

THE ROLE OF PHYSICS IN DEVELOPING STUDENTS' PROFESSIONAL COMPETENCE THROUGH THE USE OF DIGITAL AND ARTIFICIAL INTELLIGENCE TECHNOLOGIES

Qahhorov Siddiq Qahhorovich

*Professor, Doctor of Pedagogical Sciences, Lecturer in Physics,
Bukhara State University*

Husenova Maxliyo Sayfulloyevna

*Lecturer in Medical and Biological Physics, Bukhara Innovation
University of Education and Medicine*

Abstract:

This article analyzes the possibilities of enhancing students' professional competence — problem-solving, modeling, and data-analysis skills — in Uzbekistan's higher education system through the physics discipline by means of digital and artificial intelligence (AI) technologies. The study was conducted within the context of the “Digital Uzbekistan – 2030” strategy and the concept for developing the higher education system, and draws on foreign empirical studies and meta-analyses indexed in the Scopus and Web of Science databases between 2020 and 2025. The effectiveness of virtual laboratory platforms such as PhET Interactive Simulations, Labster, and Algodoo, as well as AI-based intelligent tutoring systems (ITS) and generative language models, in physics education is examined on a statistically grounded basis. On the basis of the study's findings, a three-stage pedagogical model for integrating digital and AI tools into the teaching of physics, together with practical methodological recommendations, has been developed.

Keywords: digital education, artificial intelligence, physics education, virtual laboratory, PhET, Labster, Algodoo, intelligent tutoring systems, professional competence, “Digital Uzbekistan – 2030”.

Introduction

The educational reforms being carried out in the Republic of Uzbekistan are aimed at raising the continuous education system to the level of international standards and preparing competitive personnel. The “Concept for the Development of the Higher Education System until 2030,” approved by Decree No. PF-5847 of the President of the Republic of Uzbekistan dated 8 October 2019, established as a priority task the introduction of advanced pedagogical and digital technologies into the educational process and the development of students' independent thinking, critical analysis, and practical skills. This direction was, in turn, continued in the “Digital Uzbekistan – 2030” strategy, approved by Decree No. PF-6079 of 5 October 2020, which legally reinforced the tasks of equipping educational institutions with digital infrastructure, developing electronic educational resources, and popularizing digital skills. The “Uzbekistan – 2030” strategy, approved by Decree No. PF-158 of 11 September 2023, likewise set out the development of human capital and the expansion of innovative approaches in science and education[1-4].

As a discipline that shapes a natural-scientific worldview, physics forms the fundamental basis for numerous professional fields such as engineering, medicine, agrotechnology, and information technology. At the same time, traditional physics education is frequently associated with difficulties in visualizing abstract concepts, limited opportunities for conducting real experiments, and challenges in helping students apply problem-solving skills in practice. Foreign studies show that virtual laboratory platforms (PhET, Labster, Algodoo) and AI-based adaptive learning systems serve as effective tools for overcoming these problems and contribute to developing students' professional competencies such as analytical thinking, modeling, and data analysis[5].

The purpose of the study is to analyze, on the basis of foreign empirical data, the role of digital and artificial intelligence technologies in enhancing students' professional competence through physics education, and to develop a pedagogical model applicable to the higher education practice of Uzbekistan. To achieve this purpose, the following tasks were set: 1) to examine the effectiveness of virtual laboratory platforms in physics education; 2) to analyze the impact of AI-based adaptive learning systems on students' problem-solving and analytical thinking skills; 3) to generalize empirical studies from 2020–2025 that measured the impact of digital tools on professional competence; 4) to propose a concrete pedagogical model for integrating digital and AI tools into physics education[6-9].

Methods

The study employed a systematic literature review and qualitative synthesis methodology. The search for sources was carried out in the Scopus, Web of Science, Springer Nature Link, ScienceDirect, IOPscience, Frontiers, and ERIC databases. The following criteria were applied in selecting sources: a) publication year within the range 2013–2025 (with the main emphasis placed on empirical studies from 2020–2025); b) the study conducted in the context of physics or broader STEM education; c) the presence of quantitative indicators (effect size, mean values, level of statistical significance); d) the study published in a journal indexed in Scopus or Web of Science, or in the proceedings of an international conference. Among the sources identified in the initial search, articles that were duplicative, methodologically weak, or based on approximate data were excluded[10].

The analysis was conducted along three lines: (1) meta-analyses and experimental studies on virtual laboratory and simulation platforms; (2) meta-analyses on the cognitive impact of AI-based intelligent tutoring systems (ITS) and generative language models; (3) systematic reviews examining the impact of digital tools on professional competence in the STEM field (problem-solving, modeling, data analysis). The collected quantitative indicators (Cohen's *d*, Hedges' *g*, percentage growth) were entered into a comparative table, and their mutual consistency and differences were analyzed. Uzbekistan's regulatory-legal documents were also examined as contextual grounding.

