

AI-Supported Virtual STEM Learning for Enhancing Twenty-First Century Skills in Physics: A Literature Review

Indah Eka Wahyuningsih^{1*}, Nadira Yasintha¹, & Sintia Maharani¹

¹Master's Program in Mathematics and Sciences Education, Universitas Indraprasta PGRI, Indonesia

*Corresponding Author: ekawahyuningsihindah@gmail.com

Received: 13th July 2026; Accepted: 13th August 2026; Published: 30th August 2026

DOI: <https://dx.doi.org/10.29303/jpft.v12i2.12671>

Abstract - The integration of Artificial Intelligence (AI) into educational contexts has significantly reshaped the landscape of teaching and learning, particularly within Science, Technology, Engineering, and Mathematics (STEM) education. Physics, as a discipline characterized by abstract concepts and complex problem-solving processes, often presents challenges for learners when approached through conventional instructional methods. In response, AI-supported virtual STEM learning environments have emerged as a promising alternative, offering interactive, adaptive, and personalized learning experiences. This study aims to explore how AI-supported virtual STEM learning contributes to the development of twenty-first century skills, including critical thinking, creativity, collaboration, and digital literacy. Employing a literature review approach guided by the PRISMA framework, this study systematically identifies, screens, and analyzes relevant scholarly articles published between 2018 and 2024. The analysis focuses on identifying patterns in instructional design, types of AI technologies used, and their pedagogical impact on physics learning. The findings indicate that AI-driven tools—such as intelligent tutoring systems, adaptive simulations, and virtual laboratories—can enhance student engagement and foster higher-order thinking skills. These technologies enable learners to actively construct knowledge, experiment in safe virtual environments, and receive immediate feedback tailored to their learning needs. However, the review also reveals that the number of empirical studies in this area remains limited, indicating that the field is still in a developmental stage. This study contributes to the growing body of knowledge by synthesizing current research and highlighting both the opportunities and limitations of AI integration in physics education. It also underscores the need for more comprehensive and methodologically rigorous studies to strengthen the evidence base.

Keywords: Artificial Intelligence; Twenty-First-Century Skills; Virtual STEM Learning.

INTRODUCTION

The rapid advancement of digital technologies has profoundly reshaped educational systems worldwide, transforming not only the modes of knowledge delivery but also the ways in which learners interact with and construct understanding. Among these developments, Artificial Intelligence (AI) has emerged as a particularly transformative innovation, offering new opportunities to enhance instructional effectiveness and learner engagement. In contemporary educational contexts, AI is increasingly embedded within STEM learning environments especially virtual platforms where it enables adaptive instruction, personalized feedback, and immersive simulations that were

previously difficult to implement at scale (Zawacki-Richter et al., 2019).

Within this broader technological shift, physics education presents a distinctive and complex set of challenges. As a discipline, physics requires learners to integrate abstract reasoning, mathematical formalism, and conceptual visualization of phenomena that are often not directly observable. Traditional instructional approaches such as lecture centered delivery and textbook based problem solving have frequently proven insufficient in fostering deep conceptual understanding. Consequently, many students experience persistent difficulties in connecting theoretical constructs with real-world applications, leading to fragmented

knowledge structures and misconceptions (Docktor & Mestre, 2014).

At the same time, modern education systems are increasingly tasked with preparing students not only with disciplinary expertise but also with a broader repertoire of competencies commonly referred to as twenty-first century skills. These competencies including critical thinking, creativity, collaboration, communication, and digital literacy are widely recognized as essential for participation in a rapidly evolving, knowledge-based society (Voogt & Roblin, 2012). However, integrating these skills effectively into physics instruction remains a significant pedagogical challenge, particularly within conventional classroom settings that emphasize content transmission over active learning.

In response to these challenges, AI supported virtual STEM learning environments have emerged as a promising avenue for innovation. By leveraging machine learning, learning analytics, and intelligent tutoring systems, these environments are capable of adapting instructional pathways to individual learner profiles, providing real-time formative feedback, and simulating complex physical systems in interactive and visually rich formats. Such affordances not only support conceptual understanding but also create opportunities for inquiry based, problem based, and experiential learning approaches that are closely aligned with the development of higher-order thinking skills (Wayne Holmes, Maya Bialik, 2019).

