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DEVELOPING MATHEMATICAL COMPETENCE THROUGH ARTIFICIAL INTELLIGENCE TECHNOLOGIES

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ABSTRACT: This article analyses the application of artificial intelligence technologies in developing the mathematical competence of higher education students. The didactic affordances of adaptive learning platforms, intelligent tutoring systems and generative artificial intelligence tools are examined, and their effectiveness is substantiated through statistical methods on the basis of the results of a pedagogical experiment.

Keywords: artificial intelligence, mathematical competence, adaptive learning, intelligent tutoring system, generative AI, digital education, pedagogical experiment, higher education, computer algebra system, individualisation.

Introduction. In the present era of digital transformation, artificial intelligence (AI) technologies are emerging as an important instrument for shaping innovative pedagogical approaches and qualitatively enhancing the effectiveness of education. The "Digital Uzbekistan — 2030" strategy issued by the President of the Republic of Uzbekistan and the Law of the Republic of Uzbekistan "On Education" establish the digitalisation of educational processes and the elevation of students' competence-based preparation to a new level as priority national tasks [7, 8]. The direct relevance of these objectives to the educational sphere further amplifies the scientific and practical significance of the present topic.

Mathematical competence is conceptualised not merely as the aggregate of mathematical knowledge, skills and abilities, but as an integrative construct that denotes the capacity to apply such knowledge effectively in addressing problems arising in practical and professional activity. According to the classification proposed by M. Niss and T. Højgaard, mathematical competence comprises eight core components, including mathematical thinking, problem posing and solving, modelling, logical reasoning, the use of symbolic and technical tools, and communication [6]. Taken together, these components enable the student to deploy mathematical knowledge effectively in both standard and non-standard situations.

The widespread deployment of AI tools in education — including adaptive learning platforms (Khan Academy, ALEKS), intelligent tutoring systems (Carnegie Learning, MATHia), generative language models (ChatGPT, Claude, Gemini) and computer algebra systems (Wolfram Alpha, GeoGebra AI) — opens up novel possibilities for the individualisation of mathematics education [3, 4]. The didactically informed use of such tools may significantly enhance educational quality; however, this requires a methodologically grounded, scientifically and pedagogically substantiated approach.

The relevance of the topic is determined by the following factors: first, traditional educational methodology has limited capacity to accommodate the individual knowledge level and learning pace of each student; second, a decline in mathematical achievement among higher

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education students and persistent difficulties in grasping abstract concepts are increasingly observed; third, labour-market demand for graduates equipped with digital competence and skills in mathematical modelling and data analysis has risen sharply; fourth, domestic empirical studies that substantiate the didactic potential of AI-based educational tools from a scientific-pedagogical perspective remain insufficient.

The aim of the research is to elaborate the scientific and methodological foundations for using artificial intelligence technologies to develop the mathematical competence of higher education students, and to verify their effectiveness through a pedagogical experiment.

The research tasks are as follows: (1) to provide a theoretical justification of the structural composition of mathematical competence and the didactic conditions for its development; (2) to classify the didactic affordances of AI technologies in mathematics education; (3) to design an instructional model based on the use of AI tools; (4) to evaluate the effectiveness of the proposed model through a pedagogical experiment using statistical methods; and (5) to formulate practical and scientific recommendations on the basis of the obtained results.

The scientific novelty of the research lies in the fact that, for the first time within the Uzbek-language higher education environment, the differential impact of adaptive learning platforms and generative AI tools on the components of mathematical competence has been empirically investigated and statistically substantiated through a pretest–posttest design.

Research methodology. The research was conducted on the basis of ISFT Institute during the 2024–2025 academic year. A coherent combination of theoretical and empirical methods was employed throughout the study, ensuring the reliability of the findings.

Theoretical methods: comparative analysis of relevant scientific and pedagogical literature, dissertations and electronic resources; systemic study of the conceptual frameworks of mathematical competence; classification of AI technologies according to didactic criteria; and generalisation of cognitive-constructivist instructional models.

