the UAV. The control error signal is defined as:

$$e(t) = r(t) - y(t) \quad (5)$$

where $r(t)$ is the reference input signal, $y(t)$ is the measured system output, and $e(t)$ is the control error. The mathematical expression of the PID controller is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (6)$$

where $u(t)$ represents the controller output signal, K_p is the proportional gain coefficient, K_i is the integral gain coefficient, and K_d is the derivative gain coefficient.

The proportional term provides an immediate response to the error signal, the integral term reduces the accumulated steady-state error, and the derivative term improves damping characteristics and suppresses oscillations (Li et al., 2006). The combined operation of these three components enables effective stabilization of UAV attitude parameters, especially in roll, pitch, and yaw control channels (Bouabdallah et al., 2004; Mahony et al., 2012).

UAV stabilization equations. The PID-based roll stabilization equation is expressed as:

$$u_\phi(t) = K_{p\phi} e_\phi(t) + K_{i\phi} \int_0^t e_\phi(\tau) d\tau + K_{d\phi} \frac{de_\phi(t)}{dt} \quad (7)$$

Similarly, the pitch stabilization equation is written as:

$$u_{\theta}(t) = K_{p\theta}e_{\theta}(t) + K_{i\theta} \int_0^t e_{\theta}(\tau)d\tau + K_{d\theta} \frac{de_{\theta}(t)}{dt} \quad (8)$$

The yaw stabilization equation can be represented as:

$$u_{\psi}(t) = K_{p\psi}e_{\psi}(t) + K_{i\psi} \int_0^t e_{\psi}(\tau)d\tau + K_{d\psi} \frac{de_{\psi}(t)}{dt} \quad (9)$$

The corresponding control error equations are given below:

$$e_{\phi}(t) = \phi_{ref}(t) - \phi(t) \quad (10)$$

$$e_{\theta}(t) = \theta_{ref}(t) - \theta(t) \quad (11)$$

$$e_{\psi}(t) = \psi_{ref}(t) - \psi(t) \quad (12)$$

where $\phi_{ref}(t)$, $\theta_{ref}(t)$, and $\psi_{ref}(t)$ are the desired reference attitude angles for roll, pitch, and yaw motions.

Simulation environment. A simulation environment was developed to evaluate the performance of the proposed PID-based UAV stabilization system. The mathematical model was implemented using a second-order dynamic system, and different PID coefficient combinations were analyzed to investigate their influence on the system response characteristics.

The simulation parameters used in this study are presented in Table 1.

Table 1
Main simulation parameters

Parameter	Description	Value
J	Moment of inertia	0.025 kg·m ²
ϕ_{ref}	Reference roll angle	10°
θ_{ref}	Reference pitch angle	10°
ψ_{ref}	Reference yaw angle	15°
Simulation time	Total simulation duration	10 s
Sampling time	Time interval	0.01 s
K_p	Proportional gain	1.2-3.0
K_i	Integral gain	0.05-0.4
K_d	Derivative gain	0.2-0.8

The performance of the UAV control system was evaluated using overshoot percentage and steady-state error criteria. The overshoot value is calculated as:

$$M_p = \frac{y_{max} - y_{ss}}{y_{ss}} \times 100\% \quad (13)$$

The steady-state error is defined as:

$$e_{ss} = |r - y_{ss}| \quad (14)$$

where y_{max} is the maximum output response, y_{ss} is the steady-state output value, and r is the reference input signal.

The simulation results obtained from these equations were used to analyze the influence of PID parameters on UAV flight stability, dynamic response, and control accuracy.

Results

This section presents the simulation results obtained for the PID-based UAV flight-control system. The analysis focuses on the dynamic response of the UAV attitude-control model, including response speed, overshoot, settling time, steady-state error, and stability comparison between different PID gain configurations.

Step response analysis. The step response of the UAV attitude-control system was analyzed using three different PID configurations: low-gain PID, medium-gain PID, and optimized PID. The aim was to determine how the variation of PID coefficients affects the stabilization process of the UAV.

Table 2

PID gain configurations used in simulation

Controller type	K_p	K_i	K_d
Low-gain PID	1.2	0.05	0.20
Medium-gain PID	2.0	0.20	0.45
Optimized PID	2.8	0.35	0.70

The simulation showed that the low-gain PID controller produced a slow response and required more time to reach the reference angle. The medium-gain PID controller improved the response speed, but a small overshoot was observed. The optimized PID controller provided the best balance between fast response, low overshoot, and minimum steady-state error.

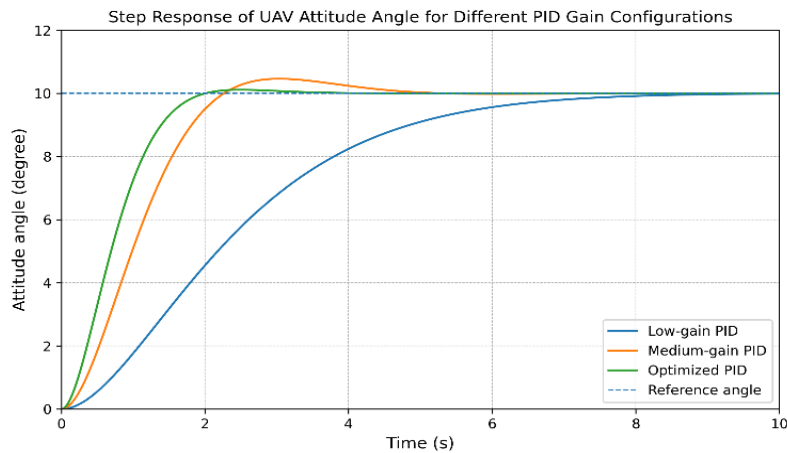


Figure 1

Step response of UAV attitude angle for different PID gain configurations

Figure 1 illustrates the step response of the UAV attitude angle under different PID gain configurations. The low-gain PID controller shows a slower response and reaches the reference value later. The medium-gain PID controller improves response speed but produces a small overshoot. In comparison, the optimized PID controller reaches the reference attitude angle more rapidly and maintains a stable response with minimal overshoot. These results confirm that appropriate PID parameter tuning significantly improves UAV attitude stabilization performance.

