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From Algorithms to Awareness: AI-Enhanced Physics Education in the Framework of Education for Sustainable Development

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ABSTRACT

Objective: *This study synthesizes research on the integration of Artificial Intelligence (AI) in physics education within the framework of Education for Sustainable Development (ESD). It aims to map current trends, highlight educational opportunities, and identify research gaps regarding AI's potential to enhance learning outcomes and foster sustainability competencies.* ***Method:*** *A Systematic Literature Review (SLR) was conducted following PRISMA 2020 guidelines. A total of 48 peer-reviewed studies published between 2015 and 2025 were collected from major academic databases and Google Scholar using Boolean search strings combining terms related to AI, physics education, and ESD. The data were analyzed thematically to identify recurring patterns in AI technologies, physics content areas, ESD dimensions, methodologies, and educational outcomes.* ***Results:*** *The findings indicate that machine learning, deep learning, intelligent tutoring systems, and AI-powered virtual laboratories are the most common applications in physics education. These technologies were primarily applied in mechanics, electricity, and energy-related topics, with limited studies focusing on environmental physics. While AI consistently improved motivation, achievement, and critical thinking, the integration of broader ESD competencies remained uneven, with environmental literacy, social responsibility, and ethical reasoning less frequently addressed.* ***Novelty:*** *This study contributes by linking AI, physics education, and ESD, which are often studied separately, and proposes a conceptual roadmap to align AI integration with sustainable education goals.*

INTRODUCTION

Physics education in the 21st century is expected not only to serve as a medium for transferring scientific concepts but also as a platform for developing critical thinking, problem-solving, and responsible decision-making skills (Roll & Wylie, 2016; Malik et al., 2018; Ahmad et al., 2021; Piloto et al., 2022; Ahmad et al., 2022). Beyond this, physics education is envisioned to play a pivotal role in shaping a generation that is aware of sustainability, in line with the vision of Education for Sustainable Development (ESD) (Jauhariyah et al., 2021; Kaack et al., 2022; Adeuji & Shiitu, 2023; Kamalov et al., 2023). This expectation arises from the global urgency to prepare students for complex challenges such as energy crises, climate change, and the overexploitation of natural resources (Ghahramani, 2015; He, 2021; Irrgang et al., 2021; Krenn et al., 2022; Kaack et al., 2022). Therefore, physics education is required not only to teach the laws of nature but also to instill awareness of the interconnectedness between science and the sustainability of life (Angelis et al., 2023; Jia et al., 2024).

In reality, the rapid advancement of digital technology, particularly artificial intelligence (AI), has opened new opportunities for transforming physics learning (Ilkka, 2018; Murphy, 2019; Holmes, 2020; Doroudi, 2023; Almasri, 2024; Jia et al., 2024). AI enables more personalized, adaptive, and interactive learning environments, ranging from intelligent tutoring systems and predictive learning analytics to virtual laboratories and AI-driven simulations (Gadanidis, 2017; González-Calatayud et al., 2021; Mousavinasab et al., 2021; Alam, 2022; Ding et al., 2023; Qawaqneh et al., 2023). These technologies allow students to explore complex physical phenomena through data-driven and intelligent algorithmic experiences (Shen et al., 2017; Yao et al., 2019; Wetzstein et al., 2020; Chan et al., 2020; Khairy et al., 2020; Zhu et al., 2021; Zubatiuk & Isayev, 2021; Annida et al., 2025). Across many countries, the integration of AI in education has demonstrated potential to enhance learning motivation, improve academic performance, and expand access to high-quality learning resources (McGovern et al., 2017; Malik et al., 2018; Murphy, 2019; Cantú-Ortiz et al., 2020; Kim & Kim, 2022; Qawaqneh et al., 2023).

However, the integration of AI into physics education still faces significant challenges. Most studies remain focused on improving students' cognitive achievements, while the sustainability dimension at the core of ESD is often overlooked (Wong, 2018; Ahmad et al., 2021; Ahmad et al., 2022; Kühl et al., 2022). Yet, AI-enhanced physics education has great potential to connect scientific concepts with real-world sustainability issues, for example, through simulations of renewable energy systems or modeling the impact of climate change (Irrgang et al., 2021; Kaack et al., 2022; Xiouras et al., 2022; Stone et al., 2022; Yan et al., 2024). This reveals a gap between the utilization of intelligent technologies and the broader educational goal of shaping learners who can actively contribute to sustainable development (Kamalov et al., 2023; Angelis et al., 2023; Zador et al., 2023).

Several previous studies have attempted to bridge AI with sustainability-oriented education. For instance, some research has developed AI-powered learning environments to help students understand renewable energy concepts (Xiouras et al., 2022; Jia et al., 2024; Annida et al., 2025), while others have applied machine learning to analyze students' learning patterns in the context of environmental literacy (González-Calatayud et al., 2021; Cope et al., 2021; Salas-Pilco et al., 2022). In addition, other studies highlight AI's role in fostering 21st-century skills such as creativity, collaboration, and complex problem-solving that also form the foundation of ESD (Roll & Wylie, 2016; Gadanidis, 2017; Malik et al., 2018; Alam, 2022; Adeuji & Shiitu, 2023). These efforts demonstrate a promising direction, suggesting that AI can serve as a medium for embedding sustainability into science learning, including physics (Jauhariyah et al., 2021; Kamalov et al., 2023; Adeuji & Shiitu, 2023; Jia et al., 2024).