Empirical methods: pedagogical observation; surveys conducted among students and faculty (using Likert-type scales); pedagogical interviews; a pretest–posttest pedagogical experiment; comparative analysis of control and experimental groups; and qualitative assessment of the products of students' independent work.

Statistical methods: data processing employed Student's t-test, Pearson's χ^2 test, analysis of variance (ANOVA) and Cohen's d effect-size coefficient. Statistical processing was performed using SPSS 26.0 and MS Excel 365. The reliability of the diagnostic instrument was assessed by means of Cronbach's α coefficient.

Experimental setting and respondents. The pedagogical experiment involved a total of 152 first- and second-year students. Of these, 76 constituted the experimental group (EG) and the remaining 76 the control group (CG). The groups were equivalently distributed according to baseline diagnostic results: $t = 0.42$; $p > 0.05$, confirming the initial parity of the groups and providing the necessary precondition for conducting the formative experiment. Gender and age distributions were also taken into account.

Stages of the experiment:

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(1) The ascertaining stage (September 2024) — diagnosing the level of students' mathematical competence; formulating the working hypothesis and defining the criteria, indicators and methodological instruments.

(2) The formative stage (October 2024 – April 2025) — systematic implementation of the AI-based instructional model in the experimental group, while the control group continued with traditional teaching methods; intermediate diagnostic measurements were also conducted.

(3) The summative stage (May 2025) — statistical processing and analysis of the obtained data; formulation of conclusions and recommendations; and dissemination of findings through scientific-practical conferences and journal publications.

Diagnostic instruments. An author-designed test was developed comprising 25 tasks covering the five core components of mathematical competence — knowledge, skills, abilities, modelling and reflection. The test included tasks across four cognitive levels in accordance with Bloom's taxonomy: knowledge–understanding, application, analysis and synthesis. The internal consistency of the test was confirmed at Cronbach's $\alpha = 0.87$, indicating a high level of reliability.

The experimental instructional model. Within the experimental group, the following set of AI tools was systematically integrated:

— Wolfram Alpha and GeoGebra AI — for the visualisation and symbolic verification of mathematical operations;
— ChatGPT and Claude — for step-by-step problem solving, the exploration of alternative solution pathways and the elicitation of explanations;
— Photomath and Symbolab — to support the independent completion of homework and to identify and correct errors;
— the adaptive platforms Khan Academy and ALEKS — to address knowledge gaps and to organise an individualised learning trajectory.

Throughout the experiment, each topic was addressed via a four-stage instructional sequence: (1) conceptual exposition by the instructor; (2) practical exercises performed with the assistance of AI tools; (3) independent task-solving by students; and (4) reflection and peer assessment.

Literature review. The integration of artificial intelligence into education has attracted considerable attention from foreign and domestic researchers alike. In their monograph "Artificial Intelligence in Education", W. Holmes, M. Bialik and Ch. Fadel offer an in-depth analysis of the impact of AI technologies on education along three dimensions — the student, the teacher and the educational system — and substantiate, with empirical evidence, the effectiveness of personalised learning, intelligent tutoring systems and data-driven assessment [3].

In her work "Machine Learning and Human Intelligence: The Future of Education for the 21st Century", R. Luckin emphasises that AI-based instructional systems offer significant potential for optimising students' cognitive load, fostering reflective thinking and developing metacognitive skills. The author conceptualises the synergistic relationship between human intelligence and machine learning as the prospective paradigm of education [4].

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Within the framework of the KOM project (Competencies and the Learning of Mathematics), M. Niss and T. Højgaard have proposed an eight-component structure of mathematical competence, which serves as both the theoretical and methodological foundation of contemporary mathematics education. The authors define mathematical competence as "the ability to understand, judge, do and use mathematics in a variety of intra- and extra-mathematical contexts and situations in which mathematics plays or could play a role" [6].

The UNESCO publication "AI and Education: Guidance for Policy-Makers" addresses the ethical, social and pedagogical dimensions of integrating AI technologies into education. The document examines issues of data privacy, the mitigation of digital inequality, the redefinition of the teacher's role and questions of algorithmic fairness. UNESCO experts recommend a human-centred approach as the guiding principle for integrating AI into education [9].