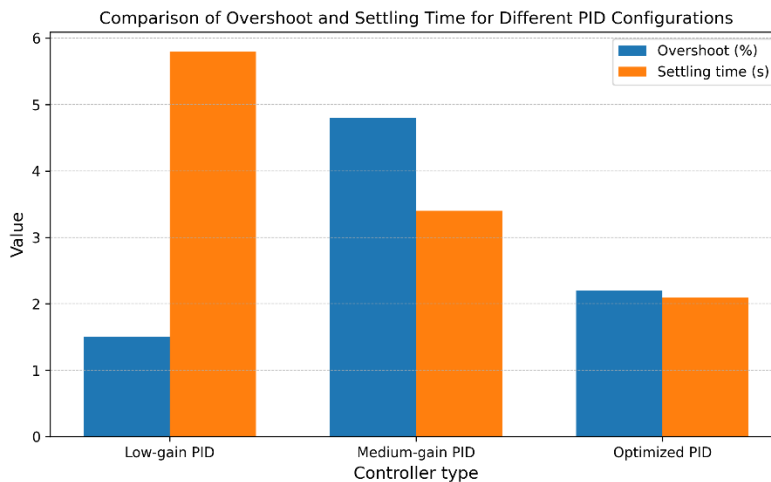
Dynamic response indicators. The main dynamic response indicators obtained from the simulation are presented in Table 3. These indicators are commonly used to evaluate the performance of flight-control and stabilization systems.

Table 3*Dynamic response characteristics of PID-based UAV control system*

Controller type	Rise time, s	Settling time, s	Overshoot, %	Steady-state error, degree
Low-gain PID	2.40	5.80	1.5	0.42
Medium-gain PID	1.55	3.40	4.8	0.18
Optimized PID	0.95	2.10	2.2	0.05

According to the obtained results, the optimized PID controller reduced the settling time from 5.80 s to 2.10 s compared with the low-gain PID configuration. This indicates that the optimized controller achieved faster stabilization after the reference command was applied. At the same time, the steady-state error decreased from 0.42° to 0.05° , which demonstrates improved angular accuracy.

Overshoot and settling time comparison. Overshoot and settling time are important parameters in UAV flight stabilization. High overshoot may cause unwanted oscillations and reduce flight safety, while long settling time may delay the stabilization process after maneuvering or external disturbance.

**Figure 2***Comparison of overshoot and settling time for different PID configurations*

The results show that the medium-gain PID controller produced the highest overshoot value, while the optimized PID controller-maintained overshoot at an acceptable level. Although the low-gain PID controller had relatively low overshoot, its settling time was significantly longer. Therefore, the low-gain configuration cannot be considered effective for fast UAV stabilization.

Stability comparison. The stability comparison was carried out by evaluating the response smoothness, convergence speed, and final error value. The optimized PID controller demonstrated the most stable response because it reached the reference angle faster and maintained the output close to the desired value.

Table 4*Stability comparison of PID configurations*

Evaluation criterion	Low-gain PID	Medium-gain PID	Optimized PID
Response speed	Low	Medium	High
Overshoot level	Low	Medium	Low
Settling performance	Weak	Acceptable	Good

Steady-state accuracy	Medium	Good	High
Oscillation tendency	Low	Medium	Low
Overall stability	Acceptable	Good	High

The results confirm that proper PID parameter selection has a direct influence on UAV stabilization performance. Increasing the proportional gain improves response speed, but excessive values may increase overshoot. The integral gain reduces steady-state error, while the derivative gain improves damping and reduces oscillation. Therefore, balanced tuning of K_p , K_i , and K_d are necessary for reliable UAV flight control.

Overall, the optimized PID configuration demonstrated better stabilization performance than the low-gain and medium-gain configurations. It provided faster response, lower steady-state error, and more stable attitude control behavior.

Quantitative performance improvement assessment

In order to provide a quantitative comparison of the PID configurations, the performance improvement of the optimized PID controller was calculated relative to the low-gain PID controller. The improvement rate was determined using the following expression:

$$I_p = \frac{P_{low} - P_{opt}}{P_{low}} \times 100\% \quad (15)$$

where I_p is the improvement percentage, P_{low} is the parameter value obtained for the low-gain PID controller, and P_{opt} is the corresponding parameter value obtained for the optimized PID controller.

Table 5

Quantitative improvement of optimized PID controller compared with low-gain PID

Performance parameter	Low-gain PID	Optimized PID	Improvement, %
Rise time, s	2.40	0.95	60.4
Settling time, s	5.80	2.10	63.8
Steady-state error, degree	0.42	0.05	88.1
Overshoot, %	1.5	2.2	-46.7

The calculation results show that the optimized PID controller reduced the rise time by 60.4%, settling time by 63.8%, and steady-state error by 88.1% compared with the low-gain PID controller. Although the overshoot value slightly increased, it remained within an acceptable stability range. Therefore, the optimized PID configuration demonstrated a more effective dynamic response and higher stabilization accuracy for UAV attitude control.