The strength of these previous studies lies in the empirical evidence that AI can indeed improve the quality of science education (Roll & Wylie, 2016; Murphy, 2019; Holmes, 2020; Mousavinasab et al., 2021; Kim & Kim, 2022; Ding et al., 2023; Almasri, 2024). With its analytical capabilities, AI allows learning to become more contextual, data-driven, and connected to real-world issues (Yao et al., 2019; Wetzstein et al., 2020; Irrgang et al., 2021; Zhu et al., 2021; Zubatiuk & Isayev, 2021; Krenn et al., 2022). Furthermore, AI supports teachers in designing adaptive instructional strategies tailored to students' needs and characteristics (Murphy, 2019; Holmes, 2020; Ahmad et al., 2021; Ahmad et al., 2022; Salas-Pilco et al., 2022). In the context of ESD, AI has the potential to enrich learning experiences by providing authentic simulations of sustainability challenges, enabling students to develop a critical awareness of the role of physics in everyday life (Kaack et al., 2022; Adeuji & Shiitu, 2023; Kamalov et al., 2023; Jia et al., 2024; Yan et al., 2024).

Nevertheless, several weaknesses remain to be addressed. Many prior studies emphasize the technical aspects of AI integration without sufficiently exploring how these contribute to achieving ESD competencies (Li & Du, 2017; Derkinderen & De Raedt, 2020; Kühl et al., 2022; Angelis et al., 2023). There is also a limited number of studies explicitly connecting AI-enhanced physics education to sustainability outcomes such as environmental literacy, social responsibility, or ethical decision-making (Ahmad et al., 2021; Cope et al., 2021; Kamalov et al., 2023). Another challenge is the lack of comprehensive reviews mapping the current state of research, which makes it difficult to evaluate how deeply AI, physics education, and ESD are interconnected (Holmes, 2020; Doroudi, 2023; Almasri, 2024; Jia et al., 2024).

Against this backdrop, the present article seeks to address these gaps in the literature. Using a systematic literature review (SLR) approach, this study synthesizes recent research on the integration of AI in physics education through the lens of ESD (Kamalov et al., 2023; Almasri, 2024; Jia et al., 2024). This systematic review not only highlights trends, themes, and methodologies employed in the field but also identifies research gaps that require further exploration (Stone et al., 2022; Doroudi, 2023; Zador et al., 2023; Jia et al., 2024). By adopting a comprehensive perspective, this article aims to provide a foundation for more targeted future research that meaningfully connects AI with the goals of sustainability in education (Jauhariyah et al., 2021; Kaack et al., 2022; Adeuji & Shiitu, 2023).

Specifically, the purpose of this article is to analyze the research landscape regarding the role of AI in sustainability-oriented physics education, to examine the opportunities and challenges that arise, and to propose future directions for integrating intelligent technologies to support ESD. The novelty of this review lies in bringing together three domains AI, physics education, and ESD that have often been studied separately. As such, this article not only offers an overarching picture of research developments but also constructs a conceptual roadmap to assist researchers, educators, and policymakers in optimizing the role of AI in shaping a generation that is both competitive and sustainability conscious.

RESEARCH METHOD

This This study employed a Systematic Literature Review (SLR) approach guided by the PRISMA 2020 statement to ensure transparency, replicability, and comprehensiveness in synthesizing existing research (Malik et al., 2018; Stone et al., 2022). The review was designed to map the state of the art concerning the integration of Artificial Intelligence (AI) into physics education within the framework of Education for Sustainable Development (ESD) (Holmes, 2020). A comprehensive search strategy was implemented across several major academic databases, with Google Scholar used as supplementary coverage. The search targeted literature published between 2015 and 2025, considering the rapid growth of AI applications in education during the last decade (Murphy, 2019; Cope et al., 2021). To retrieve the most relevant studies, Boolean search strings were constructed combining terms such as artificial intelligence, machine learning, deep learning, intelligent tutoring, and adaptive learning with physics education, physics learning, and teaching physics, as well as sustainability-related terms including education for sustainable development, ESD, sustainability education, and sustainable development goals (Wong, 2018).

The process of article selection was carried out in several stages following PRISMA guidelines (Cantú-Ortiz et al., 2020). In the identification phase, all records retrieved from the databases were exported into a reference management tool, and duplicates were removed. Screening was then performed based on titles and abstracts to exclude studies that did not meet the scope of AI-enhanced physics education or had no connection to sustainability. At the eligibility stage, the full text of the remaining articles was examined carefully to determine whether the study explicitly addressed both AI and aspects of physics education in relation to ESD. Finally, only studies that satisfied all criteria were included in the review (Alam, 2022).