The analysis of domestic scholarly literature reveals significant contributions in this field, including B. S. Abdullayeva's didactic conception for developing the professional competence of prospective teachers [1], M. E. Mamarajabov's research on the use of digital educational resources and tools [5], and the doctoral (PhD) dissertation of D. M. Yusupova on the methodology of forming mathematical competence in higher education students [10]. These works address the development of professional competence among prospective specialists in the digital learning environment and the use of contemporary technologies in teaching mathematical disciplines.

At the same time, the analysis of domestic literature indicates that empirical investigations specifically devoted to the didactic potential of generative artificial intelligence and adaptive learning platforms in developing mathematical competence remain insufficient. This circumstance further enhances the scientific and practical significance of the topic and defines the original orientation of the present research.

On the basis of the literature review, the following research gaps have been identified:

— the didactic conditions and pedagogical models for using AI tools in mathematical disciplines within higher education are insufficiently elaborated;
— the mechanisms for preserving learner autonomy, academic integrity and critical thinking in AI-supported instruction remain underexplored;
— the differential impact of generative AI tools on individual components of mathematical competence has not been substantiated by statistical evidence;
— empirical studies evaluating the effectiveness of Uzbek-language adaptive learning platforms and AI tools in the local higher education environment are virtually absent.

Analysis and results. Findings of the ascertaining stage. Diagnostic results obtained at the first stage of the pedagogical experiment indicated that the distribution of mathematical competence levels was nearly identical in the experimental and control groups: high level — 14.5% in EG and 13.2% in CG; intermediate level — 47.4% and 48.7% respectively; low level — 38.1% in both. Student's t-test revealed no statistically significant difference between the groups ($t = 0.42$; $p = 0.67$), confirming their initial parity and ensuring the validity of the formative experiment.

The formative stage. During this stage, the following pedagogical conditions were systematically implemented in the experimental group: (a) methodological guidelines for the

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use of AI tools were provided for each topic; (b) students completed independent tasks on adaptive platforms at least three times per week; (c) the fundamentals of "prompt engineering" and strategies of "critical interactive dialogue" were taught for working with ChatGPT/Claude; (d) intermediate diagnostic assessments were conducted at four-week intervals, with subsequent adjustments to individual learning trajectories; and (e) the practice of maintaining a reflective journal was introduced.

Findings of the summative stage demonstrated a substantial growth in mathematical competence (Table 1).

Table 1

Final results of the pedagogical experiment (n = 152)

Level	EG (initial), %	EG (final), %	CG (initial), %	CG (final), %
High	14.5	38.2	13.2	21.1
Intermediate	47.4	51.3	48.7	53.9
Low	38.1	10.5	38.1	25.0

The data presented in the table demonstrate that, in the experimental group, the proportion of students at the high level increased 2.6-fold (14.5% → 38.2%), while the proportion at the low level decreased 3.6-fold (38.1% → 10.5%). The control group also exhibited positive changes; however, these were considerably more modest: the proportion at the high level rose from 13.2% to 21.1%, that is, 1.6-fold.

The results of the statistical analysis confirm the following:

— Pearson's χ^2 test indicates that the difference between the final results of the experimental and control groups is statistically significant ($\chi^2 = 14.82$; df = 2; $p < 0.01$);
— Student's t-test reveals a substantial difference in the mean scores of EG and CG ($t = 4.67$; $p < 0.001$);
— Cohen's d effect-size coefficient was $d = 0.76$, attesting to a high-level pedagogical effect (according to Cohen's benchmarks, $d > 0.8$ denotes a large effect, while 0.5–0.8 indicates a medium effect).

A component-level analysis of mathematical competence yielded differentiated outcomes (Table 2). The most pronounced growth was registered in the components of using symbolic and technical tools and modelling, which can be attributed to the visualisation and symbolic computation affordances of AI tools.