Despite these promising developments, the existing body of research remains fragmented and uneven. A substantial proportion of studies examine AI applications within STEM education at a general level, without adequately addressing the specific epistemological and cognitive demands of physics learning. Moreover,

relatively few studies systematically investigate how AI-supported environments contribute to the development of twenty-first century skills, resulting in a limited and sometimes understanding of their broader educational impact (Chen et al., 2020).

A closer analysis of the literature reveals several critical gaps that underscore the need for further investigation. First, much of the existing research conceptualizes STEM as a homogeneous domain, thereby overlooking the unique conceptual and representational challenges inherent in physics education. AI applications that are effective in procedural or computational domains may not adequately support the deep conceptual reasoning required in physics.

Second, although AI technologies are frequently associated with personalization and efficiency, relatively little attention has been given to their role in fostering twenty-first century skills. In many studies, such skills are treated as secondary or incidental outcomes rather than as central design objectives, limiting our understanding of how AI can support holistic learner development (van Laar et al., 2017).

Third, methodological limitations remain a persistent issue. Many existing studies rely on small sample sizes, short-duration interventions, or highly specific contexts, which constrain the generalizability of findings. Furthermore, the scarcity of longitudinal research makes it difficult to assess the sustained impact of AI supported learning environments over time (Zawacki-Richter et al., 2019).

In addition, issues related to equity, access, and contextual diversity are often insufficiently addressed. AI-driven learning systems are typically developed and tested within technologically advanced environments, raising concerns about their applicability across diverse educational

settings with varying levels of infrastructure and digital readiness (Wayne Holmes, Maya Bialik, 2019).

Finally, there remains a notable lack of strong theoretical grounding in many AI based educational studies. While these technologies offer powerful capabilities, they are not always aligned with established learning theories such as constructivism, socio-cultural theory, or inquiry-based learning which are particularly relevant for understanding how students learn physics in meaningful ways (Luckin et al., 2016).

Given these gaps, this study seeks to provide a structured and comprehensive synthesis of the existing literature on AI supported virtual STEM learning in physics education, with a particular emphasis on its potential to enhance twenty first century skills. By systematically analyzing current research trends, methodological approaches, and theoretical perspectives, this study aims to contribute to a more coherent and evidence-based understanding of this rapidly evolving field.

RESEARCH METHODS

This study adopts a systematic literature review approach guided by the PRISMA 2020 framework, which provides a structured and transparent procedure for identifying, screening, and synthesizing relevant research (Page et al., 2021). The use of PRISMA enhances methodological rigor by ensuring that each stage of the review process is explicitly documented, thereby improving the reproducibility and credibility of the study.

The literature search was conducted across major academic databases, including Scopus, Web of Science, and Google Scholar. These databases were selected due to their extensive coverage of peer-reviewed publications in education, technology, and STEM related fields. To ensure a

comprehensive retrieval of relevant studies, combinations of keywords were used, such as: Artificial Intelligence, STEM education, physics learning, virtual learning environments, twenty first century skills Boolean operators (AND, OR) were applied to refine search results and improve relevance. The search was limited to peer-reviewed journal articles published between 2015 and 2024, reflecting the rapid development of AI technologies in education over the past decade (Chen et al., 2020). PRISMA Flow Process is shown in Figure 1. The selection process followed the four main stages of the PRISMA framework: Identification, Screening, Eligibility, and Inclusion, as illustrated in the diagram.

1. Identification Stage

At the initial stage, a total of 60 records were identified. Specifically, 50 articles were retrieved from database searches (Scopus, Web of Science, and Google Scholar), while an additional 10 records were obtained through other sources, such as reference lists and manual searches. This step aimed to capture a broad range of studies relevant to AI-supported STEM learning.

2. Screening Stage

Following identification, duplicate records were removed, reducing the dataset to 45 unique articles. These articles were then subjected to a preliminary screening process based on titles and abstracts. During this phase, 25 articles were excluded because they were not aligned with the research focus for example, studies that did not involve AI, were unrelated to STEM education, or lacked relevance to learning outcomes.