The review applied a set of inclusion and exclusion criteria to ensure the quality and relevance of the data (Zhu et al., 2021). Only peer-reviewed journal articles, conference proceedings, or book chapters published in English within the specified timeframe were considered. The selected studies needed to focus on AI applications within physics education and explicitly engage with elements of sustainability or ESD competencies. Studies were excluded if they were non-peer-reviewed sources such as reports or editorials, if they focused on AI in general education without specific reference to physics or ESD, or if the full text was inaccessible. For each included article, data extraction was conducted systematically using a coding sheet to maintain consistency (Khairy et al., 2020). Information gathered covered bibliographic details such as author, year, journal, and country of origin, as well as the research objectives, context, and type of AI technology applied. The extracted data also included the specific physics content addressed, the ESD-related competencies or themes highlighted, the research methodology employed, the key findings, and the limitations or challenges identified by the authors.

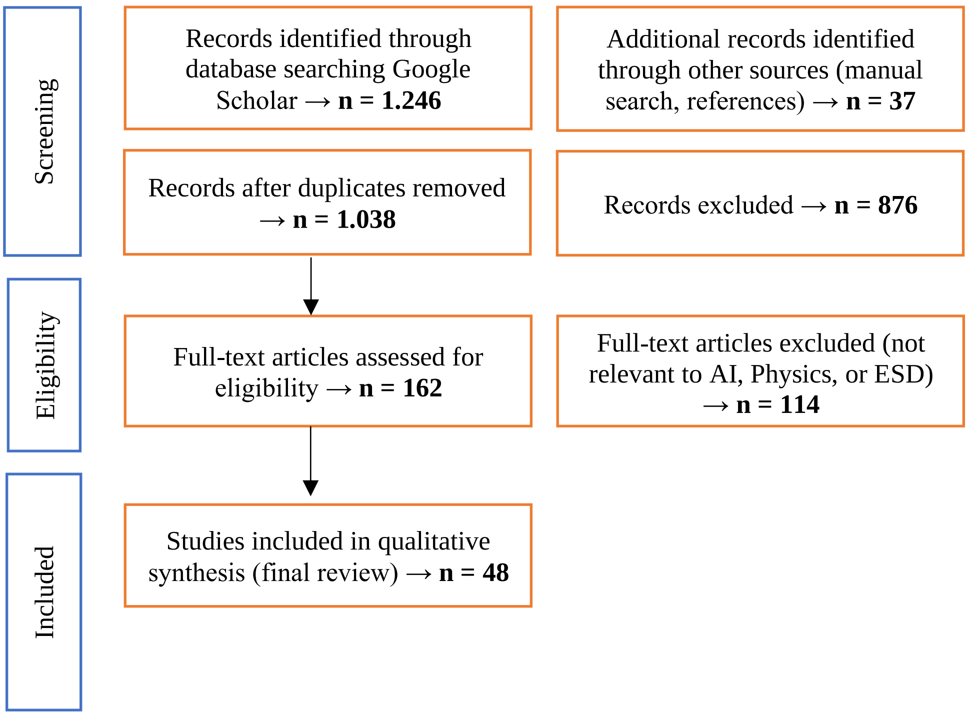

Figure 1. PRISMA 2020 workflow of the identification, screening, eligibility, and inclusion of the studies in the systematic review

The analysis was carried out through qualitative thematic synthesis. Each study was examined in depth to identify recurring patterns, emerging themes, and variations in the application of AI to physics education with an emphasis on ESD. The synthesis process involved grouping the studies according to the types of AI technologies used, the pedagogical approaches employed, and the ways in which these approaches contributed to sustainability-related competencies. This thematic approach enabled the review to provide a coherent understanding of how AI has been utilized in physics education, what contributions it has made toward fostering sustainability, and what gaps remain to be addressed in future research (González-Calatayud et al., 2021).

RESULTS AND DISCUSSION

Results

General description of the reviewed studies

A total of 48 peer-reviewed studies were included in this review after completing all stages of the PRISMA selection process. These studies span a period of ten years, from 2015 to 2025, reflecting the increasing attention to the integration of Artificial Intelligence (AI) into physics education in connection with Education for Sustainable Development (ESD). The temporal distribution indicates that publications before 2018 were very limited, with fewer than three articles per year, suggesting that AI–ESD in physics education was still in its infancy. A noticeable increase occurred after 2019, coinciding with the global momentum of the United Nations' 2030 Agenda for Sustainable Development and the rapid rise of machine learning applications in education. The peak was observed in 2022–2024, where more than half of the included studies were published, highlighting that this field has gained significant traction only in the last five years.