Discussion

The simulation results show that the optimized PID controller improves UAV stabilization compared with the low-gain and medium-gain configurations. As seen in Table 3 and Figures 1-2, it provides shorter settling time, lower steady-state error, and a more stable response. The PID controller affects the system through three main components: the proportional term increases response speed, the integral term reduces steady-state error, and the derivative term decreases oscillations. The controller is expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (16)$$

The results indicate that balanced selection of K_p , K_i , and K_d is important for stable UAV attitude control. However, fixed PID parameters may be less effective under nonlinear dynamics, payload changes, and external disturbances. Therefore, adaptive and AI-based tuning methods may be considered in future UAV control studies. Similar quadrotor flight dynamics and stabilization behavior were also discussed by Hoffmann et al. (2007).

Conclusion

This study examined the application of PID-based control for improving the stabilization performance of unmanned aerial vehicles. A simplified mathematical model of UAV attitude motion was developed for roll, pitch, and yaw channels, and the effect of PID parameters on the dynamic response of the system was evaluated through simulation.

The obtained results indicate that the selection of proportional, integral, and derivative coefficients has a direct influence on flight stability. In comparison with low-gain and medium-gain configurations, the optimized PID controller demonstrated shorter settling time, lower steady-state error, and smoother attitude response. The analysis also showed that the proportional term mainly improves response speed, the integral term compensates for steady-state error, and the derivative term contributes to damping and oscillation reduction.

Although PID control is a practical and computationally efficient method for UAV stabilization, its effectiveness depends strongly on parameter tuning. Fixed PID coefficients may not always provide the same performance under nonlinear flight dynamics, payload variation, or external disturbances. Therefore, further improvement of UAV control systems may require adaptive tuning strategies and intelligent optimization methods.

Overall, the study confirms that PID-based control can be effectively used for UAV attitude stabilization. Future research may focus on adaptive PID structures, fuzzy logic, neural-network-based controllers, and AI-assisted tuning approaches to increase control accuracy, robustness, and autonomous flight performance under more complex operating conditions.

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The Impact of Social Media Technologies on Language Dynamics: A Sociolinguistic Analysis of Code-Switching and Code-Mixing in Communication

Yegana Gahramanova 

Abstract. *This study examines the sociolinguistic impact of social media technologies and digital communication platforms on the contemporary dynamics of the Azerbaijani language, with particular attention to its lexical and syntactic structure. The primary focus of the study is on instances of “code-switching” and “code-mixing” observed between Azerbaijani and other languages, particularly English and Russian, during digital communication. The study draws on digital materials collected from Instagram, WhatsApp, TikTok, and X between September 2025 and February 2026. An initial dataset consisting of approximately 120,000 words of digital text was compiled, from which 100 instances of code-switching and code-mixing were selected for structural and functional analysis. The examples were categorized according to Poplack’s classification into intra-sentential, inter-sentential, and tag-switching categories. The quantitative analysis revealed that intra-sentential switching accounted for 57%, inter-sentential switching for 28%, and tag-switching for 15% of the analyzed cases. The qualitative analysis indicates that code-switching can be associated with such functions as communicative economy, terminological convenience, audience adaptation, expressiveness, and digital identity. The study also demonstrates that the adaptation of foreign-origin lexical items to the morphological system of Azerbaijani should be considered as a distinct process within digital language practices. The findings suggest that digital multilingualism constitutes an important component of the contemporary development dynamics of the Azerbaijani language.*

Keywords: *digital sociolinguistics, social media, code-switching, code-mixing, Azerbaijani language, multilingualism, digital communication, digital corpus*

Introduction

The rapid development of digital technologies in the twenty-first century has brought about significant changes in human communication patterns. Social networking sites, instant messaging applications, microblogging platforms, and video-based communication channels have, to a certain extent, blurred the traditional boundaries between written and spoken communication, giving rise to new communicative modes. In digital communication, writing, speech, visual elements, emojis, hyperlinks, hashtags, and other multimodal resources can be combined within the same communicative act. Tagg (2015) regards digital communication not merely as a technological medium, but as a communicative environment that enables the observation of changing forms of language use, identity, and social interaction.

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Language choice in social media environments is likewise affected by this transformation. In particular, multilingual users can alternate between and combine different linguistic resources within the same communicative act and employ them functionally for particular social purposes. Androutsopoulos's (2014) study of linguistic repertoires in social networking demonstrates that users' language choices are closely related to network audiences, interaction, and sharing practices. Thus, social media is not merely a space in which existing language forms are transmitted; it is also a social environment in which new linguistic practices emerge.

In sociolinguistic literature, the alternation between two or more language codes within the same communicative process is described as code-switching, whereas the combination of elements belonging to different languages within the same syntactic structure is generally described as code-mixing. Poplack's (1980) study is of particular importance in the classical classification of the structural features of code-switching. The author distinguished between intra-sentential and inter-sentential code-switching, as well as the switching of short discourse elements into another language. In her 2013 authorial introduction to the classic study, Poplack emphasized that distinguishing code-switching from borrowing remains an issue discussed in subsequent research (Poplack, 2013).

Code-switching has not only structural but also grammatical characteristics. Myers-Scotton's (1993) Matrix Language Frame model is one of the widely used theoretical models for explaining the functional relationship between the matrix language and the embedded language in mixed speech. According to this approach, the principal syntactic and morphological frame in a mixed construction may be provided by one language, while the other language contributes lexical or other elements to that frame.

These processes may become more complex in digital environments. On the one hand, social media users take into account the need for rapid and concise communication; on the other hand, they employ linguistic resources appropriate to their audience, topic, and social identity. Examining Facebook interactions, Halim and Maros (2014) found that code-switching may serve various functions, including quotation, addressee specification, repetition, explanation, emphasis, emotional expression, and communicative economy.