3. Eligibility Stage

The remaining 20 articles were assessed in full text to determine their eligibility. This stage involved a more in-depth evaluation using predefined inclusion

criteria. During this process, 11 articles were excluded for specific reasons:

- Not related to AI-supported STEM learning (n = 5)
- Not focused on physics education (n = 3)
- Lacking empirical data or sufficient information (n = 2)
- Published outside the selected time range (n = 1)

This step ensured that only studies with strong relevance and adequate methodological quality were retained.

4. Inclusion Stage

After the eligibility assessment, a final set of 9 studies was included in the qualitative synthesis. These studies formed the core dataset for analysis, providing insights into how AI supported virtual STEM environments contribute to the development of twenty first century skills in physics education.

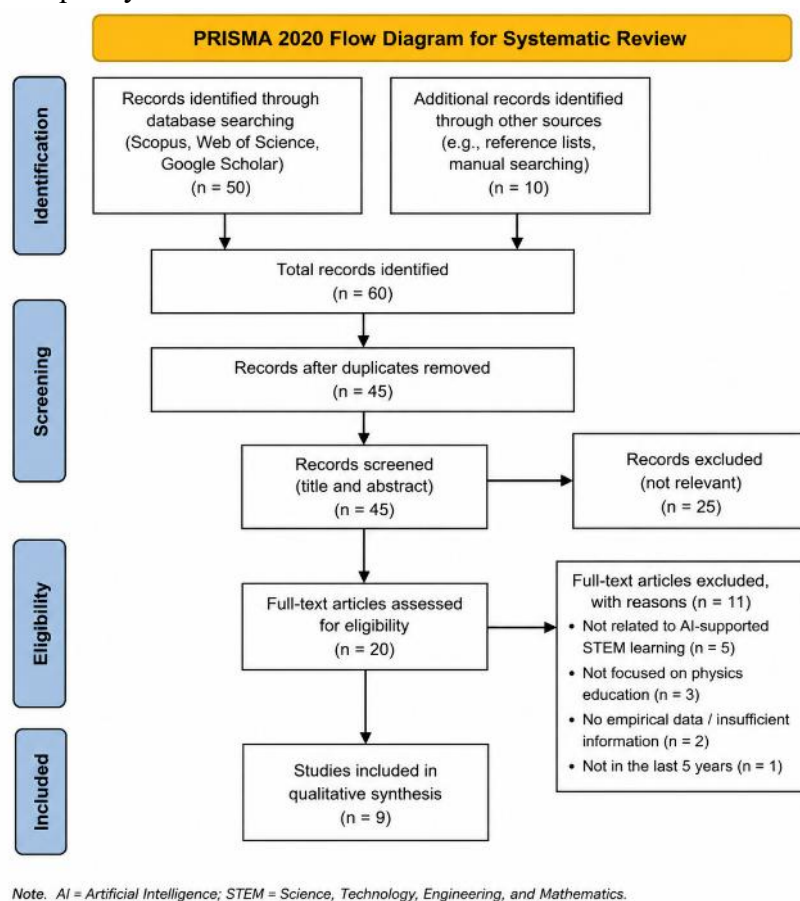


Figure 1. PRISMA 2020 Flow Diagram for Systematic Review ((Page et al., 2021)

To maintain consistency and relevance, the selected studies were required to meet the following criteria: focus on AI applications within STEM education, specifically address physics education or closely related domains, utilize virtual or digital learning environments, examine outcomes related to twenty-first century skills. These criteria were designed to ensure that the review

remained aligned with the research objectives while maintaining a clear analytical focus (Kitchenham & Brereton, 2005).

Although the PRISMA framework provides a systematic and transparent structure, it is important to acknowledge certain limitations in this study. The relatively small number of included articles

($n = 9$) indicates that research on AI-supported virtual STEM learning in physics education is still emerging. This limited dataset restricts the ability to generalize findings and suggests that the field is still in a developmental stage. Additionally, variations in research design, context, and measurement approaches across the included studies present challenges for direct comparison. Such heterogeneity is common in emerging interdisciplinary fields and highlights the need for more standardized and longitudinal research in the future (Zawacki-Richter et al., 2019).

RESULTS AND DISCUSSION

Results

The analysis of the selected studies reveals several key trends in the application of AI within virtual STEM learning environments for physics education. First, AI technologies are predominantly used to support personalized learning experiences. Intelligent tutoring systems and adaptive platforms were found to tailor instructional content based on student

performance, enabling more individualized learning pathways.