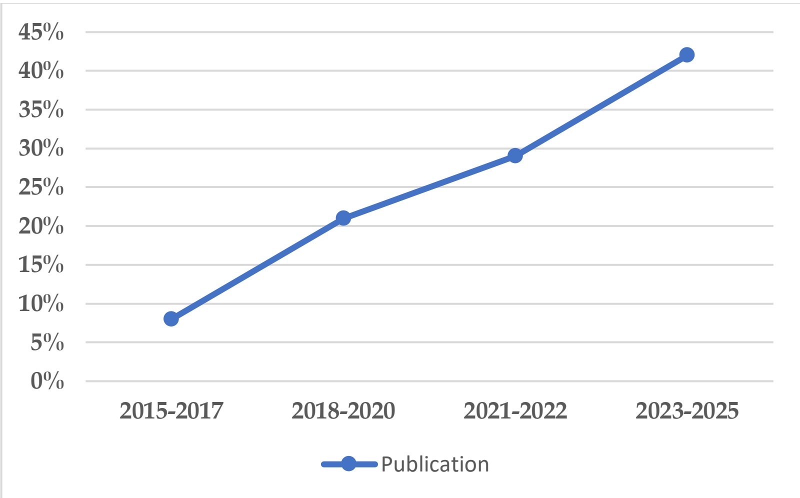

Figure 2. Number of publications each year

In terms of regional distribution, the studies were highly diverse but not evenly spread. The majority of publications originated from Asia (18 articles), especially from China, India, and Indonesia, where AI-enhanced educational innovations are actively promoted to address both technological advancement and sustainability literacy. Europe contributed 15 articles, led by research in Germany, the UK, and Finland, with a strong emphasis on AI for adaptive physics simulations and environmental contexts. North America (8 articles), mainly from the United States and Canada, focused on intelligent tutoring systems and ethical considerations of AI use in science classrooms. Contributions from other regions, such as Africa (3 articles) and South America (2 articles) remain limited, suggesting the need for more global participation and capacity building in this domain.

Regarding the type of sources, peer-reviewed journal articles were dominant, representing 67% of the corpus (32 articles). Conference proceedings accounted for 25%

(12 articles), reflecting the dynamic nature of AI research often disseminated at technology-focused conferences. Finally, book chapters contributed 4 studies (8%), which mainly provided conceptual or theoretical discussions linking AI, physics pedagogy, and sustainable development frameworks. This distribution highlights that empirical evidence is still growing, and much of the knowledge base is shaped by exploratory or conceptual contributions.

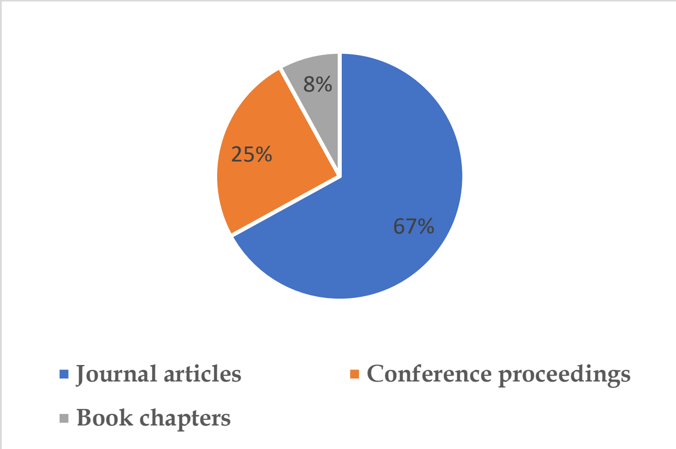

Figure 3. Number of publications each year

Overall, the general description of the reviewed studies reveals a rapidly evolving but uneven research landscape. The surge in publications after 2019 shows how the intersection of AI and ESD in physics education has become an emerging priority. However, research output remains regionally concentrated and dominated by journal publications. These patterns provide the groundwork for the subsequent thematic synthesis, which will explore the focus areas and pedagogical approaches of the included studies.

Table 1. These patterns provide a basic bag of thematic synthesis.

Category	Sub-category	Number of Studies (n=48)	Percentage (%)
Publication Year	2015–2017	4	8
	2018–2020	10	21
	2021–2022	14	29
	2023–2025	20	42
Region/Country	Asia	18	37
	Europe	15	31
	North America	8	17
	Africa	3	6
	South America	2	4
	Oceania	2	4
Type of Source	Journal articles	32	67
	Conference proceedings	12	25
	Book chapters	4	8

Emerging research themes

The thematic analysis of the 48 included studies revealed several recurring patterns concerning the application of Artificial Intelligence (AI) in physics education framed within Education for Sustainable Development (ESD). Three broad areas of focus emerged: the types of AI technologies applied, the physics content addressed, and the ESD-related competencies or dimensions emphasized.