The Azerbaijani language is also part of this global digital linguistic environment. In particular, the widespread use of English in technology, social media, marketing, and popular culture has created conditions for numerous lexical transfers in Azerbaijani digital communication. Gadirli (2024), who examines the interaction between the Azerbaijani language and digital technologies, emphasizes the importance of studying changes occurring at the structural and lexical levels of the language from a sociolinguistic perspective. Qəhrəmanova's (2026) study of the semantic and syntactic features of Azerbaijani in the context of digitalization and artificial intelligence likewise demonstrates the significance of the interaction between the Azerbaijani language and digital technologies for contemporary linguistics.

Within this context, the main aim of the study is to identify the structural types and possible communicative functions of code-switching and code-mixing between Azerbaijani and other languages on social media platforms.

The study seeks to answer the following research questions:

1. Which types of code-switching and code-mixing between Azerbaijani and other languages are most frequently observed on social media platforms?
2. What proportion of intra-sentential, inter-sentential, and tag-switching occurrences is observed in digital communication environments?

3. What communicative, lexical, audience-related, and identity-related factors can be observed in the occurrence of code-switching?
4. In what forms is the integration of foreign-language elements into the morphological and syntactic structure of Azerbaijani manifested?

Theoretical Framework

Code-switching is a broad sociolinguistic phenomenon referring to alternation between languages during multilingual communication. Poplack's (1980) classical classification distinguishes three principal forms of code-switching: intra-sentential switching, inter-sentential switching, and tag-switching. Intra-sentential switching refers to the use of elements from different languages within the syntactic structure of a single sentence, whereas inter-sentential switching involves a change of language code when moving from one sentence or discourse unit to another. Tag-switching is characterized by the use of interjections, discourse markers, or short fixed expressions in another language.

Poplack's 2013 publication is significant because it reconsiders the classical study within a subsequent scholarly context. In this work, the author demonstrates that distinguishing code-switching from borrowed elements entering a language remains a subject of theoretical and methodological debate (Poplack, 2013).

This distinction is particularly important for the analysis of digital language data. For example, it would not be methodologically appropriate to automatically classify every occurrence of words such as “deadline,” “feedback,” and “update” as code-switching. If a foreign-origin unit has become established in a user's linguistic repertoire and has been adapted to the morphological structure of Azerbaijani, another form of language contact—borrowing or adaptation—must also be taken into account.

This issue is further clarified in the study by Poplack, Robillard, Dion, and Paolillo on language-contact phenomena. The authors distinguish between code-switching, established loanwords, and newly emerging nonce borrowings, demonstrating that phonetic and morphosyntactic integration do not constitute the same process. According to their findings, morphosyntactic integration may serve as a more reliable indicator for distinguishing language-contact phenomena (Poplack et al., 2020). Although the article was made available online on Cambridge Core in 2026, its bibliographic publication information belongs to the 2020 issue of *Language*.

Myers-Scotton's (1993) Matrix Language Frame model explains the structural relationship between language elements in mixed sentences. Within this model, the matrix language provides the principal syntactic and morphological frame, while the embedded language contributes particular elements to that frame. Forms such as “postlamaq,” “like eləmək,” and “check etmək” in Azerbaijani can therefore be analyzed not only from a lexical perspective but also in terms of morphological integration.

Methods

A mixed-methods approach was employed in the study. The quantitative analysis aimed to determine the frequency of code-switching and code-mixing according to their structural types, whereas the qualitative analysis sought to describe the communicative contexts in which these switches occurred.

The data were compiled from digital language material observed on Instagram, WhatsApp, TikTok, and X between September 2025 and February 2026. The initial database consisted of a digital corpus of approximately 120,000 words. A total of 100 instances of code-switching and code-mixing were selected from this corpus for structural and functional analysis.

Examples obtained from Instagram, TikTok, and X were based on publicly accessible digital texts, whereas the WhatsApp material consisted of voluntarily provided examples of private correspondence. Personal names, usernames, telephone numbers, and other identifying information were excluded from the analysis or anonymized.

The examples were coded into three principal categories in accordance with Poplack's (1980, 2013) classification:

1. *Intra-sentential switching* – the use of a word, expression, or construction belonging to another language within a sentence;
2. *Inter-sentential switching* – a change of language code between sentences or discourse units;
3. *Tag-switching* – the use of interjections, discourse markers, and short expressions in another language.

The distinction between code-switching and lexical borrowing was also taken into consideration. Hybrid forms adapted to the morphological system of Azerbaijani, such as “postlamaq,” “like eləmək,” and “cancel eləmək,” were noted separately, and an effort was made not to equate them automatically with code-switching at the level of the entire sentence. This approach is consistent with the findings of Poplack and colleagues concerning the differentiation of language-contact phenomena on the basis of morphosyntactic integration (Poplack et al., 2020).

Descriptive statistics were used for the quantitative analysis. The frequency of each category was calculated using the following formula:

$$\text{Percentage (\%)} = (\text{number of instances in the category} / \text{total number of instances}) \times 100$$

The jamovi software was used for the initial statistical processing of the data and for preparing the tables.

In the qualitative analysis, the communicative contexts in which code-switching occurred were examined. Particular attention was paid to functional aspects such as communicative economy, lexical choice, technological terminology, audience adaptation, expressiveness, and digital identity.

Results

Various forms of code-switching and code-mixing between Azerbaijani and other languages were observed in the 100 digital samples analyzed. The most frequently observed language pairing was Azerbaijani and English, while Russian-origin lexical elements were also found in some examples.

Table 1
Structural types of Code-Switching instances

Type of code-switching	Description	N	%
Intra-sentential switching	Use of an element from another language within a sentence	57	57%
Inter-sentential switching	Change of language code between sentences	28	28%
Tag-switching	Use of a short discourse marker, interjection, or expression in another language	15	15%
Total	—	100	100%

Source. Compiled by the author.

