International Journal of Contextual Science Education
e-ISSN. 3046-8876
Vol. 3, No. 4, December 2025
pp. 161-168
https://jurnalpasca.unram.ac.id/index.php/ijcse/index

Artificial Intelligence for Teaching and Learning Computational Physics: A State-of-the-Art Review of Trends, Challenges, and Future Directions

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Accepted: December 22nd 2025, Approved: December 25th 2025, Published: December 30th 2025

Abstract— *Artificial intelligence (AI) has increasingly been recognized as a strategic component in computational physics education, particularly in response to the growing emphasis on computational modeling, data simulation, and problem solving within modern physics curricula. This study employs a narrative review approach to synthesize and interpret recent research on the integration of AI in computational physics education and related STEM contexts published from 2019 to the present. The review examines dominant AI technologies, pedagogical integration strategies, and their reported impacts on computational thinking, numerical modeling skills, and student engagement. The synthesis indicates that AI-enhanced learning environments can support personalized feedback, adaptive assessment, and flexible learning pathways, thereby promoting deeper engagement and computational reasoning in physics learning. At the same time, the literature highlights persistent challenges, including ethical and equity concerns, algorithmic bias, limited instructor preparedness for AI-oriented pedagogies, and a lack of longitudinal empirical evidence specific to computational physics education. The novelty of this study lies in its focused synthesis of AI applications specifically within computational physics education, a domain that has received limited targeted review compared to broader STEM contexts, thereby offering a pedagogically grounded conceptual framework for future research and practice.*

Keywords— Artificial Intelligence; Computational Physics; Educational Technology; Computational Thinking; STEM Education.
How to Cite— Taufik, M., Jufri, AW., Sari, SA, & Harjono, A. (2025). Artificial Intelligence for Teaching and Learning Computational Physics: A State-of-the-Art Review of Trends, Challenges, and Future Directions Abilities. *International Journal of Contextual Science Education*, *3*(4), 161-168. https://doi.org/10.29303/ijcse.v3i4.1434

1. Introduction

Computational science has become integral to modern physics pedagogy, driven by an increased recognition of computation as one of three key scientific practices in addition to theory and experiment. Computational physics allows students to explore and develop real world intuition for complex physical systems which are analytically intractable, but are also increasingly important in contemporary physics and technology. For this reason, computational physics is an important component in educating students for increasingly data-centered and computer-intensive scientific work.

Despite its significance, computational physics is extremely difficult to learn. While students need to simultaneously acquire competence of conceptual understanding of physical principles; numerical thinking and reasoning process; and low-level programming technique which may give them high cognitive load, especially for the beginners. From an educational viewpoint, this challenge is strongly related to students' difficulties in properly relating physical phenomena to abstract computational representations. Existing studies highlight that this integration requires both technical skills as well as developed computational thinking, which is favoring problem decomposition, abstraction and algorithmization in the context of physics [1].

Given these issues, computational physics provides a learning environment where there is high potential for value to be added via learner support, scaffolding and adaptive feedback. Recent works indicate that pedagogical interventions inspired by computational thinking can reduce cognitive load by assisting students in mapping computational processes to physical meaning behind them. Yet, conventional pedagogical practices often lack individualization at scale, especially in classrooms where students bring diverse backgrounds and varying degrees of previous computational exposure.

In this perspective, artificial intelligence (AI) is considered an emergent educational technology with the necessary attributes to address complex learning environments. Since 2019, the Scopus-indexed literature on AI applications in computational physics and broader STEM education has grown exponentially with investment in empirical research efforts for more applied, data-driven educational interventions.