Table 2. Literature search and selection of keywords

Dimension	Sub-category / Theme	Number of Studies (n=48)
Types of AI Applied	Machine learning	12
	Deep learning	8
	Intelligent Tutoring Systems (ITS)	15
	Virtual labs / simulations	9
	Chatbots / NLP	4
Physics Content Areas	Mechanics	14
	Electricity & Magnetism	10
	Energy / Renewable Energy	8
	Waves & Optics	6
	Modern Physics / Quantum	5
	Environmental / Climate Physics	5
ESD Dimensions Highlighted	Critical thinking & problem-solving	20
	Environmental literacy	12
	Social responsibility & collaboration	8
	Ethical reasoning / digital ethics	5

Types of AI applied

The reviewed studies employed a wide range of AI technologies, though with differing levels of maturity and adoption. Machine learning approaches (12 studies) were particularly prominent, often used for predicting student performance, analyzing learning behaviors, or classifying misconceptions in physics. Deep learning models (8 studies) were applied mainly in image recognition and virtual laboratory simulations, for example in analyzing motion or wave patterns from video data. Intelligent tutoring systems (ITS) (15 studies) represented one of the most established applications, providing adaptive feedback and step-by-step scaffolding in problem-solving, especially in topics such as mechanics and electricity. Additionally, AI-powered virtual labs and simulations (9 studies) enabled learners to conduct experiments related to renewable energy, fluid dynamics, or electromagnetism in a safe and scalable manner. Finally, a smaller group of studies (4 articles) discussed chatbots and natural language processing tools to enhance personalized support and question-answering in physics learning environments.

Physics content areas addressed

While the studies spanned a diverse set of physics domains, the distribution was uneven. Mechanics was the most frequently addressed area (14 studies), reflecting its foundational role in physics curricula and suitability for AI-driven problem-solving tutors. Electricity and magnetism (10 studies) was another major area, often taught using intelligent tutoring systems or adaptive simulations to help students overcome abstract conceptual barriers. Energy-related topics (8 studies), including renewable energy and thermodynamics, were increasingly linked to sustainability issues, making them fertile ground for AI-powered simulations. Studies focusing on waves and optics (6 studies) and modern physics/quantum concepts (5 studies) used AI largely for visualization and virtual experimentation. Less attention was given to environmental physics and climate-related content (5 studies), although this represents a promising link between AI-enhanced pedagogy and the sustainability agenda.

ESD-related dimensions highlighted

The integration of ESD elements varied in depth across the reviewed literature. Critical thinking and problem-solving was the most prominent competency, cited in 20 studies, particularly where AI was used to foster inquiry-based approaches or adaptive learning pathways. Environmental literacy and sustainability awareness appeared in 12 studies, usually connected to physics content related to energy, climate, or environmental systems. Social responsibility and collaboration was emphasized in 8 studies, often involving AI tools that enabled group-based problem solving or collaborative experiments in virtual labs. Finally, ethical reasoning and digital citizenship was explicitly addressed in only 5 studies, typically in discussions of the responsible use of AI in education, algorithmic bias, and data privacy. This imbalance suggests that while AI has clear potential to support ESD, most current applications still prioritize cognitive outcomes over broader socio-ethical dimensions.

Research methodologies applied

The reviewed 48 studies employed diverse research methodologies, reflecting both the exploratory nature of AI applications in education and the need to evaluate their pedagogical impact. Quantitative approaches were the most common, adopted in 21 studies. These typically involved quasi-experimental or pre-test/post-test designs to measure learning gains, motivation, or problem-solving performance after the use of AI-powered tools such as intelligent tutoring systems or adaptive simulations. Many of these studies reported statistically significant improvements in student outcomes, supporting the argument that AI can enhance the teaching and learning of physics when compared with traditional methods.

Qualitative methodologies were employed in 9 studies, often through interviews, classroom observations, and content analysis of student reflections. These approaches provided rich insights into how learners and teachers perceived AI in physics classrooms, particularly in terms of usability, ethical concerns, and alignment with sustainability values. A subset of these qualitative studies highlighted the importance of contextual factors such as school infrastructure and teacher readiness, which strongly influence the success of AI adoption.

Mixed-methods designs were found in 12 studies, combining surveys, experimental data, and qualitative feedback to obtain a more comprehensive understanding of AI's role in physics education. Mixed-methods were particularly effective in studies linking AI to ESD, as they allowed researchers to capture not only learning gains but also shifts in attitudes, awareness, and collaborative skills. In addition, design-based research (DBR) frameworks were reported in 3 studies, typically involving iterative cycles of designing, testing, and refining AI-supported physics learning environments. These DBR studies emphasized co-design with teachers and offered practical design principles for sustainable AI integration.

Table 3. Distribution of studies by AI type, physics area, and ESD dimension

Category	Sub-category	Number of Studies (n=48)
Methodologies	Quantitative	21
	Qualitative	9
	Mixed-methods	12
	Design-Based Research (DBR)	3
	Experimental (subset)	18
	Case studies	3
Target Population	High school students	26
	Undergraduate students	15
	Teachers	7

In terms of target populations, the majority of studies (26) were conducted with high school students, reflecting the importance of introducing both physics concepts and sustainability awareness at this educational stage. Undergraduate students formed the second largest group (15 studies), particularly in physics majors or teacher education programs, where AI was used to deepen conceptual understanding or to prepare future educators. A smaller number of studies (7) focused on teachers, either examining their self-efficacy in integrating AI tools or exploring professional development interventions. The limited attention to teachers highlights a research gap, as successful AI integration into physics education depends significantly on teachers' digital competence and pedagogical adaptation.