As shown in Table 1, the highest proportion belongs to the intra-sentential switching category. In 57 instances, representing 57% of the total sample, words and expressions from another language were used within sentences constructed in Azerbaijani.

Among the observed examples, lexical units such as “deadline,” “check,” “feedback,” “update,” “story,” “like,” and “target” were particularly noticeable. In some cases, these words received Azerbaijani morphological markers: “deadline-ı” [the deadline + Azerbaijani accusative marker], “story-ni” [the story + Azerbaijani accusative marker], “like etmək” [to like], “check etmək” [to check], and so forth.

This finding demonstrates that digital language data involve not only switching between two languages but also the adaptation of foreign-origin elements to the morphological system of Azerbaijani.

Inter-sentential switching constituted the second most frequent category, with 28 instances. In these cases, users expressed the main part of an idea in Azerbaijani and then switched to English in the following sentence. For example:

“Mən artıq təqdimatı bitirdim. By the way, did you see the new update?”
[I have already finished the presentation. By the way, did you see the new update?]

Here, the language shift occurs at a syntactic sentence boundary and is associated with a new idea, a question, or an additional communicative purpose.

Tag-switching accounted for 15% of the examples. This category included discourse elements such as “honestly,” “anyway,” and “by the way.” These units can establish an attitude, emphasis, or discourse connection without altering the main propositional content.

Observations by Platform

On Instagram and TikTok, code-mixing was observed primarily in short post texts, comments, and expressions associated with visual content. On these platforms, the retention of English-language terms related to social media and popular culture was particularly noticeable.

In the WhatsApp examples, code-mixing occurred mainly in everyday, informal, and interactive communication. Here, language choice appeared to be closely associated with interpersonal relationships, established communication habits, and topic.

On the X platform, short written texts expressing opinions, reactions, and attitudes predominated. In this environment, code-switching was observed to serve the functions of shortening discourse and retaining certain expressions in their original form.

Functional Characteristics

The qualitative analysis indicated that code-switching and code-mixing could be associated with several communicative functions.

The first function is communicative economy and lexical convenience. Users may express certain digital concepts through widely familiar English-origin terms. Since units such as “update,” “story,” “feedback,” “post,” and “like” are familiar to users in digital communication contexts, they may be selected more quickly than their Azerbaijani equivalents.

The second function is the influence of digital terminology. English-derived terms are particularly widespread in technology, marketing, design, and social media. However, the absence of an

Azerbaijani equivalent for every foreign term, or the limited circulation of an existing equivalent among users, may contribute to the retention of the foreign form.

The third function is expressiveness and stylistic choice. Memes, social media trends, popular expressions, and Internet slang may produce a particular communicative effect when retained in their language of origin. In such cases, code choice is related not only to the transmission of content but also to the stylistic and emotional characteristics of the expression.

The fourth function is audience adaptation. Users may select particular linguistic elements with consideration for the linguistic repertoire of their interlocutors. Androutsopoulos (2014) emphasizes the relationship between linguistic repertoire, audience, and sharing practices in social networks. The findings of Halim and Maros (2014) likewise demonstrate that online code-switching can perform functions such as addressee specification and message clarification.

The fifth function is digital identity. Social media users can display particular social and cultural affiliations through their language choices. From this perspective, the use of English may be associated with global digital culture. However, this finding should not be interpreted as a universal claim about users' motivations, but rather as a possible social function of the communicative practice observed.

Discussion

The findings of the study demonstrate certain parallels with previous research in digital sociolinguistics. Cárdenas-Claros and Isharyanti (2009) showed that code-switching and code-mixing in Internet chatting may be associated with communicative context and terminological needs. Their study represents one of the earlier examples demonstrating that code-switching in digital written communication does not necessarily occur randomly but may emerge under specific communicative conditions.

Halim and Maros (2014) identified a number of communicative functions of code-switching in Facebook interactions. Their identification of functions such as quotation, explanation, emphasis, emotional expression, and communicative economy is relevant for comparison with the functional patterns observed in the present study. Nevertheless, the findings of studies conducted across different languages and platforms should not be treated as directly equivalent.

Sutrisno and Ariesta (2019) examined the language use of social media influencers on Instagram and demonstrated that code-mixing can be systematically observed in social media content. This finding suggests that the code-mixing patterns observed in the Instagram environment in the present study may be characteristic of digital communication.

Hayati and Anindhita (2024) found that students use code-switching and code-mixing on social media, involving English, Indonesian, and Javanese. This finding suggests that the use of multilingual repertoires by young users in digital environments is a recurring phenomenon across different social and linguistic contexts.

The approach of Androutsopoulos (2014), meanwhile, demonstrates the importance of studying digital language use not merely as structural change but within the framework of social interaction and relationships with audiences. From this perspective, code-switching observed in the Azerbaijani social media environment should not be evaluated merely as the “use of foreign words”; its communicative context should also be taken into account.

The status of Azerbaijani in the digital environment is of interest not only in relation to these general tendencies but also in terms of the language's own structural characteristics. Gadirli (2024) considers the impact of digital communication technologies on Azerbaijani in the context of sociolinguistic and structural changes. Qəhrəmanova's (2026) study brings into focus the interaction between digitalization, artificial intelligence, and the agglutinative morphosyntactic characteristics of Azerbaijani. These approaches demonstrate that the digital linguistic environment represents an important field of research for understanding the future developmental dynamics of Azerbaijani.

One of the most important findings of our study is that intra-sentential code-switching has the highest proportion, at 57%. This figure indicates that, within the Azerbaijani digital language material analyzed, the insertion of foreign-language elements into the syntactic structure of the principal language is widespread. However, this result should not be generalized to all Azerbaijani social media users. Since the sample consists of 100 instances, the figures reflect the characteristics of the particular dataset.