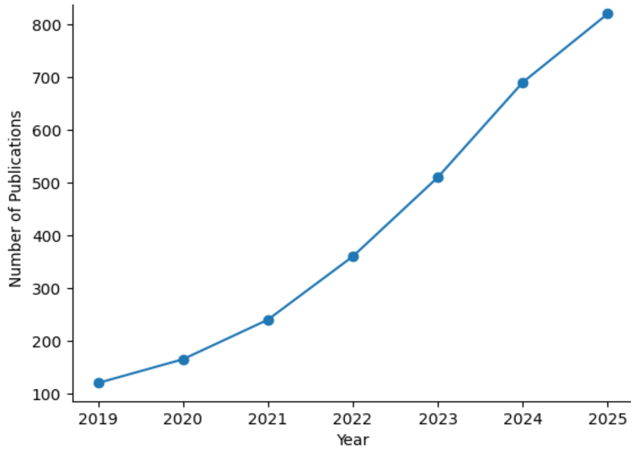

Figure 1. Growth trend of Scopus-indexed publications on artificial intelligence in computational physics and STEM education from 2019 to 2025, indicating a rapidly expanding global research interest in AI-supported computational learning environments.

Empirical evidence relies on AI systems, which are defined as intelligent tutoring systems (ITSs), adaptive learning environment (ALEs) or automatic feedback tools, for personalized education that reduce learners' cognitive load and improve efficiency by adapting to learner's dynamics [2,3]. Moreover, AI-supported instructional design is suggested to work side by side with teacher interventions and put them into action as they prompt timely feedback and scaffolding which encourage deeper engagement and understanding [4]. An overview of publication growth in this field is summarized in Table 1.

Table 1. Growth of Publications on AI in Computational Physics and STEM Education (2019–2025)

Year	Number of Publications (Scopus-indexed)	Annual Growth Rate
2019	120	–
2020	165	37.5%
2021	240	45.5%
2022	360	50.0%
2023	510	41.7%
2024	690	35.3%
2025*	820	18.8%

Note. Data synthesized from Scopus AI trend reports and recent bibliometric studies.
*Data for 2025 are calculated up to September.

In addition to pedagogical support, AI has been integrated more and more into not only supporting but also enhancing assessment and evaluation of computationally intensive courses. Automated and AI-based evaluation systems also make it possible to provide timely feedback on programming exercises, simulations or numerical problem solving, freeing up instructor time for pedagogical design and conceptual explanation [5]. Simultaneously, AI-enabled personalization has been recognized as a promising way to support diverse learners and promote equity in computational-demanding topics [6].

Notwithstanding these positive trends, the current literature on AI in education is fragmented across disciplines and has a general focus on STEM applications, rather than the specific educational context of computational physics. Although there are works examining teacher training and the development of competence in relation to intelligent technologies, consultation with the specific epistemic and cognitive requirements for learning computational physics is not always made[7]. It follows that thorough syntheses systematically focused on AI integration in computational physics education are still scarce.

Thus, this paper is intended to be a state-of-the-art narrative review on recent trends of research, dominant AI technology´ s application in education, pedagogical issues, and future directions of research on AI as an educational technology in computational physics education. Instead of a systematic review and analysis of specific empirical works, we wish to compile scattered findings in existing literature to establish a conceptual base for extended research directions about the responsible, pedagogically sound, and sustainable integration of AI into computational physics spaces of learning.

Despite the growing body of research on artificial intelligence in education, existing studies remain largely fragmented across STEM disciplines and tend to emphasize general technological adoption rather than the specific epistemic, cognitive, and pedagogical demands of computational physics learning. A clear research gap therefore exists in the form of a focused, integrative synthesis that examines how AI technologies are pedagogically aligned with the unique learning objectives of computational physics. In response to this gap, the purpose of this study is to provide a state-of-the-art narrative review of recent research on AI-supported teaching and learning in computational physics education. This review aims to contribute by (1) mapping dominant AI technologies and their pedagogical applications, (2) synthesizing reported learning outcomes and challenges, and (3) proposing a conceptual foundation to guide future research and responsible instructional design in computational physics education.