Overall, the methodological diversity of the reviewed studies demonstrates the field's multidimensional nature. While quantitative studies dominate, the combination of mixed-methods and design-based approaches is gradually expanding the knowledge base, linking empirical evidence with design insights. However, more longitudinal and large-scale studies remain necessary to assess the long-term effects of AI-enhanced physics education on both cognitive and sustainability-related competencies.

Key findings

The synthesis of the 48 reviewed studies highlights clear evidence that Artificial Intelligence (AI) has a significant and multifaceted impact on physics learning outcomes. Student motivation and engagement emerged as one of the strongest effects, reported in 19 studies. Learners consistently demonstrated higher levels of curiosity and persistence when interacting with AI-powered tools such as intelligent tutoring systems, chatbots, or adaptive simulations. The ability of AI to provide instant feedback and personalized pathways was particularly effective in reducing anxiety and fostering a sense of achievement.

In terms of academic performance and conceptual achievement, 22 studies found measurable improvements when AI was integrated into physics education. Students who engaged with AI-driven simulations, automated problem solvers, or machine learning tools for data analysis outperformed peers in traditional classrooms on standardized assessments and problem-solving tasks. The adaptive scaffolding provided by AI systems enabled students to work at their own pace, bridging gaps in understanding and addressing misconceptions more effectively than conventional instruction.

Table 4. Summary of physics learning outcomes and ESD competencies identified in the reviewed studies

Dimension	Sub-category / Effect	Number of Studies (n=48)
Physics Learning Outcomes	Motivation & engagement	19
	Academic achievement & conceptual gains	22
	Personalization of learning	15
	Critical thinking & problem-solving	17
ESD Competencies	Sustainability awareness	14
	Environmental responsibility	10
	Systems thinking	9
	Ethical decision-making	6

Personalization of learning was another key benefit observed in 15 studies. AI systems tailored tasks, hints, and examples according to each learner's progress, making physics education more inclusive. This was especially impactful in diverse classrooms, where students had varying levels of prior knowledge. Similarly, critical thinking and higher-order problem-solving skills were strengthened in 17 studies. AI-powered environments encouraged inquiry-based learning, challenged students with open-ended tasks, and supported collaborative problem-solving, which are all essential competencies in modern physics education.

Beyond immediate learning outcomes, AI-supported physics education contributed meaningfully to Education for Sustainable Development (ESD) competencies. Sustainability awareness was enhanced in 14 studies, particularly in contexts where AI simulations involved renewable energy, climate systems, or environmental physics. These applications made abstract sustainability concepts more tangible and relevant to learners. Environmental responsibility was explicitly emphasized in 10 studies, where AI-supported projects encouraged learners to consider the ecological impacts of energy use or technological innovation. Systems thinking was fostered in 9 studies through AI-driven modeling of complex physical and environmental systems, helping students to understand interdependencies between physics concepts and sustainability challenges. Finally, ethical decision-making appeared in 6 studies, where discussions of AI use itself such as algorithmic bias, data privacy, and the ethical use of simulations—were incorporated into physics lessons, thus linking digital ethics with sustainability education.

Taken together, these findings demonstrate that AI in physics education not only enhances traditional learning outcomes but also broadens the scope of education toward competencies aligned with sustainable development. However, the balance is uneven: while motivation, achievement, and critical thinking are widely documented, fewer studies have addressed the deeper socio-ethical and environmental dimensions of ESD, leaving room for further research in these underexplored areas.

Identified research gaps

Despite the promising contributions of AI to physics education within the framework of Education for Sustainable Development (ESD), the review identified several persistent gaps. The most notable is that AI applications often prioritize technical performance over explicit integration with ESD competencies. Out of the 48 studies, the majority focused on evaluating the accuracy, adaptability, or efficiency of AI systems in supporting physics learning, while only a minority explicitly linked these innovations to sustainability outcomes such as environmental literacy or ethical reasoning. This suggests that AI is frequently treated as a technological enhancement rather than as a transformative tool for advancing sustainable education.

Table 5. Future research directions for AI-enhanced physics education within ESD

Research Gap	Description
Overemphasis on technical performance	Focus on AI efficiency or adaptability rather than ESD outcomes
Lack of socio-cultural or affective focus	Minimal exploration of values, empathy, collaboration, or ethics
Limited longitudinal studies	Short-term experiments dominate; few long-term investigations
Lack of real classroom implementations	Studies mostly in controlled or pilot settings, not in authentic classrooms

A second major gap lies in the limited attention to affective and socio-cultural aspects of sustainability. While motivation and critical thinking were addressed in many studies, dimensions such as empathy, social justice, and community engagement which are central to ESD were rarely explored. Only a handful of studies investigated how AI-supported learning environments influence students' values, attitudes, or collaborative practices in ways that contribute to sustainability. This narrow focus risks underestimating the broader role of physics education in preparing learners to become responsible global citizens.