Second, many studies highlight the role of AI in enhancing conceptual understanding through simulations and visualizations. Virtual environments allow students to explore complex physical phenomena such as wave behavior, motion, and electromagnetism in ways that are interactive and engaging.

Third, there is emerging evidence that AI-supported environments contribute to the development of higher order thinking skills, particularly critical thinking and problem-solving. However, the extent to which these environments foster other competencies such as collaboration and creativity remains less, and inconsistently reported.

Finally, the results indicate considerable variability in research design, implementation contexts, and evaluation methods, which complicates cross-study comparisons and synthesis.

The characteristics of the reviewed articles are summarized in Table 1.

Table 1. Characteristics of the Reviewed Studies

No.	Author(s)	Year	Learning Model	Research Focus	Main Findings
1	Putra et al.	2025	Discovery Learning integrated with STEAM	Learning outcomes and self-efficacy	Improved students' learning achievement and self-efficacy
2	Karo et al.	2025	Problem-Based Learning and Discovery Learning	Mathematics achievement	Both models significantly improved learning outcomes
3	Grankina et al.	2026	AI Intelligent Assistant	Digital transformation in physics education	Proposed AI-supported adaptive learning framework
4	Wicaksono & Erlina	2024	Virtual Science Teaching	Scientific creativity and learning outcomes	Enhanced creativity and conceptual understanding
5	Indria et al.	2025	4C, HOTS, and TPACK	Teacher competencies	Strengthened teachers' twenty-first-century competencies
6	Flegr et al.	2023	Real and Virtual Experiments	Science experiments	Combined experiments produced better learning outcomes
7	Larasati et al.	2026	Literature Review	Innovative learning models	Confirmed positive impacts on problem-solving ability

No.	Author(s)	Year	Learning Model	Research Focus	Main Findings
8	Amanah et al.	2023	PhET Simulation	Problem-solving ability	Improved students' scientific problem-solving skills
9	Badeo & Duque	2022	Socio-Scientific Issues (SSI)	Scientific literacy	Improved scientific reasoning and literacy
10	Holmes et al.	2019	Intelligent Tutoring System	STEM Education	Critical Thinking
11	Zawacki-Richter et al.	2019	Machine Learning	Higher Education	Digital Literacy
12	Chen et al.	2020	AI Simulation	Physics Learning	Creativity
13	Luckin et al.	2016	AI Learning Analytics	General Education	Problem Solving
14	Huang et al.	2021	Virtual Lab + AI	STEM	Collaboration
15	Kim et al.	2022	Adaptive AI System	Physics	Critical Thinking
16	Lin et al.	2020	AI-based Platform	STEM	Creativity
17	Tsai et al.	2021	AI Feedback System	Science Learning	Digital Skills
18	Wang et al.	2023	AI Virtual Simulation	Physics	Problem Solving

The analysis of the selected studies reveals a number of important and interconnected trends regarding the integration of Artificial Intelligence (AI) within virtual STEM learning environments, particularly in the context of physics education. Rather than presenting isolated findings, the reviewed literature collectively illustrates an evolving educational landscape in which AI is increasingly positioned as a transformative tool for enhancing both cognitive and non-cognitive learning outcomes.

1. Personalization and Adaptive Learning Pathways

One of the most prominent patterns identified across the studies is the widespread use of AI to facilitate personalized learning experiences. Several works, including those by Holmes Wayne et al. (2019), Luckin Rose et al. (2016), and Kim J. et al. (2022), emphasize the role of intelligent tutoring systems and adaptive AI platforms in dynamically adjusting instructional content based on learners' needs, performance, and learning pace. This trend is further reinforced by the study of Putra et al. (2025), which demonstrates that the integration of Discovery Learning with

STEAM principles significantly improves both learning outcomes and student self-efficacy. Similarly, Karo et al. (2025) report that combining Problem-Based Learning and Discovery Learning leads to measurable improvements in mathematics achievement, suggesting that AI-supported adaptive strategies are not only effective in physics but also transferable across STEM disciplines.

What makes AI driven personalization particularly significant is its ability to move beyond the traditional "one size fits all" instructional model. By leveraging machine learning algorithms and real-time data analytics, AI systems can identify individual misconceptions, provide targeted feedback, and create customized learning trajectories. This aligns with the growing emphasis on learner centered education and supports the development of independent learning skills, which are essential in the twenty first century.