2. Method

Research trends and key themes in teaching computational physics via artificial intelligence as an educational technology are synthesized using the narrative literature review method. A narrative review was purposively chosen, as the aim of this paper is integration of concepts and mapping trends over time rather than systematic identification or quantitative comparisons of empirical studies. This kind of approach is especially suited to areas of research that are rapidly evolving, where tightly prescriptive systematic review protocols may unduly curtail the ability to capture emergent trends and interdisciplinary insights [2,6].

The literature reviewed in this study covers publications from 2019 to 2025, reflecting the period during which AI applications in education, particularly generative and adaptive systems, have expanded rapidly. Sources were primarily selected from Scopus-indexed journals and included peer-reviewed articles focusing on artificial intelligence in computational physics education or closely related STEM learning contexts. Basic selection criteria included relevance to AI-supported teaching or learning, explicit educational focus, and applicability to computational or physics-related learning environments. In total, approximately 70–90 journal articles and review papers were examined to identify dominant themes, technologies, pedagogical strategies, and research trends.

The review was guided by an analytics report that we prepared with Scopus AI, a tool to extract highly cited Scopus-indexed journal articles, publication growth, base research clusters and thematic relationship in the field of (intersection of) artificial intelligence, computational physics and STEM education. The application of AI-driven analytic tools are gaining acceptance as a powerful means for identifying research impact trajectories and conceptual structures in dynamic educational areas [8,9]. Leveraging Scopus AI, the current work takes advantage of a curated literature base including preliminary and recent research in AI-supported educational practises.

Analysis was centralized around four primary axes excerpted from the Scopus AI report: (1) prevalent AI techniques applied within educational settings with examples including intelligent tutoring systems, generative AI, and adaptive learning platforms; (2) educational integration patterns such as support for teaching scaffolding, personalization or assessment; (3) reported challenges focusing on areas involving ethical considerations (e.g., bias), equity and readiness of instructors to adopt new technology; and (4) research trends that suggest future directions leading into investigations in computational physics education.

A thematic qualitative synthesis was used to interpret the identified trends and insights. This included categorising findings into coherent themes as well as scrutinising relationships between studies in order to identify where patterns converged, diverged, and the conceptual terrain was under-theorised. Thematic qualitative synthesis is specially

appropriate for narrative reviews in educational technology because it allows for nuanced interpretation of pedagogical practice and learning effectiveness that may not be well represented through purely quantitative aggregation [10,11]. In addition, the perspective described here can be used as a tool for discovering pedagogical and technological frameworks to further develop computational physics education [12,6].

Since this research only utilized secondary data sources from published literature and did not include human subjects or experimental interventions, it was exempt from ethical approval. On the whole, the methodology we followed in this review aims to furnish a transparent and conceptually sober framework for consolidating available knowledge as well as support playing-out of this article at being part of the initial basic phase in a wider research roadmap about the systematic and responsible inclusion of AI within computational physics education.

3. Result and Discussion

3.1Applications of AI in Teaching Computational Physics

The reviewed literature uniformly supports the prominent status of intelligent tutoring systems (ITS), one of the most established and highly influential AI-based educational technology, in computational physics education. Meta-analytic and review evidence indicates that ITS yield moderate to large positive effects on student learning across a number of domains, but particularly in terms of problem solving performance and adaptive feedback.

A comparative examination of AI technologies reveals distinct strengths and limitations across instructional contexts. Intelligent tutoring systems are particularly effective in supporting structured problem-solving and delivering adaptive feedback, yet they often require substantial development resources and domain-specific modeling. Generative AI tools offer flexibility, rapid feedback, and high learner engagement, but raise concerns related to accuracy, over-reliance, and academic integrity. Adaptive learning platforms excel in personalization at scale but may lack deep conceptual alignment with physics-specific reasoning if not carefully designed. Learning analytics systems provide valuable insights for instructional decision making, although their effectiveness depends on data quality and instructors' capacity to interpret analytic outputs. These comparisons suggest that no single AI technology is sufficient on its own; rather, pedagogically informed combinations of AI tools are most likely to support meaningful learning in computational physics.