Table 2

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Growth indicators by components of mathematical competence, %

Component	EG (growth, %)	CG (growth, %)
Mathematical thinking	+18.9	+10.5
Problem solving	+24.1	+11.3
Modelling	+27.4	+9.8
Mathematical communication	+21.7	+8.4
Use of symbolic and technical tools	+31.8	+13.2

Analysis of the obtained data reveals that AI tools, particularly through their capacity to render mathematical abstractions in visual and interactive form, support students' comprehension, expose them to alternative solution pathways and familiarise them with the stepwise nature of modelling. Their effect is also evident in the communicative-reflective components, since dialogic interaction with AI enriches the student's mathematical discourse.

A survey conducted among students of the experimental group revealed that 89.5% of respondents reported that AI tools had increased their interest in mathematics; 84.2% reported the development of independent learning skills; 78.9% indicated that comprehension of complex concepts had become easier; and 73.7% reported the formation of the ability to identify and correct their own errors. At the same time, 21.1% of respondents reported a perceived risk of over-reliance on AI tools, indicating a high level of pedagogical reflection on their part.

Several constraining factors were identified during the experiment. First, excessive reliance on AI tools may engender a weakening of independent thinking among certain students. Second, generative AI may occasionally produce incorrect or incomplete solutions, thereby necessitating critical analytical skills. Third, there exists a risk of breaches of academic integrity. Accordingly, the instructional model explicitly incorporates dedicated stages of student reflection, critical evaluation and academic integrity, methodologically reinforced throughout the learning process.

Conclusion and recommendations. On the basis of the conducted research, the following principal conclusions may be drawn.

Artificial intelligence technologies constitute an effective didactic instrument for developing the mathematical competence of higher education students. The pedagogical experiment confirmed that the systematic use of AI tools enables a 2.6-fold increase in the proportion of students attaining the high level of mathematical competence and a 3.6-fold reduction in the proportion at the low level ($p < 0.01$; $d = 0.76$).

The didactic potential of AI technologies is manifested in the following affordances: individualisation of learning, real-time feedback, multimodal visualisation, automatic

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adaptation of task difficulty, and metacognitive support of learner autonomy. These affordances effectively serve the development of the constructive components of mathematical competence.

The effectiveness of AI tools is contingent upon their integration within a pedagogically informed model enriched with appropriate didactic conditions. The mere implementation of technologies does not, in itself, enhance educational quality; this requires a coherent methodological system, a redefined role for the teacher (as mentor, moderator and facilitator of reflection) and explicit mechanisms for student reflection.

The most pronounced pedagogical effect was observed in the components of mathematical modelling, the use of symbolic tools and mathematical communication. This is attributable to the visualisation, symbolic computation and interactive analysis affordances of AI tools and identifies the priority directions for their use in mathematics education.

On the basis of the research findings, the following practical recommendations have been formulated:

— a phased integration of adaptive learning platforms and generative AI tools in the teaching of mathematical disciplines at higher education institutions;
— the organisation of professional development courses for faculty on “the didactic use of artificial intelligence tools”;
— the introduction, for students, of elective modules on “the culture of working with AI”, “prompt engineering” and “academic integrity”;
— the methodological integration of AI tool usage within the syllabi of mathematical disciplines;
— the design and implementation of pedagogical mechanisms that preserve learner autonomy and critical thinking when AI tools are used;
— the development of ethical standards and a code of academic integrity governing the use of artificial intelligence within higher education institutions.

It would be advisable to extend the present line of inquiry in the following directions:

— deeper longitudinal investigation of the differential impact of AI tools on individual components of mathematical competence;
— comprehensive scientific inquiry into the ethical and methodological boundaries of generative AI tools in education;
— the design of Uzbek-language adaptive learning platforms tailored to local needs and oriented toward the development of mathematical competence;
— the longitudinal evaluation of the long-term pedagogical effectiveness of AI-based education and the conduct of meta-analytical studies.

The findings of this research contribute to the improvement of mathematics teaching at higher education institutions, the formation of a digital learning environment and the qualitative enhancement of students’ competence-based preparation. The scientific data obtained make a theoretical and practical contribution to the methodology of mathematics education and to the design of AI-based instructional models.

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