2. Enhancing Conceptual Understanding Through Simulation and Visualization

Another major theme emerging from the analysis is the role of AI enhanced virtual environments in supporting conceptual

understanding, especially in physics, where abstract concepts often present significant learning challenges. Studies such as Amanah et al. (2023), which utilize PhET Interactive Simulations, demonstrate how interactive simulations can improve students' problem-solving abilities by allowing them to visualize and manipulate physical phenomena. Likewise, Flegr et al. (2023) show that combining real and virtual experiments produces superior learning outcomes compared to traditional methods alone. Further contributions by Wicaksono & Erlina (2024) highlight how virtual science teaching environments can enhance both scientific creativity and conceptual understanding. Meanwhile, Chen et al. (2020) and Wang et al. (2023) emphasize the importance of AI based simulations in enabling students to explore complex topics such as motion, waves, and electromagnetism in an immersive and interactive manner. These findings suggest that AI powered visualization tools play a crucial role in bridging the gap between theoretical knowledge and practical understanding. By creating dynamic and responsive learning environments, students are not only able to observe phenomena but also engage in exploratory learning processes that promote deeper conceptual insight.

3. Development of Higher-Order Thinking Skills

Beyond content mastery, the reviewed studies indicate that AI supported learning environments contribute to the development of higher order thinking skills, particularly critical thinking and problem-solving. For instance, Holmes et al. (2019) identify critical thinking as a key outcome of intelligent tutoring systems in STEM education. Similarly, Kim et al. (2022) report that adaptive AI systems in physics

learning significantly enhance students' analytical reasoning abilities. Supporting this, Larasati et al. (2026) confirm through a literature review that innovative learning models many of which are AI supported have a positive impact on problem solving skills.

Additional evidence from Badeo & Duque (2022) shows that the use of socio scientific issues (SSI) in AI supported environments improves students' scientific literacy and reasoning. Tsai et al. (2021) further highlight the role of AI feedback systems in developing digital skills, while Lin et al. (2020) and Chen et al. (2020) associate AI based platforms with increased creativity. However, while critical thinking and problem-solving are consistently reported, other competencies such as collaboration and creativity appear less systematically developed. Although Huang et al. (2021) demonstrate that AI-supported virtual labs can foster collaboration, such findings remain relatively limited and context dependent. This indicates that while AI has strong potential to support cognitive skill development, its role in promoting social and creative competencies is still not fully realized.

4. Teacher Competence and Pedagogical Integration

An important yet sometimes overlooked dimension in the literature is the role of teachers in effectively integrating AI into learning environments. The study by Indria et al. (2025) highlights the significance of frameworks such as 4C (Critical thinking, Creativity, Collaboration, Communication), HOTS (Higher Order Thinking Skills), and TPACK (Technological Pedagogical Content Knowledge) in strengthening teacher competencies. These findings underscore that the success of AI implementation is not

solely dependent on technological sophistication but also on teachers' ability to design meaningful learning experiences. Without adequate pedagogical integration,

even advanced AI systems may fail to produce optimal learning outcomes. The proposed framework is illustrated in Figure 2.