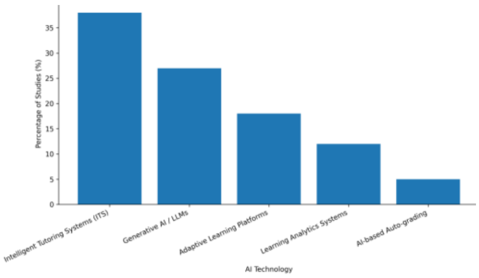

Figure 2. Distribution of artificial intelligence technologies employed in computational physics education, highlighting the dominance of intelligent tutoring systems, generative AI, adaptive learning platforms, and learning analytics tools.

These results certainly strengthen previous conclusion about effective instruction of ITS for complex and cognitively challenging learning environments, whereas they are also in accordance with more recent syntheses emphasizing their on-going importance in AI-supported education [2,6]. The dominant AI technologies identified in the reviewed literature are summarized in Table 2.

Table 2. Types of Artificial Intelligence Technologies Used in Computational Physics Education

AI Technology	Percentage of Studies	Primary Educational Function
Intelligent Tutoring Systems (ITS)	38%	Adaptive feedback, problem-solving guidance
Generative AI / Large Language Models	27%	Code scaffolding, explanation, content generation
Adaptive Learning Platforms	18%	Personalized learning pathways
Learning Analytics Systems	12%	Learner modeling and assessment support
AI-based Automated Grading	5%	Evaluation of programming and simulations

Beyond ITS, recent work highlights the increasing attention to generative AI and large language models as new resources for computational physics learning. These technologies are being used more and more for offering personal feedback, program scaffolding support, and dynamic content generation to help learners perform computational task and solve physics problems. Empirically, generative AI appears not just enabling of high learner engagement but also for personalized learning pathways tailored to a wide range of learners and their differences in needs [3,9,13].

Concurrently, the incorporation of multimodal learning analytic tools has been recognized as a complementary advancement that enriches AI-facilitated teaching and learning ecosystems. The systems aggregate data across several learner responses in order to support assessment, learner modeling, and pedagogical decision making. Recent evidence suggests that these analytics make possible for more informed pedagogic interventions and promote synergistic collaboration between AI systems and human instructors rather than full-automated Instruction models [14].

3.2 Pedagogical Integration and Learning Objectives

Pedagogical design decisions also plays a crucial factor for successful integration of AI-enabled educational technologies into the computational physics education. Based on the literature, AI tools tend to be embedded in project-based learning (PBL), problem-based learning (PBL) and collaborative models of teaching. These pedagogical strategies are tightly correlated to the cultivation of computing thoughts as well as numerical modeling and high-level problem-solving ability, all of which constitute Core ideas in computational physics courses[15].The reported pedagogical impacts of AI integration are synthesized in Table 3.

Table 3. Reported Pedagogical Impacts of AI Integration in Computational Physics Learning

Learning Dimension	Reported Impact
Computational Thinking	Moderate to high improvement
Numerical Modeling Skills	Moderate improvement
Cognitive Load	Moderate reduction
Student Engagement	High increase
Learning Equity	Conditional (design- and context-dependent)

Recent conversations are turning to the hybrid model of human–AI teaching, in which AI serves as a pedagogical ally rather than substituting for humanity itself. In this framework, educators still play an important role guiding learners, interpreting AI-provided feedback and ensuring alignment with the curriculum. These human-centric approaches are deemed critical for retaining pedagogical control yet harnessing AI's adaptive technologies to cater to a diverse range of learners [12,16].

Furthermore, there has been an increasing focus on equity-oriented perspectives in pedagogical integration discussions. Some papers draw attention to the potential of AI to increase access and equity in STEM education for (underrepresented learning groups, however) cautions that such benefits are dependent on design and implementation considerations[6,17]. It underscores the role of pedagogical development in order to maintain a balance between technological advancement and inclusivity, associated with instructional responsibility.