The high proportion of intra-sentential switching is also noteworthy from the perspective of Myers-Scotton's Matrix Language Frame model. In many examples, Azerbaijani provides the principal syntactic frame, while English-origin units are inserted into that frame. In examples such as “feedback almaq” [to receive feedback], “story paylaşmaq” [to share a story], “check etmək” [to check], and “like etmək” [to like], the foreign-origin lexical element is used in a manner compatible with the syntactic and morphological system of Azerbaijani.

Nevertheless, it would not be methodologically appropriate to classify all such forms as “code-switching” at the same level. The later research of Poplack and colleagues on language contact demonstrates the need to distinguish code-switching from established borrowing and nonce borrowing. Consequently, future studies of digital Azerbaijani should measure not only the frequency of foreign elements but also their degree of morphological integration, stability of use, and distribution across different speakers.

This approach also requires special investigation of hybrid forms such as “postlamaq” [to post], “like etmək” [to like], and “cancel etmək” [to cancel]. On the one hand, such forms demonstrate that foreign lexical elements can enter the agglutinative morphological system of Azerbaijani; on the other hand, they indicate the emergence of new word-formation processes in digital communication environments.

Conclusion

The study examined the influence of social media technologies on multilingual communication practices in Azerbaijani through examples of code-switching and code-mixing. Analysis of 100 examples selected from an initial digital corpus of 120,000 words demonstrated that code-switching occurs in various structural forms.

The highest proportion belonged to the intra-sentential switching category, accounting for 57% of the sample. Inter-sentential switching accounted for 28%, while tag-switching accounted for 15%. These findings indicate that, within the specific sample analyzed, intra-sentential language switching was more widespread.

The qualitative analysis demonstrated that code-switching and code-mixing could be associated with functions such as communicative economy, terminological convenience, expressiveness, audience adaptation, and digital identity. At the same time, it is not possible to conclude that these functions constitute the same motivations for all users.

Another important finding concerns the adaptation of foreign-language elements to the morphological system of Azerbaijani. Forms such as “deadline-ı” [the deadline + Azerbaijani accusative marker], “story-ni” [the story + Azerbaijani accusative marker], “check etmək” [to check], “postlamaq” [to post], and “like etmək” [to like] demonstrate that lexical contact in digital communication may be accompanied by morphological integration. This process can theoretically be related to the findings of Poplack and colleagues concerning the importance of morphosyntactic integration in language-contact phenomena.

However, the limitations of the study should also be taken into account. First, the analytical sample of 100 instances does not represent the language behavior of Azerbaijani social media users as a whole. Second, because user profiles and communicative characteristics differ across platforms, direct cross-platform comparisons should be made cautiously. Third, the motivations underlying observed language switching can only be inferred to a limited extent from textual data; future studies may employ interviews and survey methods to investigate users' subjective motivations more precisely.

Recommendations

1. *Systematic updating of digital terminology.* It is advisable to develop functional and user-friendly Azerbaijani terminological equivalents in the fields of technology, social media, artificial intelligence, and digital marketing.
2. *Expansion of the Azerbaijani digital corpus.* The creation of a dedicated digital subcorpus consisting of social media, blogs, forums, and instant-messaging data could provide an important database for future sociolinguistic and NLP research.
3. *Distinguishing code-switching from borrowing.* Future studies should not be limited to counting foreign words; they should also take into account the degree to which such elements are integrated into the morphological and syntactic system of Azerbaijani.
4. *Expansion of cross-platform comparison.* In addition to Instagram, TikTok, WhatsApp, and X, YouTube, Telegram, and other digital communication platforms could be incorporated into future research to provide a broader picture.
5. *Longitudinal corpus research.* To identify the dynamic nature of digital language change, longitudinal studies comparing the use of the same linguistic units across different years are recommended.

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The Role of Artificial Intelligence in Historical Research: Investigation of Documents, Manuscripts, Resources, and Sources

Zaur Aliyev 

Abstract. *The Role of Artificial Intelligence in Historical Research: Investigation of Documents and Sources. The article analyzes the role of artificial intelligence technologies in the fields of historical science, source criticism, paleography, and archival studies from the perspective of a historian and scholar. Avoiding complex mathematical and technical terminology, the paper explains the methodological innovations brought by the Digital Humanities in an accessible language. It explores the capabilities of AI in deciphering ancient and faded manuscripts, detecting forged documents through stylometric analysis, establishing global archival networks, and digitally reconstructing damaged stone inscriptions and clay tablets. Furthermore, the ethical boundaries of AI and the problems of algorithmic bias are evaluated in the light of the traditional principles of source criticism. The study explores how artificial intelligence can enhance the examination of historical materials by facilitating the digitization, recognition, organization, and analysis of complex documentary and manuscript collections. A qualitative and comparative approach is applied to assess the usefulness of AI-assisted research techniques while emphasizing the importance of source verification and scholarly interpretation in maintaining the reliability of historical findings.*

Keywords: *artificial intelligence, historiography, source criticism, paleography, digital archives, stylometry, semantic translation*

Introduction

Historical science has always been associated with dusty archival shelves, yellowed papers, ancient documents preserving the scent of time, and manuscripts that take months to decipher. We, as historians, source critics, and archivists, dedicate our lives to seeking a light, a truth, within the dark chambers of the past. However, the technological leap of the 21st century has ignited a completely new, distinct, and powerful digital lantern before the humanities: artificial intelligence (AI). Although artificial intelligence and Big Data may initially seem like cold, mathematical fields detached from the humanities and human emotions, AI is actually becoming our greatest ally in resurrecting the past and fluently conveying forgotten voices to us.