Furthermore, the review highlighted the scarcity of longitudinal studies and real classroom implementations. Most of the reviewed research was short-term and experimental in nature, conducted under controlled settings with small sample sizes. Very few studies tracked the long-term impact of AI integration on students' sustained engagement with sustainability issues or examined how AI could be embedded into everyday classroom practices at scale. Without longitudinal and classroom-based evidence, the potential of AI to systematically support ESD through physics education remains under-validated.

Overall, these gaps reveal a critical need for future research to move beyond technical optimization and to embrace more holistic, context-rich investigations. Addressing socio-cultural aspects, embedding AI interventions into real classrooms, and conducting long-term studies will be essential for realizing the full potential of AI as a catalyst for sustainable physics education.

Thematic synthesis

The synthesis of the reviewed literature revealed four dominant clusters that characterize how Artificial Intelligence (AI) is being applied in physics education with links to Education for Sustainable Development (ESD). These clusters represent both the educational opportunities provided by AI technologies and the broader challenges of embedding them into sustainable pedagogy.

Table 6. Four dominant clusters of Artificial Intelligence (AI) characteristics

Thematic Cluster	Number of Studies (n=48)	Key Focus Areas
AI for personalized physics learning with ESD orientation	15	Adaptive tutoring, machine learning for personalization, sustainability problem sets
AI for virtual labs and simulations on energy or environment	12	Renewable energy, climate models, safe and accessible virtual experimentation
AI as a tool to foster sustainability awareness and literacy	11	NLP for reflections, ML for decision-making, systems thinking, environmental literacy
Challenges and ethical issues of AI use in physics classrooms	10	Algorithmic bias, privacy, teacher mediation, sustainable use of technology

The first cluster concerns AI for personalized physics learning with an ESD orientation. Fifteen studies in this category focused on adaptive learning systems, intelligent tutoring platforms, and machine learning models that tailored physics content to individual learners' needs. Personalization enabled students to progress at their own pace, receive immediate feedback, and engage with tasks that were aligned to their performance level.

Importantly, several of these studies extended personalization beyond academic support to include sustainability contexts, such as energy use or climate-related problem sets, thereby embedding ESD competencies into core physics learning.

The second cluster highlights AI-driven virtual laboratories and simulations. Twelve studies demonstrated how AI-supported simulations allowed students to experiment with complex physical systems, including renewable energy technologies, climate models, and environmental processes. These virtual labs reduced barriers to experimentation by overcoming constraints of cost, safety, and accessibility. For instance, AI-powered simulations of solar and wind energy systems helped students explore the physics of renewable energy while simultaneously building awareness of sustainable technologies. This cluster is particularly relevant to ESD, as it connects theoretical physics concepts with practical sustainability challenges.

The third cluster identifies AI as a tool for fostering sustainability awareness and literacy. Eleven studies explicitly designed AI applications to enhance learners' understanding of sustainability issues within physics contexts. For example, natural language processing tools were used to analyze student reflections on environmental topics, while machine learning models helped evaluate patterns in decision-making related to resource consumption. These approaches promoted higher-order thinking and systems understanding, which are critical for developing ESD-related competencies such as environmental literacy and responsible citizenship.

The final cluster revolves around challenges and ethical issues of AI use in physics classrooms. Ten studies raised concerns about algorithmic bias, data privacy, and the ethical dimensions of relying on AI in education. Some highlighted the risk of over-dependence on technology, while others stressed the importance of teacher mediation to balance AI-driven personalization with human judgment. A recurring theme was that although AI can enhance engagement and outcomes, its deployment must be accompanied by critical discussions about ethics, equity, and the sustainable use of digital technologies in education.

Together, these clusters demonstrate that AI has the potential not only to enhance physics learning outcomes but also to contribute to the broader objectives of sustainable development. At the same time, they underscore the need for careful, ethically grounded implementation that aligns technological innovation with the humanistic values at the core of ESD.

Discussion

The findings of this review clearly indicate that Artificial Intelligence (AI) integration in physics education has shown strong positive impacts on student learning outcomes while also opening pathways to embed sustainability competencies. Several studies emphasize how intelligent tutoring systems, machine learning models, and adaptive simulations significantly enhance motivation, engagement, and conceptual mastery in physics classrooms (Roll & Wylie, 2016; Malik et al., 2018; Ahmad et al., 2021; Ahmad et al., 2022; Ding et al., 2023; Almasri, 2024). The personalization features of AI not only improve inclusivity by addressing students' diverse prior knowledge levels but also provide instant feedback that boosts persistence in problem-solving (Murphy, 2019; Mousavinasab et al., 2021; Kim & Kim, 2022; Qawaqneh et al., 2023). This is in line with the broader literature showing that AI can create learner-centered environments and expand access to quality resources (Gadanidis, 2017; González-Calatayud et al., 2021; Alam, 2022; Jia et al., 2024).