Results

1. Effectiveness of virtual laboratory platforms

According to the results of a meta-analysis summarizing 47 effect sizes drawn from 20 empirical studies on PhET Interactive Simulations published between 2018 and 2023, the impact of PhET simulations on physics education was highly positive, with an overall effect size of $d = 0.83$; the studies involved 4,563 students. The magnitude of the effect was especially high for abstract topics such as electricity and waves, and at the secondary-school level. In another meta-analysis, the impact of PhET-based worksheets on learning outcomes was estimated at a moderate level ($ES = 1.117$), corresponding to a 32.73% increase in students' achievement indicators. Studies conducted at higher education institutions have likewise recorded a statistically significant positive effect of PhET simulations on academic achievement in physics[11-13].

Studies conducted on the Algodoo program have shown that it helps students master the laws of mechanics, impulse, and conservation of energy through visual modeling. In particular, in an experiment on modeling collision processes (elastic, semi-elastic, inelastic) using Algodoo, it was found that the program accurately reflected the change in conserved impulse and kinetic energy in accordance with theoretical principles, and helped students achieve a deeper grasp of the concept. Algodoo, as an open-structured “microworld,” has also been recommended as a tool for developing modeling skills in STEM education by allowing students to freely design and creatively approach physical phenomena[14].

More than 20 studies on Labster-type virtual laboratories have confirmed their positive impact on motivation, self-confidence, and learning outcomes [6]. In particular, it has been found that the use of virtual platforms in chemistry laboratory courses significantly increased students' experimental self-efficacy. A study conducted with immersive (VR) virtual laboratory simulations found that students' test results and self-assessment indicators were significantly higher than with the traditional lecture method. Although Labster is mainly used widely in the fields of biology and chemistry, its didactic principles — scenarios based on revolutionary thinking, immediate feedback, and a safe virtual environment — can also be applied in designing virtual laboratory courses in physics[15].

2. Impact of AI-based adaptive learning systems

A large meta-analysis on intelligent tutoring systems (ITS) analyzed 107 effect sizes drawn from 14,321 participants, finding that the impact of ITS relative to teacher-led group instruction was $g = 0.42$, and relative to conventional computer programs, $g = 0.57$. In another comprehensive meta-analysis, based on the results of 50 controlled studies, intelligent tutoring provided an average increase equivalent to 0.66 standard deviations, corresponding to a student's rise from the 50th percentile to the 75th percentile. A separate meta-analysis conducted at the higher-education level found the impact of ITS on academic achievement to be somewhat smaller, but still statistically significantly positive ($g = 0.37$)[16-17].

A systematic review published in 2025 specifically examined the impact of AI-based ITS systems on problem-solving, critical-thinking, and logical-reasoning skills. According to the results of an analysis accounting for covariates, a statistically significant positive difference was found in post-intervention problem-solving skills ($F(1, 298) = 10.21$; $p < 0.001$), with similar results recorded for critical thinking ($F(1, 298) = 8.75$; $p < 0.001$) and logical reasoning ($F(1, 298) = 7.92$; $p < 0.001$). These results confirm that adaptive learning systems influence not only knowledge acquisition but also higher-order cognitive skills.

Generative language models, ChatGPT in particular, are coming to occupy a distinctive place in physics education. According to a systematic review and meta-analysis covering 69 experimental studies conducted between 2022 and 2024, ChatGPT had a positive effect on students' academic performance, emotional-motivational state, and tendency toward higher-order thinking, but did not have a significant effect on the indicator of effective self-assessment. A study on the use of ChatGPT in the training of prospective physics teachers showed that the language model is useful for composing and explaining physics problems, but that it is a tool requiring human oversight and pedagogical guidance.

At the same time, a study examining the role of ChatGPT and higher-order thinking skills as predictive factors for research activity in physics statistically confirmed their mutual correlation[18].

3. Impact of digital tools on professional competence

A systematic review examining the role of digital technologies in mathematical modeling education noted that advanced technological approaches create new opportunities for students at every stage of the modeling cycle — from formulating the problem to verifying the results — but that the teacher's methodological preparedness is the decisive factor in this regard. A systematic review examining the relationship between digital literacy and STEM skills established that students' ability to analyze data and solve problems using AI tools is directly dependent on their level of digital literacy.

