Sarcouncil Journal of Education and Sociology

ISSN(Online): 2945-3542

Volume- 05| Issue- 09| 2026

Review Article

Received: 05-08-2026 | **Accepted:** 30-08-2026 | **Published:** 15-09-2026

Human–AI Collaboration in Physics Learning: A Systematic Literature Review of Emerging Pedagogical Models

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Abstract: Artificial intelligence (AI) is increasingly transforming educational practices, including the teaching and learning of physics. However, the educational significance of AI depends not only on its technological capabilities but also on how effectively it collaborates with students and teachers within pedagogically meaningful learning environments. This systematic literature review examines the development of human–AI collaboration in physics learning and identifies emerging pedagogical models reported in the literature. Following the PRISMA 2020 framework, relevant studies were systematically identified, screened, assessed for eligibility, and synthesized according to their AI applications, human roles, physics learning activities, learning outcomes, and reported challenges. The synthesis identified four major pedagogical models: AI as an intelligent tutor, AI as a cognitive partner, AI as a feedback assistant, and teacher-mediated human–AI collaboration. The findings indicate that AI can support conceptual understanding, physics problem solving, critical thinking, self-regulated learning, scientific reasoning, and learner engagement. However, the educational benefits of AI are strongly influenced by the degree of student participation and teacher mediation. The review also identifies persistent challenges involving inaccurate AI-generated content, student overreliance, limited AI literacy, assessment integrity, teacher preparedness, privacy, and unequal access. Overall, the findings support a human-centered approach in which AI augments rather than replaces human reasoning. Students should remain active evaluators and decision-makers, while teachers retain responsibility for pedagogical design, disciplinary validation, and responsible AI use. The review provides a conceptual basis for developing emerging human–AI pedagogical models that promote meaningful, critical, and responsible physics learning.

Keywords: Artificial intelligence; human–AI collaboration; physics education; generative AI; pedagogical models; systematic literature review; AI-supported learning.

INTRODUCTION

Artificial intelligence (AI) has rapidly moved from a specialized technological domain into an increasingly influential component of contemporary education. The emergence of intelligent tutoring systems, adaptive learning platforms, automated feedback, conversational agents, and generative AI has expanded the ways in which students and teachers can access, produce, and evaluate educational resources. In particular, generative AI systems based on large language models have introduced new possibilities for interactive learning because they can respond to questions, generate explanations, provide examples, support problem-solving, and produce individualized feedback. This development has encouraged researchers to reconsider the traditional relationship between learners, teachers, and educational technologies. Rather than viewing AI merely as a digital tool that automates instructional tasks, recent scholarship increasingly emphasizes the importance of understanding how humans and AI can work together to support meaningful learning processes (Almasri, 2024; Liang *et al*., 2026).

The relevance of this transformation is particularly evident in physics education. Physics learning requires students to coordinate mathematical reasoning, conceptual understanding, visualization, experimentation, modeling, and problem-solving. Many physics problems also require learners to move between representations, interpret physical phenomena, construct explanations, and evaluate whether a proposed solution is scientifically reasonable. AI-based systems can potentially support these processes by providing interactive explanations, generating alternative solution pathways, offering immediate feedback, and adapting learning support to students' needs. Recent evidence indicates that AI applications in physics have been concentrated in areas such as mechanics, thermodynamics, and modern physics, while common implementations include conversational tutoring, automated feedback, and personalization (Roziqin *et al*., 2026). These developments suggest that AI may become an important component of physics learning environments, but its educational value depends substantially on how it is pedagogically integrated.

Importantly, the increasing availability of AI does not automatically imply improved learning. Physics learning involves disciplinary practices that require students to reason about evidence,

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DOI-https://doi.org/10.5281/zenodo.22774172

construct explanations, interpret mathematical relationships, and critically evaluate solutions. If learners simply accept AI-generated answers without examining the underlying reasoning, AI may reduce opportunities for independent thinking rather than strengthen them. Recent research has documented concerns regarding inaccurate AI responses, student overreliance, insufficient AI literacy, and the possibility that AI-supported learning may remain focused on short-term performance rather than deeper disciplinary reasoning (Roziqin *et al*., 2026). Similarly, empirical research on generative AI in physics education has found substantial variation in the accuracy of AI-generated solutions, while tutoring-oriented applications appear more promising than simply using AI as an answer-generating problem solver (Moundridou *et al*., 2026). These findings make the distinction between AI-assisted learning and human–AI collaborative learning particularly important.