Beyond cognitive achievement, AI applications have demonstrated potential in advancing Education for Sustainable Development (ESD). Studies reveal that AI-powered virtual laboratories and simulations help students connect physics concepts with sustainability issues, particularly in renewable energy, climate modeling, and environmental systems (Irrgang et al., 2021; Xiouras et al., 2022; Kaack et al., 2022; Jia et al., 2024; Annida et al., 2025). Through these simulations, abstract concepts such as solar energy efficiency, wind dynamics, or climate-related feedback loops become more tangible, fostering environmental literacy and systems thinking (Jauhariyah et al., 2021; Kamalov et al., 2023; Adeuji & Shiitu, 2023). In addition, AI-based tools have been found to nurture critical competencies such as creativity, collaboration, and ethical reasoning dimensions central to sustainable education (Roll & Wylie, 2016; Gadanidis, 2017; Salas-Pilco et al., 2022; Yan et al., 2024).

Nevertheless, this review highlights significant imbalances in the way AI is being integrated with sustainability-oriented education. A large proportion of studies still concentrate on technical optimization such as algorithmic accuracy, adaptability, or performance rather than explicitly embedding ESD-related outcomes like social responsibility or ethical decision-making (Li & Du, 2017; Derkinderen & De Raedt, 2020; Kühl et al., 2022; Angelis et al., 2023). Only a limited number of studies explicitly discuss how AI interventions foster empathy, equity, or community engagement (Ahmad et al., 2021; Cope et al., 2021; Kamalov et al., 2023). This reveals a gap in current research, as physics education is not only about cognitive mastery but also about shaping responsible citizens aware of sustainability challenges (Kaack et al., 2022; Zador et al., 2023).

Another concern relates to the methodological limitations of the reviewed studies. The dominance of short-term, experimental, and pilot-based designs restricts the ability to generalize findings and assess long-term impacts (Holmes, 2020; Doroudi, 2023; Almasri, 2024). Very few studies incorporated longitudinal approaches or examined AI's integration in authentic classroom contexts, making it difficult to determine whether sustainability-related gains are sustained over time (Stone et al., 2022; Jia et al., 2024). Moreover, the relatively low focus on teacher readiness and digital competence represents a major challenge, as successful AI adoption in education relies heavily on the pedagogical adaptation and professional development of educators (Murphy, 2019; Ahmad et al., 2022; Salas-Pilco et al., 2022). Addressing these gaps is crucial if AI is to be positioned as a transformative force in physics education aligned with sustainable development goals.

Taken together, the reviewed literature suggests that while AI has already proven effective in enhancing traditional learning outcomes in physics, its transformative role in embedding sustainability remains underutilized. To move forward, future research should adopt a more holistic approach by linking AI innovations not only to cognitive development but also to socio-cultural, ethical, and affective aspects of learning (Kamalov et al., 2023; Yan et al., 2024). This includes designing AI-driven environments that explicitly integrate sustainability contexts, conducting longitudinal classroom studies, and prioritizing teacher professional development (Jauhariyah et al., 2021; Kaack et al., 2022; Adeuji & Shiitu, 2023). By bridging the current gaps, AI can be fully harnessed as a catalyst for a physics education that equips learners with both scientific competence and sustainability awareness, thereby fulfilling the vision of Education for Sustainable Development.

CONCLUSION

Fundamental Finding: This review confirms that AI positively impacts physics education by improving student motivation, achievement, personalized learning, and problem-solving. AI also shows potential to advance Education for Sustainable Development (ESD) through simulations and adaptive environments, though contributions to socio-ethical competencies remain limited as most studies focus on cognitive outcomes. **Implication:** AI should be seen not only as a tool for technical efficiency but also as a medium to embed sustainability in physics curricula. Educators are encouraged to design AI-supported environments that foster environmental literacy, collaboration, and ethical reasoning, while policymakers must provide infrastructure, teacher training, and ethical guidelines. **Limitation:** The review is constrained to English-language publications from 2015–2025 and varies in methodological rigor, potentially overlooking innovative practices in grey literature or non-English sources. **Future Research:** Further studies should move beyond technical optimization to address socio-cultural, ethical, and affective aspects of AI in education. Longitudinal classroom implementations and teacher-focused research are crucial to ensure sustainable and effective AI integration.

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AUTHOR CONTRIBUTIONS

Hanan Zaki Alhusni was responsible for methodology development, data extraction and analysis, sourcing references, and drafting the manuscript. **Binar Kurnia Prahani** contributed to the conceptual framework, research design, and validation process. **Titin Sunarti** provided critical input on methodology and supported the drafting and revision of the manuscript. **Madlazim** contributed to data interpretation and provided academic supervision. **Riski Ramadani** assisted with data collection, literature review, and preparation of supporting materials. **Muhammad Rey Dafa Ahmadi** contributed to formatting, editing, and ensuring consistency of references.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest, financial or personal, that could have influenced the content or outcomes of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript adheres to established research and publication ethics. The authors affirm that the study is original, conducted with academic integrity, and entirely free from unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors confirm that no AI-based or digital writing tools were employed in the preparation of this manuscript. All stages of the research, analysis, and writing were carried out manually by the authors to ensure originality, academic rigor, and full compliance with ethical standards.

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