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Traditional historical methods are now compelled to merge with the opportunities brought by the Digital Humanities. Digital tools do not take archives and live research away from us; on the contrary, they organize vast piles of documents that would take decades or an entire lifetime for a human to process, thereby saving our time. From a historian's perspective, this technology is a tool that directly supports source criticism, paleography, and archival work, rather than operating through complex formulas. While searching for the traces of the past, we no longer rely solely on magnifying glasses but also on the analytical power of neural networks. The purpose of this article is to stay away from the dry language of technical sciences and investigate, from a humanitarian and critical-scientific standpoint, how AI revitalizes old sources, unlocks their hidden secrets, and simplifies the work of historians.

One of the most difficult intellectual and physical challenges an investigator faces in daily work and within archives is paleography—namely, ancient script types. Deciphering complex calligraphic forms such as *Siyaqat*, *Ta'liq*, *Shikaste*, *Naskh*, or ornate *Kufic*, as well as the intricate ligatures of medieval decrees, requires years of training, patience, and profound language proficiency. Furthermore, documents that have faded, aged, or been damaged by moisture or fire over time are often completely illegible to the human eye. A historian may spend days trying to read a single word. Artificial intelligence's image recognition and machine learning systems come to our aid at this challenging juncture. It analyzes microscopic ink traces and indentations in the paper's relief that are invisible to the human eye, predicts missing letters, and converts the text into a digital format.

Methods

This study employs a qualitative research methodology to examine the role of artificial intelligence in historical research, with particular emphasis on the investigation, interpretation, classification, and preservation of historical documents, manuscripts, resources, and sources. The methodological framework combines document analysis with a systematic review of relevant academic literature and technological applications. The purpose of this approach is to identify the main ways in which AI-based tools can support historians while also considering the methodological limitations and risks associated with their use.

The first stage of the research involves a review and analysis of scholarly publications addressing artificial intelligence, digital humanities, historical research, manuscript studies, optical character recognition, natural language processing, and digital preservation. Academic articles, books, conference papers, institutional reports, and relevant digital resources are examined to establish a theoretical foundation for understanding the interaction between AI technologies and historical research. Particular attention is given to studies that demonstrate practical applications of AI in the digitization, transcription, classification, and interpretation of historical materials.

The second stage focuses on the analysis of AI-assisted methods for examining historical documents and manuscripts. These methods include optical character recognition, handwritten text recognition, natural language processing, image analysis, and automated metadata generation. The study considers how these technologies can transform scanned or photographed historical materials into searchable digital data. AI-supported text recognition is examined particularly in relation to manuscripts containing difficult handwriting, damaged pages, faded ink, unusual spelling, and obsolete linguistic forms.

The third methodological component involves comparative analysis. Traditional approaches to historical source analysis are compared with AI-assisted procedures in terms of processing speed, accessibility, classification capacity, consistency, and the ability to identify relationships between large collections of sources. The comparison does not assume that AI can replace conventional

historical methods; instead, it examines AI as an additional research instrument that can facilitate the work of historians and enable them to investigate larger volumes of material.

Source verification constitutes another important element of the methodology. Since AI systems may generate inaccurate transcriptions, misinterpret historical terminology, or incorrectly identify persons, dates, places, and events, AI-generated results are treated as preliminary research outputs rather than definitive historical evidence. The reliability of identified information is therefore assessed through comparison with original documents, established archival records, scholarly publications, and other independent sources. This verification procedure is intended to reduce the possibility of reproducing computational errors in historical interpretation.

Finally, the study evaluates the methodological and ethical challenges associated with the use of AI in historical research. These include algorithmic bias, incomplete digitization of archival collections, language limitations, loss of contextual information, inaccurate transcription, questions of authorship, and the potential misinterpretation of culturally or historically sensitive materials. Based on the analysis, the research considers AI most effectively as a complementary technology that assists historians in discovering, organizing, and examining sources while leaving contextual interpretation and final scholarly judgment to the researcher.

Results

The Digital Lantern of Historical Science and New Methodological Challenges

Optical Character Recognition (OCR) and particularly Handwritten Text Recognition (HTR) technologies used in the modern world have revolutionized the digitalization of handwritten heritage (Abbasov, 2023; Boonstra et al., 2014; Hitchcock, 2013; Mühlberger et al., 2019). Thanks to new digital platforms, thousands of Arabic manuscripts, Ottoman-era official documents, and medieval European Latin texts are being decrypted at a rapid pace. Artificial intelligence does not merely isolate letters; it also learns a scribe's individual style. Once the system learns the handwriting characteristics of a specific scribe, it can read other obscure documents belonging to that same scribe with greater accuracy. However, as scholars, let us not forget that the system only reads and digitalizes the text visually; its true historical meaning, philosophical distinction, and context are still left to us—living scholars (Habibova, 2026; Terras, 2011).

The most vital yet challenging part of source criticism and archival work is the internal and external criticism of documents. A researcher must first ask this question: Is this document authentic, or is it a forgery created later for a specific purpose? Throughout history, due to political interests, land claims, throne disputes, or property issues, false decrees have often been written in the name of rulers, wills have been altered, or subsequent insertions have been made into chronicles. Verifying the authenticity of a document through classical methods involves analyzing the chemical composition of the paper, watermarks, and ink; this requires laboratory conditions and can sometimes cause irreversible damage to the physical structure of a rare document.

Artificial intelligence examines the language, style, and sentence structure of a document without physically touching it. Every author, historian, calligrapher, or court scribe possesses a unique choice of words, sentence structure habits, and punctuation preferences. Neural networks quickly discover this hidden "stylistic fingerprint" (Juola, 2008; Mosteller & Wallace, 2012). For instance, if an investigated Safavid decree or a letter from an Ottoman prince contains foreign words or grammatical forms that do not fit the lexicon of that era and emerged in later centuries, AI identifies this anachronism within seconds. This serves as a filter protecting the historian from drawing incorrect conclusions based on forged sources and from distorting history.