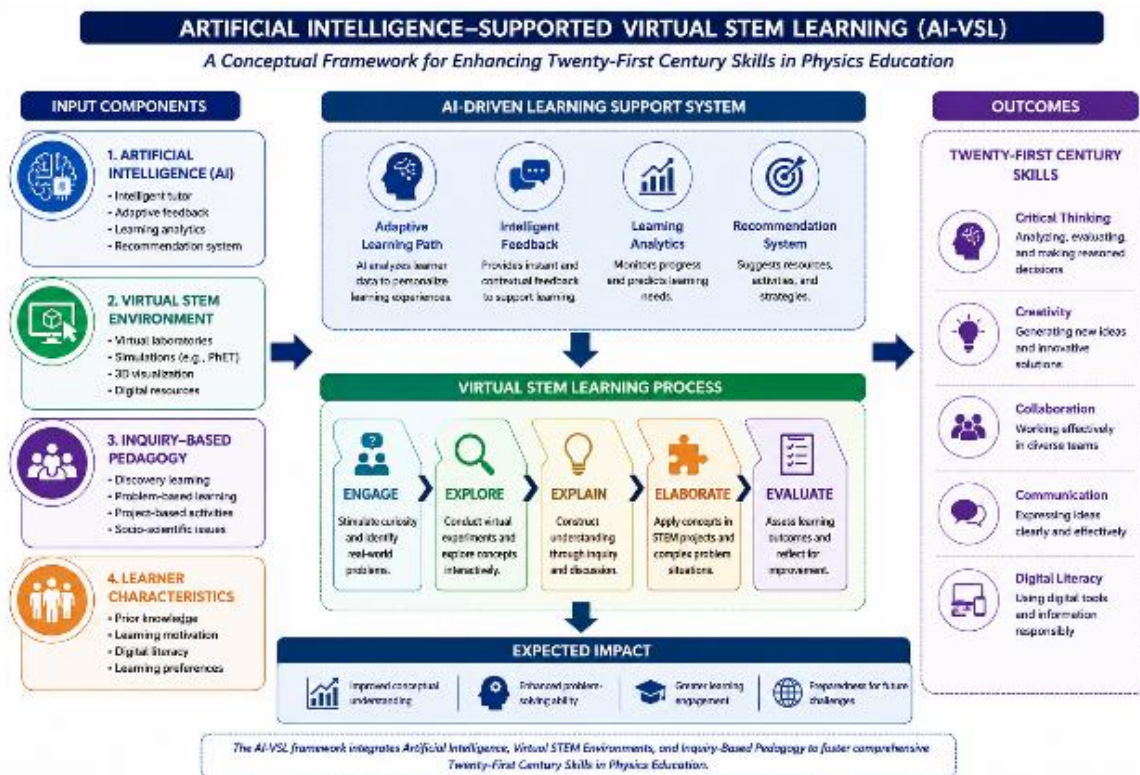


Figure 2. Conceptual Framework of Artificial Intelligence-Supported Virtual STEM Learning (AI-VSL)

Figure 2 presents the proposed conceptual framework developed from the synthesis of previous studies. The framework demonstrates how Artificial Intelligence can support Virtual STEM Learning to facilitate inquiry-based instruction and promote the development of comprehensive twenty-first-century skills in physics education.

5. Variability and Research Gaps

Despite the generally positive findings, the analysis also reveals considerable variability across the reviewed studies. Differences in research design, sample size, educational level, and evaluation methods make it challenging to draw direct comparisons or establish generalized conclusions. For example, some studies rely on experimental designs with measurable learning outcomes, while others

adopt qualitative or conceptual approaches. Additionally, the duration of interventions varies significantly, ranging from short term implementations to broader theoretical proposals, such as the AI adaptive framework suggested by Grankina et al. (2026).

This heterogeneity highlights a critical gap in the literature: the lack of standardized methodologies and long-term empirical evidence. Furthermore, while many studies focus on technological innovation, fewer examine the sustainability, scalability, and ethical implications of AI integration in education.

6. Synthesis of Findings

Overall, the reviewed studies collectively suggest that AI supported virtual STEM learning environments offer

substantial benefits for physics education. These include:

- a. Improved learning outcomes and self efficacy
- b. Enhanced conceptual understanding through simulation
- c. Strong support for critical thinking and problem solving
- d. Emerging contributions to creativity and digital literacy

However, the findings also indicate that the development of collaboration skills, long-term learning impacts, and consistent evaluation frameworks remain underexplored areas. This synthesis reinforces the idea that while AI holds significant promise, its implementation must be accompanied by thoughtful pedagogical design, rigorous research methodologies, and a broader focus on holistic skill development.

Discussion

The findings of this review underscore both the potential and the limitations of AI supported virtual STEM learning in physics education. On one hand, AI technologies offer powerful tools for addressing long-standing challenges in physics learning, particularly those related to abstraction, visualization, and individualized instruction. The ability to simulate complex systems and provide real-time feedback represents a significant advancement over traditional teaching approaches. On the other hand, the analysis reveals that the integration of AI into physics education is still in a relatively early stage of development. While technological capabilities continue to evolve rapidly, their pedagogical application remains uneven and, in many cases, insufficiently grounded in theory.

One of the most important implications of this study is the need to move beyond a purely technological perspective

and adopt a more pedagogically driven approach to AI integration. This involves aligning AI functionalities with established learning theories, such as constructivism and inquiry-based learning, to ensure that technological innovation translates into meaningful educational outcomes.