A comparative table of the quantitative indicators presented above is given below (Table 1):

Table 1. Comparative overview of the quantitative indicators discussed

Tool / system	Source of study	Effect size / result	Sample size
PhET simulations	Meta-analysis, iJOE	$d = 0.83$ (high)	4,563 students, 20 studies
PhET (worksheets)	Chotimah, Festiyed	$ES = 1.117$; +32.73%	10 national articles
Virtual laboratories (Labster-type)	Diwakar et al.	Significant increase in motivation and self-efficacy	Computers & Education, 2023
Intelligent tutoring systems (ITS)	Ma et al.	$g = 0.42$ (vs. conventional teaching)	14,321 participants, 107 effects
ITS (average effect)	VanLehn	0.66 standard deviation (50th–75th percentile)	50 controlled studies
ChatGPT / AI assistants	Computers & Education meta-analysis	Positive effect on academic performance and thinking	69 experimental studies (2022–2024)

As the table shows, virtual laboratory platforms produce a stable and statistically significant positive effect primarily on conceptual understanding and motivation, whereas intelligent tutoring systems produce such an effect primarily on problem-solving and analytical-thinking skills. This complementary relationship between the two directions gives rise to the need to integrate them within a single pedagogical model.

Discussion

The results of the foreign studies analyzed confirm the substantial role of digital and artificial intelligence technologies in shaping students' professional competence within physics education. At the same time, a number of factors need to be taken into account when interpreting these results within the context of Uzbekistan's higher education system. First, the majority of the studies reviewed were conducted in the educational systems of Asia (Indonesia, Rwanda), Europe, and North America, whereas comparably broad, Scopus/WoS-level empirical studies of this kind are still insufficient at higher education institutions in Central Asia, including Uzbekistan. This situation points to the need to launch pilot projects adapted to local conditions and studies on a national scale[19].

Second, the financial accessibility of free, open-source platforms such as PhET and Algodoo creates a convenient opportunity for their introduction in the conditions of Uzbekistan's higher education institutions, since these platforms do not require additional licensing costs and can operate in offline mode even in regions with slow internet speeds. This aspect is of particular importance for regional higher education institutions and technical colleges. Commercial platforms such as Labster, while providing high-quality 3D visualization, would be more appropriately regarded, under conditions of limited financial resources, as a supplementary tool rather than as a priority direction[20].

Third, two divergent tendencies can be observed in the literature regarding the impact of intelligent tutoring systems and generative artificial intelligence tools such as ChatGPT: on the one hand, they have a positive effect on problem-solving and higher-order thinking skills; on the other hand, there is also cautionary evidence that using them without appropriate pedagogical guidance may lead to intellectual passivity among students and a decline in their capacity for independent critical thinking. It follows that, in integrating artificial intelligence tools into physics education, priority should be given to the principle of designing them as tools that guide and reinforce students' independent work, rather than as tools that replace it[21].

Fourth, the tasks of creating IT infrastructure and developing electronic educational resources set out within the framework of the “Digital Uzbekistan – 2030” strategy, as well as the direction of introducing advanced pedagogical technologies envisaged in the concept for developing the higher education system until 2030, create a regulatory-legal basis for introducing virtual laboratories and AI-based adaptive platforms at physics departments on an institutional level. However, fully translating these opportunities into practice will require enhancing teachers' digital-pedagogical qualifications and developing appropriate methodological materials and assessment criteria[22].

Conclusion

The analysis conducted shows that, when integrated with digital and artificial intelligence technologies, physics serves as a favorable platform for effectively developing students' professional competence — their problem-solving, modeling, and data-analysis skills. Foreign empirical studies confirm a statistically significant, above-moderate positive effect of virtual laboratory platforms and intelligent tutoring systems on learning outcomes. On the basis of these conclusions, the following three-stage pedagogical model is proposed.

Stage 1. Visual-simulation foundation. The study of physical phenomena begins with the help of open-source virtual laboratories such as PhET and Algodoo. At this stage, the student observes the theoretical concept through an interactive model, testing hypotheses by varying parameters. The goal is to develop conceptual understanding and visual-analytical skills.

Stage 2. Adaptive practice and AI tutoring. The student completes a set of problems adapted to their individual level of knowledge through an intelligent tutoring system or an AI-based problem generator. The system detects errors in real time and provides explanatory feedback, which deepens problem-solving and logical-reasoning skills.

Stage 3. Project-based analytical practice. Working in groups, students carry out a physical-technical project (for example, building a model of a mechanical system or performing statistical analysis of experimental data) based on real or simulated data sets, present their results, and prepare a report and visualization with the help of AI tools. This stage consolidates the final component of professional competence — modeling and data analysis.

The following are proposed as practical recommendations: 1) incorporate the PhET and Algodoo platforms into the mandatory laboratory sessions of physics departments; 2) organize professional development courses for teachers on the use of AI-based educational tools; 3) introduce project-based practical assignments alongside traditional written assessments in evaluating student knowledge; 4) organize pilot studies on a national scale to measure the effectiveness of PhET, Algodoo, and locally developed AI tutoring systems, which will serve to build up an empirical database specific to the conditions of Uzbekistan going forward.

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