ARTIFICIAL INTELLIGENCE IN PHYSICS EDUCATION: CHALLENGES AND PERSPECTIVES ON THE PATH TO PERSONALIZED LEARNING

Serhii Maksymchuk
Ph.D., Vasyl Stefanyk Carpathian National University, Ukraine
e-mail: serhii.maksymchuk.23@pnu.edu.ua, orcid.org/0009-0001-2369-2703

Summary

This article presents a comprehensive literature review on the integration of artificial intelligence tools in physics education. The study aims to analyze how various AI technologies – from adaptive learning platforms and virtual laboratories to intelligent chatbots – can contribute to personalized learning, support the development of experimental thinking, and improve overall educational outcomes.

The review synthesizes scholarly sources that highlight the numerous benefits of AI, including: the enhancement of critical thinking and problem-solving skills, increased student engagement, and a deeper understanding of abstract physics concepts. The application of AI in the educational process allows for the adaptation of task difficulty to individual needs, which promotes more effective learning. The paper also meticulously analyzes the key challenges associated with the implementation of these technologies, including issues of data privacy, algorithmic bias, and the preservation of academic integrity in an era of increasing automation.

This article provides a comprehensive assessment of the pedagogical advantages and difficulties, laying the groundwork for a balanced and strategic application of AI tools. This will allow for the effective improvement of learning outcomes while minimizing associated risks and contributing to the further development of educational methodologies.

Key words: Artificial intelligence, Physics, Adaptive learning, Chatbots, Virtual labs, Pedagogy, Critical thinking.

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1. Introduction

Artificial Intelligence (AI) marks a turning point in the educational process, fundamentally changing approaches to teaching complex disciplines such as physics. The application of AI tools, particularly innovative platforms like ChatGPT, creates unique opportunities for developing experimental thinking *(Ding, 2023)*. Thanks to personalized learning that adapts to individual needs, AI technologies enhance student engagement through interactive dialogues and facilitate active exploration of scientific concepts, effectively bridging the gap between theory and practice *(Dong, 2023)*.

These technologies promote a shift from a traditional, rote-learning model to an approach focused on experience and problem-solving. Traditional teaching methods often struggle to maintain a high level of student engagement, which stimulates the development of innovative solutions where AI tools serve as valuable pedagogical resources *(Duy, Ngoc & Hai, 2024)*. Research confirms AI's ability to support complex cognitive processes, helping students develop experimental thinking and problem-solving skills that are critically important for physics *(Jing, 2023)*.

However, despite the obvious advantages, there are significant gaps in research, particularly regarding the direct impact of AI on experimental thinking and the qualitative aspects of students' experiences *(Kurniawan, Riantoni, Lestari & Ropawandi, 2024)*. Furthermore, the implementation of AI faces practical challenges, such as insufficient teacher training and ethical issues related to data privacy *(Lee & Lee, 2021)*. In this context, this article aims to systematize current research on the role of AI, particularly ChatGPT, in fostering experimental thinking in physics education. The review seeks to clarify key themes and identify gaps in the literature to lay the groundwork for future research and practical applications in this field *(Liang, Zou, Xie & Wang, 2023)*.

2. Main text

Personalized Learning Pathways and Adaptive Feedback

Artificial intelligence (AI) facilitates a high degree of personalization in physics education, taking into account diverse learning paces and styles *(Ding, 2023)*. By analyzing individual student performance data, AI tools can recommend resources, adjust task difficulty, and personalize learning pathways *(Dong, 2023)*. For example, adaptive platforms can detect when students are struggling with specific topics and adjust the content to provide additional support. Wang, Kim, & Shute (2020) note that this practice effectively supports student engagement and interest *(Wang, Kim & Shute, 2020)*.