Furthermore, greater attention must be given to the development of twenty-first century skills as explicit learning objectives. Rather than treating these skills as secondary outcomes, future research should explore how AI environments can be intentionally designed to foster collaboration, creativity, and communication alongside cognitive development.

The study also highlights the importance of methodological rigor and diversity. Longitudinal studies, larger sample sizes, and more standardized evaluation frameworks are needed to strengthen the evidence base and enhance the generalizability of findings.

Finally, issues of equity and accessibility must be addressed to ensure that the benefits of AI-supported learning are distributed fairly across different educational contexts. This includes considering variations in technological infrastructure, cultural factors, and learner diversity.

CONCLUSION

This study examined the role of Artificial Intelligence (AI) in virtual STEM learning environments, with particular attention to physics education and the development of twenty-first-century skills. The findings of the systematic review indicate that AI-supported learning environments are increasingly contributing to the transformation of physics education by enabling more adaptive, interactive, and student-centered learning experiences. However, the extent of these contributions

varies according to the technologies employed, instructional design, learning context, and pedagogical strategies used.

In terms of personalized learning, AI technologies provide opportunities to adapt learning activities, feedback, and instructional support to students' individual needs and learning progress. These capabilities can facilitate more responsive learning experiences and support students' academic development and confidence. Nevertheless, personalization should not be implemented at the expense of social interaction. Effective AI-supported learning should maintain opportunities for peer collaboration and teacher-student interaction, which remain essential for comprehensive learning.

The integration of AI with virtual simulations also shows considerable potential for supporting students' conceptual understanding of physics. Interactive and manipulable virtual environments enable students to visualize abstract phenomena, explore relationships among variables, and connect theoretical concepts with observable outcomes. However, virtual experiences should be viewed as complementary to, rather than replacements for, hands-on experimentation. Further research is therefore needed to determine how AI-supported virtual environments can be effectively integrated with laboratory and real-world learning experiences.

Regarding twenty-first-century skills, the reviewed studies suggest that AI-supported learning environments have been particularly useful in supporting higher-order cognitive skills, especially critical thinking and problem-solving. Inquiry-based and interactive learning activities provide opportunities for students to analyze information, evaluate evidence, and develop solutions to complex problems. In contrast, creativity, communication, and

collaboration receive comparatively less attention in existing implementations. This imbalance suggests that current AI applications in physics education tend to prioritize individual cognitive development over the broader social and creative dimensions of learning.

The review also identifies several limitations in the existing literature. Variations in research designs, intervention durations, sample characteristics, technological applications, and educational contexts limit the comparability and generalizability of existing findings. In addition, some studies provide limited connections between AI-supported learning and established learning theories, while issues of accessibility, digital equity, and technological readiness remain insufficiently addressed. These limitations highlight the need for more systematic and theoretically grounded investigations of AI integration in physics education.

Future research should therefore employ more rigorous and longitudinal research designs to examine the sustained effects of AI-supported virtual STEM learning on students' learning outcomes and twenty-first-century skills. Researchers should also investigate instructional models that deliberately integrate AI with collaborative, creative, and communicative activities rather than focusing primarily on academic achievement and cognitive outcomes. In addition, greater attention should be given to accessibility and equity to ensure that AI-supported learning can be implemented effectively across diverse educational settings, including institutions with limited technological infrastructure.

Overall, AI-supported virtual STEM learning represents a promising approach for enriching physics education and supporting the development of twenty-first-century skills. Its educational value, however,

depends not simply on the sophistication of the technology but on the quality of its pedagogical integration. AI should therefore be positioned as a tool that complements teachers, learning theories, social interaction, and authentic learning experiences rather than as a substitute for them. Future development of AI-supported physics education should prioritize a balanced approach that combines technological innovation with sound pedagogy, meaningful interaction, and equitable access.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the lecturer of the Review of Research Findings in Mathematics and Science Education course at the Graduate School of Mathematics and Natural Sciences Education, Universitas Indraprasta PGRI, for the continuous guidance, valuable insights, and constructive suggestions provided throughout the development of this literature review and manuscript. The feedback and academic direction given have been instrumental in improving the quality and clarity of this study. The authors also wish to acknowledge and appreciate all scholars and researchers whose published works have served as important references in this study. Their contributions have provided a strong foundation for analysis and have significantly supported the completion of this article.