The concept of human–AI collaboration offers a potentially more productive perspective for addressing these concerns. In a collaborative learning arrangement, AI is not positioned as a replacement for the learner or teacher but as an interactive partner that can provide cognitive and instructional support while humans retain responsibility for interpretation, decision-making, and evaluation. Recent research on GenAI in education suggests that the effectiveness of AI-supported learning is influenced by the interaction between human control and AI automation, indicating that different forms of human–AI interaction may produce different educational outcomes (Liang *et al*., 2026). From this perspective, the critical question is no longer simply whether AI can solve physics problems or generate explanations, but how students and teachers can use AI strategically while maintaining human agency and disciplinary judgment.

Such collaboration may also be connected to self-regulated learning. Effective physics learning requires students to establish learning goals, select strategies, monitor their understanding, identify errors, and reflect on the quality of their solutions. GenAI can potentially contribute to these processes by helping students formulate learning objectives, search for and organize information, generate problem-solving strategies, receive feedback, and conduct self-assessment. A recent systematic review of GenAI and self-regulated learning identified several pedagogical affordances across the forethought, performance, and self-reflection phases of learning, suggesting that AI can potentially support students across multiple stages of the learning cycle (Xia *et al*., 2025). However, such benefits depend on students' capacity to critically evaluate AI-generated information rather than treating AI responses as inherently authoritative.

The teacher's role is consequently also changing. In AI-supported physics classrooms, teachers may increasingly function not only as providers of explanations but also as designers of learning environments, facilitators of human–AI interaction, evaluators of AI-generated content, and guides for students' critical use of AI. This shift requires teachers to possess more than technical knowledge about AI tools. They need pedagogical judgment concerning when AI should be used, what tasks should remain human-led, how students should verify AI-generated explanations, and how AI can be integrated without weakening students' independent reasoning. Research on AI literacy and teacher education similarly emphasizes that effective AI integration requires a combination of theoretical knowledge, practical competence, and professional judgment rather than simple technological familiarity (Mishra *et al*., 2024). Thus, emerging pedagogical models need to consider both the capabilities of AI systems and the professional responsibilities of teachers.

Despite the rapid expansion of research, the literature on AI-supported physics education remains fragmented. Existing reviews have examined broad AI applications, technological trends, educational benefits, challenges, and specific contexts such as secondary-school physics or generative AI. However, these studies tend to categorize AI according to the technology used or the instructional function it performs rather than systematically examining emerging models of collaboration among students, teachers, and AI. Recent reviews also indicate that much of the current evidence remains concentrated on university-level contexts, short-term learning outcomes, and tool-centered evaluations, while theory-driven pedagogical integration remains comparatively underdeveloped (Moundridou *et al*., 2026; Roziqin *et al*., 2026). Furthermore, broader educational research has begun to examine human–AI interaction, but its implications for the specific epistemic and pedagogical demands of physics learning have not yet been sufficiently synthesized.

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Therefore, this systematic literature review aims to examine how human–AI collaboration is conceptualized and implemented in physics learning and to identify the emerging pedagogical models that characterize this relationship. Specifically, the review seeks to synthesize the roles assigned to AI, students, and teachers; identify the physics learning activities and competencies supported through human–AI collaboration; examine reported learning outcomes and pedagogical benefits; identify challenges and risks associated with AI-supported physics learning; and map the theoretical and instructional approaches underlying existing models. By shifting the analytical focus from AI as a technological tool to human–AI collaboration as a pedagogical relationship, this review is expected to provide a more nuanced understanding of how AI can be integrated into physics education while preserving student agency, teacher expertise, critical reasoning, and the epistemic practices central to learning physics.

LITERATURE REVIEW

Human–AI Collaboration in Education

Human–AI collaboration refers to educational arrangements in which artificial intelligence and human participants contribute complementary capabilities to the learning process. In this perspective, AI is not conceptualized as an autonomous replacement for teachers or students but as a technological partner that can provide information, generate alternatives, offer feedback, or support decision-making, while humans retain responsibility for interpretation, judgment, and learning decisions. This distinction is important because educational value does not necessarily arise from the presence of AI itself but from how its capabilities are incorporated into pedagogical activities. Qian (2025), for example, identified a growing shift from viewing generative AI primarily as an efficiency-oriented technology toward using it to support creativity, critical thinking, learner autonomy, and other dimensions of learning. However, the same review highlights the risk that excessive dependence on AI may result in the outsourcing of cognitive and metacognitive processes.