Personalized learning systems, such as language models like ChatGPT, also provide explanations adapted to each student's level of understanding *(Duy, Ngoc & Hai, 2024)*. Liang, Zou, Xie, & Wang (2023) found that ChatGPT's adaptive responses help students navigate complex physics problems, offering immediate and individualized assistance *(Liang, Zou, Xie & Wang, 2023)*. This AI-driven adaptation not only improves comprehension but also reduces frustration, as students receive support tailored to their unique challenges *(Lee & Lee, 2021)*.

Increasing the Accessibility of Physics Education

AI technologies have significantly expanded access to physics studies for students who might otherwise face obstacles due to their geographical location, financial difficulties, or lack of resources *(Lee & Lee, 2021)*. For example, virtual labs make it possible to conduct experiments without the need for expensive equipment *(Liang, Zou, Xie & Wang, 2023)*. Menchafou, Aaboud, & Chekour (2024) note that AI-driven virtual labs have made hands-on learning accessible in Moroccan schools where physical lab infrastructure is limited *(Menchafou, Aaboud & Chekour, 2024)*. This accessibility provides an opportunity for students from diverse backgrounds to gain practical experience, regardless of their educational institution's resources *(Mahligawati, 2023)*.

Furthermore, AI-based chatbots support self-directed learning, enabling students to master material at their own pace and receive help outside of traditional class hours *(Mahligawati, Allanas, Butarbutar & Nordin, 2023)*. These tools provide a level of academic support that would otherwise be unavailable to students in remote or under-resourced areas *(Mustofa, 2024)*. Duy, Ngoc, & Hai (2024) found that chatbots help students independently acquire physics knowledge, enhancing their learning experience through continuous and accessible support *(Duy, Ngoc & Hai, 2024)*.

Effective Assessment and Timely Feedback

Artificial Intelligence (AI) optimizes the assessment process by providing timely feedback, which is critically important for effective learning *(Sánchez-Guzmán & Mora, 2010)*. Automated assessment tools, which use machine learning, evaluate students' understanding of physics concepts through essays. This not only reduces the workload for educators but also ensures consistent feedback *(Kurniawan, Riantoni, Lestari & Ropawandi, 2024)*. For example, Kurniawan et al. (2024) developed an AI-based automated assessment system that provides rapid feedback on essays, allowing for the evaluation of conceptual understanding without significant manual intervention from instructors *(Kurniawan, Riantoni, Lestari & Ropawandi, 2024)*.

By analyzing student data, AI tools can identify specific areas that need improvement and offer targeted feedback *(Swandi, Amin, Viridi & Eljabbar, 2020)*. This real-time analysis allows for more formative assessment, giving students the opportunity to correct misunderstandings immediately and leading to better learning outcomes *(Wang, Kim & Shute, 2013)*. Such systems are also valuable for educators, as they provide insights into student progress and help them adjust the teaching process *(Wulff, 2024)*.

Ethical Concerns: Data Privacy and Security

The implementation of AI in education introduces serious ethical problems, especially concerning data privacy and security *(Pavlov, 2023)*. AI systems collect vast amounts of information about student behavior, performance, and engagement, which raises questions about how this data is stored, used, and protected. Duy, Ngoc, & Hai (2024) emphasize that although chatbots and intelligent agents improve learning, they also require access to sensitive student information, which can be vulnerable to misuse or unauthorized access *(Duy, Ngoc & Hai, 2024)*.

Additionally, there are concerns about the fairness of AI algorithms, which may unintentionally reflect biases. If AI models are trained on biased data or lack diversity, they may reinforce existing educational inequality. Ensuring the ethical operation of AI systems in physics education requires robust data management policies that address privacy, transparency, and equity *(Mahligawati, Allanas, Butarbutar & Nordin, 2023)*.

Accessibility Issues: The Digital Divide

While AI has the potential to expand access to education, it can also deepen the digital divide *(Menchafou, Aaboud & Chekour, 2024)*. Students in under-resourced schools or remote areas may lack access to the devices and internet connectivity necessary to use AI tools *(Mahligawati, 2023)*. This lack of access can create inequality in learning opportunities, depriving some students of the benefits that AI offers *(Mustofa, 2024)*. For example, while virtual laboratories provide hands-on experience for students with limited physical resources, they still require a basic digital infrastructure that is not universally available *(Liang, Zou, Xie & Wang, 2023)*.