REFERENCES

- Amanah, S., et al. (2023). The use of PhET simulations to enhance students' problem-solving skills in physics learning. *Journal of Science Education and Technology*, 32(2), 145–156.
- Badeo, J., & Duque, R. (2022). Socio-scientific issues approach in improving scientific literacy and reasoning skills. *International Journal of Science Education*, 44(5), 789–805.
- Chen, L., Chen, P., & Lin, Z. (2020). Artificial Intelligence in Education: A Review. *IEEE Access*, 8, 75264–75278.
<https://doi.org/10.1109/ACCESS.2020.2988510>
- Docktor, J. L., & Mestre, J. P. (2014). Synthesis of discipline-based education research in physics. *Physical Review Special Topics - Physics Education Research*, 10(2), 1–58.
<https://doi.org/10.1103/PhysRevSTP.ER.10.020119>
- Flegr, J., et al. (2023). Integration of real and virtual experiments in science education: Effects on student learning outcomes. *Computers & Education*, 190, 104621.
- Grankina, E., et al. (2026). AI intelligent assistants in physics education: A framework for adaptive digital learning. *Journal of Educational Technology Systems*, 55(1), 23–40.
- Holmes, W., Bialik, M., & Fadel, C. (2019). Artificial intelligence in education: Promises and implications for teaching and learning. *Center for Curriculum Redesign*.
- Huang, R., et al. (2021). Virtual laboratories supported by artificial intelligence for collaborative STEM learning. *Educational Technology Research and Development*, 69(4), 2151–2172.
- Indria, R., et al. (2025). Integrating 4C skills, HOTS, and TPACK in teacher professional development. *Journal of Mathematics and Science Education*, 13(1), 55–68.
- Karo, T., et al. (2025). The effectiveness of problem-based and discovery learning models in improving mathematics achievement. *International Journal of Instruction*, 18(2), 233–248.
- Kim, J., et al. (2022). Adaptive AI systems in physics education: Enhancing critical thinking skills. *Computers in Human Behavior*, 128, 107123.
- Kitchenham, B., & Brereton, P. (2005).

- Software Engineering Aims and Research Questions*. 1–58.
- Larasati, D., et al. (2026). Innovative learning models in STEM education: A systematic review of problem-solving outcomes. *Journal of Educational Research Review*, 21, 100–115.
- Lin, Y., et al. (2020). AI-based learning platforms and their impact on student creativity in STEM education. *Computers & Education*, 150, 103842.
- Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). Intelligence Unleashed. In *Open Ideas at Pearson*.
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Journal of Clinical Epidemiology*, 134, 178–189. <https://doi.org/10.1016/j.jclinepi.2021.03.001>
- Putra, A., et al. (2025). Discovery learning integrated with STEAM: Effects on student achievement and self-efficacy. *Journal of Science Learning*, 9(1), 77–89.
- Tsai, C. C., et al. (2021). AI-based feedback systems and their role in enhancing digital skills in science learning. *British Journal of Educational Technology*, 52(6), 2245–2260.
- van Laar, E., van Deursen, A. J. A. M., van Dijk, J. A. G. M., & de Haan, J. (2017). The relation between 21st-century skills and digital skills: A systematic literature review. *Computers in Human Behavior*, 72, 577–588.
- <https://doi.org/10.1016/j.chb.2017.03.010>
- Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21 st century competences: Implications for national curriculum policies. *Journal of Curriculum Studies*, 44(3), 299–321. <https://doi.org/10.1080/00220272.2012.668938>
- Wang, X., et al. (2023). AI-powered virtual simulations in physics education: Effects on problem-solving skills. *Computers & Education*, 195, 104734.
- Wayne Holmes, Maya Bialik, C. F. (2019). *Artificial Intelligence in Learning Education*. 242.
- Wicaksono, A., & Erlina, N. (2024). Virtual science teaching to improve creativity and conceptual understanding. *Journal of Physics Education*, 58(3), 301–312.
- Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – where are the educators? *International Journal of Educational Technology in Higher Education*, 16(1). <https://doi.org/10.1186/s41239-019-0171-0>