From a pedagogical perspective, effective human–AI collaboration therefore requires an appropriate distribution of responsibilities. AI may be particularly effective at rapidly generating information, examples, explanations, and alternative solutions, whereas students contribute contextual interpretation, disciplinary reasoning, prior knowledge, and critical evaluation. Teachers contribute another layer of expertise by designing learning tasks, monitoring student progress, evaluating the quality of AI-supported learning, and establishing appropriate boundaries for AI use. This division of responsibilities suggests that human–AI collaboration should be understood as a socio-pedagogical process, rather than simply as the use of an AI application during instruction. Such an interpretation is consistent with emerging research emphasizing the importance of pedagogical scaffolding and instructional guidance when students use generative AI for learning (Liu & Zhong, 2025).

Artificial Intelligence in Physics Education

Physics education provides a particularly relevant context for examining human–AI collaboration because physics learning combines conceptual, mathematical, visual, and experimental forms of reasoning (Panjaitan *et al*., 2025). AI systems can support learners in interpreting complex concepts, generating explanations at different levels of difficulty, solving quantitative problems, analyzing experimental situations, and receiving immediate feedback. Recent empirical reviews indicate that generative AI has already been applied to physics learning through functions such as problem solving, tutoring, conceptual explanation, formative assessment, and instructional assistance. Nevertheless, the evidence remains heterogeneous, and researchers have emphasized the need for human supervision and critical evaluation because AI-generated physics explanations and solutions may contain inaccuracies. (Moundridou *et al*., 2026).

The use of AI in physics should therefore be distinguished from the broader question of whether AI can perform physics-related tasks. A system may successfully calculate an answer without necessarily supporting conceptual understanding. Similarly, an AI-generated explanation may appear scientifically plausible while containing an incorrect assumption or incomplete reasoning. Consequently, the pedagogical value of AI depends on whether learners are encouraged to interrogate, verify, compare, and revise AI-generated outputs. This creates an important opportunity for physics education because the process of evaluating an AI response can itself become a learning activity in which students engage in scientific reasoning and evidence-based judgment.

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Pedagogical Roles of AI in Learning

The pedagogical role assigned to AI represents an important dimension of human–AI collaboration. Rather than functioning as a single type of technology, AI can occupy multiple roles within learning environments. It may function as a tutor, providing explanations and hints; as a problem-solving assistant, helping students explore solution procedures; as a feedback provider, identifying potential weaknesses in student work; as a content generator, producing examples, questions, or learning materials; or as a metacognitive partner, encouraging students to reflect on their reasoning. These roles imply different levels of interaction and different responsibilities for students and teachers.

Recent systematic reviews suggest that pedagogical applications of generative AI are increasingly moving toward learning designs that emphasize autonomy, critical thinking, creativity, and interaction rather than simple content generation. Qian (2025) argues that future educational research needs to examine multimodal applications and student–teacher–AI collaboration more explicitly. Similarly, research examining GenAI-supported student learning from a TPACK perspective indicates that pedagogical scaffolding is essential because the effectiveness of AI depends on the relationship between technological capabilities, content, pedagogy, and instructional design (Liu & Zhong, 2025).

Student Agency, Critical Thinking, and Self-Regulated Learning

Human–AI collaboration also raises important questions concerning student agency. Learning with AI requires students to make decisions about when to seek AI assistance, how to formulate effective prompts, how to interpret AI responses, and whether generated information is sufficiently accurate to be accepted. Consequently, AI literacy extends beyond knowing how to operate an AI tool. Students need the ability to critically evaluate AI outputs and understand the limitations of AI-generated information. Long and Magerko (2020) conceptualize AI literacy as involving competencies that enable individuals to understand, evaluate, communicate with, and use AI appropriately. This perspective is particularly relevant to physics because students must be able to distinguish between an apparently convincing answer and a scientifically justified explanation.

Student agency is closely related to self-regulated learning. Rather than allowing AI to perform the entire cognitive process, students can use AI selectively during different stages of learning—for example, to generate alternative explanations during preparation, obtain hints during problem solving, and evaluate their reasoning during reflection. However, such use requires explicit pedagogical guidance. Research on GenAI and student learning indicates that the effectiveness of AI-supported learning is influenced by instructional design, and weaknesses such as short intervention periods and insufficient pedagogical scaffolding remain common in the literature (Liu & Zhong, 2025). Thus, productive human–AI collaboration requires students to remain active decision-makers rather than passive recipients of AI-generated answers.

Teacher–AI Collaboration and Professional Judgment

The teacher remains a central participant in AI-supported learning. Human–AI collaboration should not be interpreted as a process in which AI progressively replaces teacher expertise. Instead, teachers may assume new responsibilities as designers, facilitators, evaluators, and ethical guides. They may determine which physics tasks are appropriate for AI support, design activities requiring students to verify AI-generated solutions, identify inaccuracies in AI responses, and ensure that technology use remains aligned with curriculum objectives. This expanded role requires teachers to develop both technological knowledge and professional judgment.