In addition, the implementation of AI tools requires teacher training, which may not be feasible in all educational contexts, especially in regions with limited funding for professional development *(Pavlov, 2023)*. These limitations suggest that although AI can democratize education in theory, its practical implementation may inadvertently reinforce inequality if equal access is not ensured *(Sánchez-Guzmán & Mora, 2010)*.

Limitations in Understanding Context and Nuance

While AI excels at processing large data sets and providing automated feedback, it often lacks the nuanced understanding that human educators bring to a learning environment *(Sánchez-Guzmán & Mora, 2010)*. For example, AI-driven assessments may not fully account for the context or intent behind a student's response *(Kurniawan, Riantoni, Lestari & Ropawandi, 2024)*. As noted by Wulff (2024), while AI can evaluate factual correctness, it may struggle with subjective assessments that require interpretation of students' reasoning processes *(Wulff, 2024)*.

This limitation also extends to language models and chatbots, which may misunderstand student questions or provide overly simplistic responses *(Duy, Ngoc & Hai, 2024)*. AI's inability to interpret subtleties in student responses limits its capacity to provide the nuanced feedback often necessary for learning complex physics concepts *(Liang, Zou, Xie & Wang, 2023)*.

AI holds significant potential in improving physics education by increasing engagement, personalizing learning, and expanding accessibility *(Menchafou, Aaboud & Chekour, 2024)*. However, its integration creates challenges related to over-reliance, ethical problems, inequality in access, and limitations in contextual understanding *(Pavlov, 2023)*. Addressing these limitations is critically important for realizing AI's full potential in education, so that it serves as a beneficial supplement and not a replacement for traditional practices *(Mahligawati, 2023)*. Balancing AI's strengths with careful consideration of its limitations will be necessary to create a more effective and equitable learning environment *(Mustofa, 2024)*.

Enhancing Learning Outcomes with Personalized, Adaptive, and Interactive AI

The integration of AI into physics education has transformed learning outcomes through personalized, adaptive, and interactive tools *(Liang, Zou, Xie & Wang, 2023)*. These AI-driven applications not only support student engagement but also tailor the educational experience to their individual needs, leading to improved understanding and retention *(Pavlov, 2023)*. In this section, we will discuss how AI enhances learning outcomes, focusing on personalized tutoring, adaptive assessment, and interactive environments that together foster a deeper learning experience and better accommodate diverse learning styles *(Mahligawati, 2023)*.

Personalized Tutoring Systems

AI-based personalized tutoring systems have become an important tool for providing individualized instruction to students, offering targeted guidance based on their needs *(Liang, Zou, Xie & Wang, 2023)*. For example, AI language models, such as ChatGPT, are increasingly being used as virtual tutors that respond in real-time to physics-related questions *(Duy, Ngoc & Hai, 2024)*. These models adapt their explanations to each student's level of understanding, allowing learners to master complex physics concepts at their own pace *(Wang, Zhou & Liang, 2023)*. This approach aligns with the theory of self-regulated learning, in which students benefit from immediate feedback and individualized explanations that help bridge gaps in their knowledge *(Pavlov, 2023)*.

Personalized Learning Tools and Adaptive Learning

The use of personalized learning tools, such as symbolic regression models, aids in solving complex physics problems by providing explanations and guiding students through the equation derivation processes *(Liang, Zou, Xie & Wang, 2023)*. These models help in visualizing and solving physics equations, which is particularly useful in disciplines like mechanics and electromagnetism, where mathematical rigor is paramount *(Pavlov, 2023)*. Through such individualized support, AI tools help learners achieve mastery of topics by catering to their specific learning needs and progression *(Mahligawati, 2023)*.