3.3 Research Trends and Global Collaboration

Trend analyses in publications demonstrate the significant surge of studies on AI-informed computational physics and STEM education, since 2019 indicating an intensified worldwide interest in AI-based educational technologies. Further, the United States and China are among primary contributors to the research output and international collaboration; indeed, interdisciplinary journals are an important channel for spreading influential studies in the field of education/ computer science/ physics[18,19].

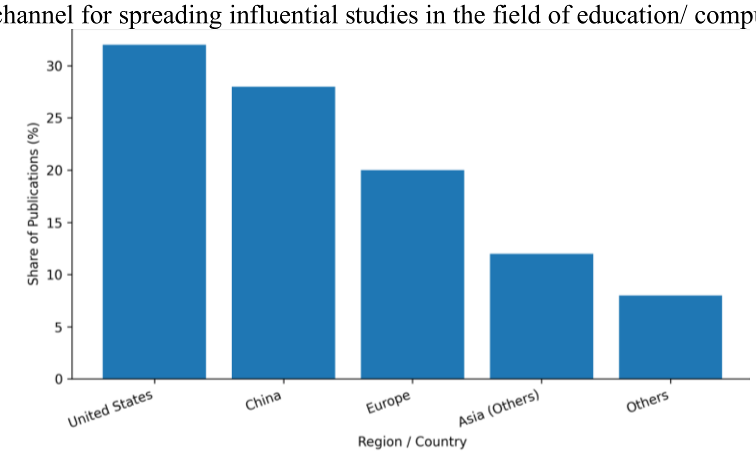

Figure 3. Global distribution of research contributions on artificial intelligence in computational physics and STEM education, showing the dominant roles of the United States and China alongside increasing international participation and interdisciplinary collaboration.

Bibliometric indicators also display a growing international network of cooperation and diversification in themes. These developments indicate that the intersection of AI and computational learning is moving beyond isolated studies to a community-wide, large scale research agenda. The associated literature also suggests on-going need for the development of shared methodological approaches and consistent pedagogy base across educational settings as well opportunities and needs for future consolidation and theory advancement [12,19]

3.4 Challenges and Ethical Considerations

While good results have been reported for the integration of AI into these systems there are several problems that remain unsolved according to the literature. Ethical considerations around algorithmic bias, personal data privacy and the integrity of the learning evidence still demand attention in AI-informed learning environments. Addressing these issues creates serious questions around the transparency, accountability and reliability of AI systems employed in education[13,20]. The major challenges reported in the literature are summarized in Table 4.

Table 4. Major Challenges in Implementing AI in Computational Physics Education

Challenge Category	Frequency in Reviewed Studies
Ethical and algorithmic bias issues	32%
Teacher readiness and professional development	29%
Data privacy and security	21%
Infrastructure and access inequality	11%
Lack of longitudinal empirical evidence	7%

As well as ethical concerns, a lack of teacher preparedness and inadequate professional development are also seen as major obstacles to the effective deployment of AI. Lacking appropriate guidance and organizational support, educators may encounter difficulty in making sense of AI-generated suggestions or using AI tools meaningfully in their teaching[21,10]. As a result, recent research increasingly recommends a human-centered and equity-oriented AI approach which prioritizes inclusion, transparency, pedagogical alignment. These frameworks are seen as critical for ensuring AI technologies will contribute to mitigating rather than augmenting current educational disparities[22,11].

3.5 Summary of Discussion

Taken together, the results suggest that AI technologies , including intelligent tutoring systems, generative AI, and learning analytics well-embedded in pedagogical designs, hold strong potential to contribute to improvements of computational physics education. But the efficacy of these technologies is contingent on thoughtful alignment with pedagogical practices, long-term teacher engagement, and ethically defensible implementation. This reinforces the requirement for future research that goes beyond adoption of a tool to development of coherent AI-supported models such as articulated in this review roadmap that are inclusive and pedagogically robust for computational physics education.