Mishra *et al*. (2024) demonstrate that AI literacy in teacher education cannot be reduced to technical knowledge (Panjaitan *et al*., 2026). Their review emphasizes the importance of theoretical knowledge, practical competence, and professional judgment in understanding how AI should be incorporated into teaching. The authors also identify a need for greater attention to teachers' practical and ethical knowledge in authentic educational contexts. These considerations are particularly important in physics education, where teachers must evaluate not only the linguistic quality of AI responses but also their scientific accuracy, mathematical validity, and consistency with established physical principles.

Emerging Pedagogical Models of Human–AI Collaboration

The literature suggests that human–AI collaboration can be organized through several emerging pedagogical models. One model positions AI as an adaptive tutor, in which students

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interact with AI to obtain explanations, hints, and feedback while the teacher monitors the broader learning process. A second model treats AI as a cognitive partner, where students compare their own reasoning with AI-generated solutions and identify agreements, contradictions, or errors. A third model positions AI as a learning-resource generator, with students and teachers using AI to create questions, examples, simulations, or alternative representations that are subsequently evaluated by humans. A fourth model involves teacher-mediated AI integration, in which teachers deliberately structure when and how students interact with AI and establish criteria for evaluating AI-generated content.

These models suggest that the quality of human–AI collaboration depends less on the sophistication of the AI system alone and more on the pedagogical structure surrounding its use. Recent reviews in education indicate that generative AI can support cognitive, affective, and behavioral learning outcomes, but they also identify limitations related to research design, intervention duration, and insufficient instructional scaffolding (Liu & Zhong, 2025). In physics education specifically, recent systematic evidence emphasizes human supervision, critical evaluation, and attention to accuracy and equity as important conditions for effective implementation (Moundridou *et al*., 2026).

METHODOLOGY

Research Design

This study employed a Systematic Literature Review (SLR) to examine the development of human–AI collaboration in physics learning and to identify emerging pedagogical models reported in the existing literature. The review was designed to synthesize empirical and scholarly evidence concerning the roles of artificial intelligence, students, and teachers in physics learning environments. Rather than focusing on a particular AI platform, the review examined how AI technologies are incorporated into pedagogical processes, including conceptual learning, problem solving, experimentation, feedback, assessment, and self-regulated learning. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework to promote transparency in the identification, screening, selection, and synthesis of relevant studies (Page *et al*., 2021).

Research Questions

The review was guided by five research questions. First, how has human–AI collaboration been implemented in physics learning? Second, what pedagogical roles are assigned to AI, students, and teachers in physics learning environments? Third, what physics learning activities and competencies are supported through human–AI collaboration? Fourth, what learning outcomes and pedagogical benefits have been reported? Finally, what challenges, limitations, ethical concerns, and emerging pedagogical models characterize human–AI collaboration in physics education? These questions were formulated to move beyond a simple inventory of AI technologies and instead examine the pedagogical relationships and instructional structures through which AI is integrated into physics learning.

Search Strategy and Information Sources

A systematic search was conducted across major academic databases relevant to education, educational technology, and science education research. The planned databases included Scopus, Web of Science, ERIC, ScienceDirect, and Google Scholar to provide broad coverage of international publications. The search strategy combined keywords related to artificial intelligence, human–AI interaction, physics education, and pedagogy. Search terms included combinations such as "artificial intelligence" AND "physics education," "generative AI" AND "physics learning," "human–AI collaboration" AND "physics," "AI-assisted learning" AND "physics," "AI tutor" AND "physics education," and "ChatGPT" AND "physics learning." Boolean operators were used to combine related concepts and broaden or narrow the search where appropriate. The search was designed to capture studies examining both conventional AI applications and emerging generative AI technologies.

Eligibility Criteria

Studies were considered eligible when they met several predefined criteria. First, the study had to address physics learning, physics education, or physics teaching as a primary educational context. Second, the study needed to involve an artificial intelligence technology or AI-enabled system that played a role in teaching, learning, assessment, feedback, problem solving, tutoring, or another educational activity. Third, studies were prioritized when they provided evidence concerning interactions among AI and human participants, particularly students and/or teachers. Fourth, only publications written in English and available as

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full-text scholarly publications were considered. Studies published within the selected review period were included to capture the rapid development of contemporary AI, particularly generative AI, in physics education. Publications were excluded when they focused exclusively on AI development without an educational component, addressed artificial intelligence in disciplines unrelated to physics, were opinion pieces without sufficient scholarly evidence, or did not provide information relevant to the research questions.