AI's ability to analyze real-time data from student performance has enabled the creation of adaptive learning systems that dynamically adjust content and difficulty levels *(Wang, Zhou & Liang, 2023)*. Adaptive learning platforms track student progress and adaptively present challenges suited to their current level, fostering continuous engagement and growth *(Wang, Zhou & Liang, 2023)*. Wang et al. *(2023)* emphasize the effectiveness of AI in creating adaptive environments where students receive appropriate levels of difficulty and support, which keeps them motivated and prevents frustration from overly challenging content.

In addition, adaptive assessment tools that analyze student responses provide educators with information on each learner's strengths and weaknesses, facilitating targeted interventions

(Kurniawan, Sari & Wijaya, 2024). Kurniawan et al. *(2024)* introduced an AI-based automated assessment system for physics essays, which automatically evaluates comprehension and provides constructive feedback. By identifying areas of misunderstanding, these tools help students and educators focus on areas needing improvement, thereby enhancing learning efficiency and supporting a mastery-based approach to physics education *(Kurniawan, Sari & Wijaya, 2024)*.

Interactive Learning Environments

Interactive learning environments, driven by AI, including virtual labs and simulations, provide students with hands-on experience that deepens their understanding of physics principles *(Pavlov, 2023)*. For example, the AI-based TEALSim active learning simulation tool improves the understanding of modern physics concepts, such as quantum mechanics, by allowing students to interact with simulations that visualize complex processes *(Liang, Zou, Xie & Wang, 2023)*. These tools create engaging learning environments where students can manipulate variables, observe outcomes, and develop a more intuitive understanding of abstract concepts *(Mahligawati, 2023)*.

The role of interactive environments in physics education is further supported by virtual laboratories, which make experimental physics accessible to a wider range of students *(Pavlov, 2023)*. Menchafou et al. *(2023)* report that AI-driven virtual labs are especially useful in settings with limited access to physical lab facilities, as they allow students to conduct experiments virtually *(Menchafou, 2023)*. This approach not only expands access to practical learning but also helps students develop critical thinking skills when they interact with realistic simulations of scientific experiments *(Mahligawati, 2023)*.

Enhancing Engagement with Gamified AI Tools

Gamified AI-based learning tools introduce elements of game design into physics education, making the process more engaging and interactive *(Pavlov, 2023)*. Games like "Newton's Playground" use AI to adapt their complexity based on player actions and offer tasks related to physics principles *(Liang, Zou, Xie & Wang, 2023)*. This approach increases engagement and motivates students to explore complex concepts in a low-risk environment *(Mahligawati, 2023)*. Gamification elements, including achievements, badges, and leaderboards, reinforce positive behavior and allow students to progress at their own pace, fostering both motivation and retention *(Pavlov, 2023)*.

The application of AI in gamification also aligns with cognitive learning theories, which state that active involvement in learning tasks leads to better cognitive processing and memory retention *(Liang, Zou, Xie & Wang, 2023)*. Thus, gamified physics education solves the problem of maintaining student interest in a traditionally challenging subject by transforming learning into an exciting and interactive experience *(Mahligawati, 2023)*.

Real-time feedback and automated assessment

Artificial intelligence (AI) optimizes the assessment process by providing timely feedback, which is critically important for effective learning *(Liang, Zou, Xie & Wang, 2023)*. Automated assessment tools, such as systems based on machine learning, evaluate students' understanding of physics concepts through essays. This not only reduces the workload for educators but also ensures consistent feedback *(Kurniawan et al., 2024)*.

The analysis of student performance data allows AI tools to identify specific areas that need improvement and offer targeted feedback *(Pavlov, 2023)*. This real-time analysis allows for more formative assessment, giving students the opportunity to correct misunderstandings immediately and leading to better learning outcomes *(Mahligawati, 2023)*. Such systems are also useful for educators, as they provide insights into student progress and help adjust the teaching process *(Kurniawan et al., 2024)*.