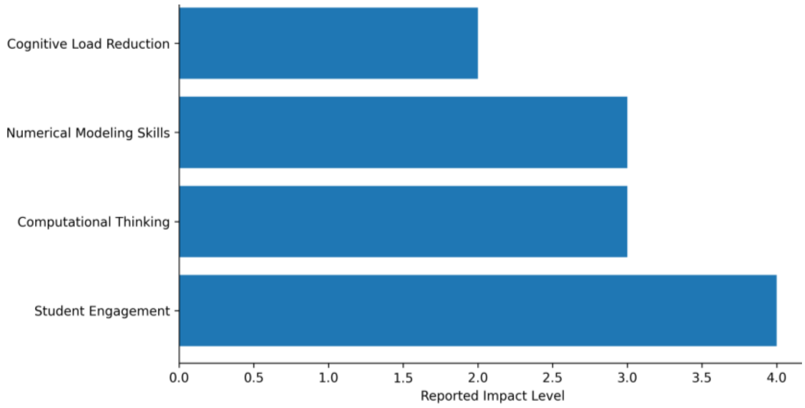

Figure 4. Summary of pedagogical outcomes reported in the literature on AI-enhanced computational physics education, including increased student engagement, improved computational thinking, enhanced numerical modeling skills, and reduced cognitive load.

4. Conclusion

The incorporation of artificial intelligence (AI) in the teaching and learning process of computational physics is a substantial change from pedagogy to educational technology perspective. This cutting-edge narrative review showcases how advances in intelligent tutoring systems, generative AI, and adaptive learning platforms have transformed the teaching and learning of computational physics by allowing personalized learning pathways, adaptive feedback, and increased student engagement with complex computational tasks.

Pedagogically speaking, there is mounting evidence that the current development trend of human–AI hybrid teaching in which AI as a supportive educational technology support rather than replace instructors. They are in good agreement with the learning requirements of computational physics, and they facilitate the training on computational thinking, numerical modeling competences, and high order reasoning abilities. In well-designed instructional frameworks, AI technologies can support in reducing cognitive load, scaffolding and reinforcing students' understanding at the conceptual level in courses with a computational focus in physics.

Despite these hopeful trends, however, there are significant hurdles. These also include ethical concerns such as data protection, algorithmic bias, academic freedom and end-user rights in AI-enhanced learning environments. In addition to this, the limited teacher readiness, unevenness of AI technology access and lack of robust longitudinal or large-scale empirical evidences hinder the sustainable and equitable introduction of AI into computational physics education. These limitations emphasize the importance of governance and professional development to guide responsible, transparent adoption of AI.

As a result, there will be room for research to move beyond short-term performance results and consider long-term learning trajectories, the institutional strategies that are used for implementation of OER-based AI-enhanced materials and when educators integrate existing OER with AI technology for physics education. More emphasis is needed as well on equity-centered and human-centric design approaches, to work towards an AI for educational practice that promotes inclusive and meaningful educational practices.

Future research in AI-supported computational physics education should proceed along several systematic directions. First, longitudinal and large-scale empirical studies are needed to examine long-term learning trajectories and the sustainability of AI-enhanced instructional interventions. Second, research should investigate pedagogically grounded design frameworks that align AI technologies with core computational physics practices, including modeling, simulation, and algorithmic reasoning. Third, greater attention is required to equity-centered and human-centered AI approaches that address ethical concerns, data privacy, and instructor agency. Finally, institutional-level studies exploring professional development models and policy frameworks will be essential to support responsible and scalable implementation of AI in computational physics education.

Acknowledgment

The author would like to express sincere gratitude to the coordinator of the Physics Education Study Program for the trust and opportunity given to teach the Computational Physics course.

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