Historical events are never confined to a single place or the borders of a single state. An internal political event or a diplomatic step taken by one state is also reflected in the documents of neighboring and allied states. For example, the decrees, treaty texts, or diplomatic letters of a certain period in our history, such as the era of the Khanates, may be scattered simultaneously across archives in Baku, Istanbul, Tbilisi, St. Petersburg, Paris, or London. It is physically and financially impossible for an individual historian to visit all these archives, leaf through millions of pages in different languages, and cross-reference them within a human lifespan.

Artificial intelligence integrated with Big Data databases and cloud technologies unites these scattered geographies within a single digital space. Millions of documents digitalized in different parts of the world are scanned by AI within seconds (Putnam, 2016). The system uncovers hidden logical, chronological, and person-oriented connections among materials written in different languages. For instance, it can reveal to whom an anonymous and undated official letter found in the Istanbul archives actually belonged, and trace how the response to that letter connects in a chain-like fashion to a digital report document in the London archives. In this manner, the puzzle of history, which has been fragmented for centuries, turns into a unified and complete picture, allowing national histories to find their true place within a global context.

Discussion

Wars, palace coups, fires, humidity, the plundering of libraries, and other natural disasters have dealt severe and incurable blows to the written memory of humanity over the centuries. Today, many ancient clay tablets, papyri, parchments, and stone inscriptions (epigraphic monuments) preserved in world museums and archives are broken, eroded, or completely erased. To find what was written in lost lines or broken parts, historians and epigraphists often resort to subjective hypotheses and personal intuition, which puts scientific certainty into question.

Today, advanced large language models and deep neural networks learn substantial data regarding the grammar of ancient languages, the literary-political language of the period, poetics, and context. These models can reconstruct the lost or broken parts of documents with scientific precision (Assael et al., 2022). Artificial intelligence does not merely fill in the blanks; it compares thousands of historical texts, formulas, and phrase patterns from the same period to restore the scientific variant that aligns with the spirit and logic of the era. Thanks to these digital reconstruction methods, stone inscriptions or decrees that previously remained incomplete enter the scientific realm as fully functioning historical sources.

Translating an ancient or medieval text into a modern language is not just about finding the contemporary equivalents of words from a dictionary. Languages change and transform like living organisms. Concepts, administrative-titular terms, and legal expressions used in the Middle Ages or even more ancient times either carry a different meaning today or have been completely forgotten and shifted into the passive vocabulary of the language. Simple, literal, and mechanical translations lead to the distortion of historical facts and the misinterpretation of events.

New-generation "contextual" language models can translate text not word-for-word, but semantically, taking into account the political, cultural, religious, and social environment of the period in which it was written (Mustafayev, 2026). Artificial intelligence investigates the real semantic field and conceptual system of words used in the century the document was penned. In this way, for example, we can understand a ruler's expression not merely through its literal dictionary meaning, but by more accurately, objectively, and scientifically capturing the underlying real political threats, hidden diplomatic messages, palace intrigues, and the nuances of diplomatic discourse (Spruit & de Jong, 2011). Given that artificial intelligence can compromise lexical semantics and render the context window ineffective, this situation demands a greater sense of responsibility (Qəhrəmanova, 2026).

These fascinating, rapid, and extensive opportunities presented by artificial intelligence in the digital humanities should not make us entirely complacent or diminish our scientific vigilance. Recent discussions in the Azerbaijani scientific community also show that the cybersecurity of historical facts and their protection against manipulations in the digital space remain urgent issues (Alizadeh, 2026). As scholars, historians, and representatives of the humanities, we must never forget that AI is not a "historian" in itself, and it can never be. By nature, it is essentially a forecasting tool operating on excellent mathematical calculation, statistical analysis, and probabilities. It possesses neither the historical thinking to comprehend historical events, nor human emotions, nor the ability to feel the hidden, mysterious spirit of history as a human does.

The machine can fully read text, restore missing parts, and digitalize it, but it cannot completely comprehend how the person, scribe, or ordinary individual who wrote that text was affected under fear, joy, psychological states, political pressure, or censorship. Furthermore, one of the greatest dangers of AI is the problem of "algorithmic bias." If the baseline dataset used during the training of artificial intelligence is one-sided, subjective, or filled with certain ideological biases, the results produced and the historical connections established by the machine will be equally biased, erroneous, and unscientific. For this reason, every finding, reading, and translation variant presented by technology must always pass through the classical scientific filter of the human historian—namely, the methodology of fundamental source criticism. The final scientific judgment, moral responsibility, and scholarly value must always stem from human creative intelligence.

Conclusion

In conclusion, we investigate history not merely out of curiosity about what happened in the past, but to understand the present and build the future on firmer ground. The speed, high accuracy, global archival connections, and restoration opportunities that AI brings to history, source criticism, and archival studies usher a new era of "Digital Awakening" into historiography. Technology does not change the historian; rather, it liberates them from tedious, mechanical, and years-long technical tasks, allowing them to engage directly in creative analysis, philosophical generalization, and scientific interpretation.

Technology is our most loyal assistant in preserving documents for future generations, making them readable, and ensuring they are accessible from anywhere in the world. The historiography of the future will be a science that combines archival dust with the digital light of the computer screen, and traditional principles of source criticism with advanced neural networks. This alliance between human intelligence and AI will bring back to light the forgotten truths, documents, and facts lost in the dark corners of history, transferring our national and global memory to future generations flawlessly and without distortion.

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