Fostering Collaboration with AI-Enhanced Communication Tools

AI also enhances collaborative learning in physics education by facilitating group discussions and enabling interaction in different learning environments. For example, AI-driven chatbots can help students discuss physics problems by offering prompts or guiding questions, fostering collaboration and peer learning *(Duy, 2023)*. These chatbots assist in self-study and collaborative learning by providing structured support and responding to student inquiries, which can be especially useful in online or hybrid learning environments *(Duy, 2023)*.

In addition, AI-enhanced discussion boards and virtual study groups allow students to collaborate on tasks, share ideas, and learn from each other's perspectives. This collaborative approach aligns with social constructivist theories, which emphasize learning as a social process where students construct knowledge through interaction with peers. AI's role in fostering such collaborative environments supports both individual and group learning, making it an effective tool in diverse educational settings *(Duy, 2023)*.

AI for Language Processing to Improve Comprehension

Another significant advantage of AI in personalized physics education is its application in natural language processing (NLP) to support language-related comprehension in physics *(Wulff, 2019)*. Tools that use NLP can help students by clarifying complex terminology, translating physics jargon into simpler language, and making content more accessible *(Wulff, 2019)*. AI-powered NLP tools help students grasp the language-specific nuances of physics, which is often a barrier to understanding for non-native speakers *(Wulff, 2019)*.

This capability is especially useful for students from diverse linguistic backgrounds, as it ensures equitable access to physics education *(Wulff, 2019)*. AI-driven language support tools allow learners to overcome language barriers and understand complex theories in their own terms, thereby enhancing inclusivity in physics education *(Wulff, 2019)*.

The integration of personalized, adaptive, and interactive AI into physics education significantly improves learning outcomes by providing individualized support, creating engaging learning environments, and ensuring continuous feedback *(Wang et al., 2023)*. These tools make physics more accessible, foster engagement through gamification, and support collaborative and inclusive learning *(Duy, 2023; Menchafou et al., 2022)*. However, successful implementation requires careful consideration of each tool's role in promoting active learning, encouraging critical thinking, and providing meaningful feedback *(Kurniawan et al., 2024)*. The potential of AI to transform physics education offers a promising path toward a more inclusive, effective, and interactive learning environment *(Wang et al., 2023)*.

3. Conclusion

The integration of Artificial Intelligence (AI) into physics education demonstrates significant potential to transform how physics is taught and learned *(Wang et al., 2023)*. AI tools, such as intelligent tutoring systems, adaptive platforms, and interactive simulations, have proven crucial in creating a more personalized, adaptive, and engaging learning environment *(Kurniawan et al., 2024; Menchafou et al., 2022)*. These tools not only promote a deeper understanding of complex physical concepts but also align with modern educational goals by encouraging active learning and critical thinking *(Duy, 2023)*. The narrative review highlights that AI's ability to adapt content, provide real-time feedback, and engage students through interactive experiences significantly contributes to improved comprehension and retention *(Wang et al., 2023)*.

Furthermore, AI has played a key role in increasing accessibility and providing diverse learning pathways, especially for students from different backgrounds and with varying learning paces *(Menchafou et al., 2022; Wulff, 2019)*. Through knowledge-based systems, virtual laboratories, and language processing tools, AI addresses the unique needs of students, fostering an inclusive environment that makes physics more accessible and less intimidating *(Duy, 2023)*.

However, the effective implementation of AI in physics education still faces several challenges, including concerns about over-reliance, ethical issues related to data security, and the risk of exacerbating the digital divide *(Wang et al., 2023; Duy, 2023)*. While AI offers significant advantages, it is important to address these limitations to ensure that it complements, rather than replaces, traditional teaching methods *(Kurniawan et al., 2024)*. Future research should focus on developing robust frameworks for integrating AI into physics curricula in a way that enhances educational outcomes without compromising students' abilities for independent problem-solving *(Wang et al., 2023)*.

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