Study Selection Procedure

The study selection process consisted of several stages. First, all records identified through the database searches were compiled and duplicate publications were removed. Second, the titles and abstracts were screened against the predetermined inclusion and exclusion criteria. Studies that clearly addressed AI-supported physics education were retained for further examination, whereas publications that were unrelated to the research focus were excluded. Third, potentially relevant studies were subjected to full-text assessment to determine whether they provided sufficient evidence concerning human–AI interaction, pedagogical implementation, or learning outcomes in physics education. The final group of studies constituted the evidence base for the systematic synthesis. The selection process was documented using a PRISMA flow diagram showing the numbers of records identified, screened, excluded, assessed for eligibility, and ultimately included in the review (Page *et al*., 2021).

Data Extraction

Data were extracted systematically from each included study using a structured extraction framework. The extracted information included publication year, authors, country or educational context, educational level, physics topic, AI technology or application, participants, research design, pedagogical purpose, role of AI, role of students, role of teachers, learning activity, reported learning outcomes, and implementation challenges. Particular attention was given to evidence describing the distribution of responsibilities between humans and AI. For example, studies were examined to determine whether AI functioned primarily as a tutor, feedback provider, problem-solving assistant, content generator, assessment tool, simulation support system, or metacognitive partner. This extraction strategy enabled the review to compare studies according to their pedagogical rather than purely technological characteristics.

Quality Assessment

The methodological quality of the included studies was assessed before synthesis. The assessment considered the clarity of the research objectives, appropriateness of the research design, description of participants and learning context, transparency of data collection procedures, appropriateness of data analysis, and clarity of reported findings. Particular attention was given to whether studies provided sufficient information to establish the relationship between AI use and reported educational outcomes. Studies with substantial methodological limitations were not necessarily excluded automatically, but their limitations were considered when interpreting the evidence. This approach was adopted because the literature on AI in physics education includes different research designs, making a single statistical quality criterion inappropriate for all types of evidence.

Data Synthesis and Analysis

Because the selected studies were expected to differ considerably in research design, educational level, AI technology, physics topic, and outcome measures, the findings were synthesized primarily through qualitative thematic analysis and descriptive evidence mapping rather than statistical meta-analysis. The analysis involved identifying recurring patterns across studies and grouping them into major categories related to AI roles, human roles, learning activities, pedagogical strategies, learning outcomes, and challenges. Particular attention was given to the emergence of different forms of human–AI collaboration, such as AI as tutor, AI as cognitive partner, AI as feedback provider, AI as problem-solving assistant, and teacher-mediated AI learning. Relationships between pedagogical models and reported outcomes were subsequently compared to identify common patterns, differences, and gaps in the literature.

Development of the Human–AI Collaboration Framework

The final stage of the analysis involved developing a conceptual framework representing emerging pedagogical models of human–AI collaboration in physics learning. The framework was derived inductively from patterns identified across the included studies. Five interconnected dimensions were considered: (1) human participants, (2) AI functions, (3) learning activities, (4) interaction and pedagogical processes, and (5) learning

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outcomes. The framework distinguishes between AI-centered approaches, in which AI performs substantial instructional or cognitive functions, and human-centered collaborative approaches, in which AI augments students' and teachers' capabilities while human participants retain responsibility for reasoning, evaluation, and decision-making. The resulting framework provides the basis for interpreting how AI is currently being integrated into physics education and for identifying directions for future pedagogical development.

RESULTS

Overview of the Reviewed Studies

The reviewed literature demonstrates a growing interest in the integration of artificial intelligence into physics learning. The studies examined AI in relation to conceptual learning, problem solving, feedback, assessment, experimentation, and personalized learning. Rather than functioning only as a source of information, AI increasingly appears as an interactive component of the learning process. Across the literature, however, substantial differences were found in how AI was positioned and how much responsibility remained with students and teachers.

The evidence suggests a gradual transition from AI-assisted instruction toward human–AI collaboration. Earlier technology-oriented applications generally emphasized automated support, whereas more recent approaches increasingly involve interaction, dialogue, critical evaluation, and teacher mediation. This development is particularly relevant to physics because learning in the discipline requires students to interpret concepts, evaluate evidence, construct mathematical reasoning, and explain physical phenomena.

Table 1. Characteristics of Human–AI Collaboration in Physics Learning

Dimension	**Main Patterns Identified**
AI technologies	Generative AI, conversational agents, intelligent tutoring systems, adaptive systems, and AI-supported assessment
Physics activities	Conceptual learning, problem solving, experimentation, assessment, and explanation
AI functions	Tutoring, explanation, feedback, content generation, problem-solving support, and data interpretation
Student involvement	Questioning, solving, evaluating, revising, and reflecting
Teacher involvement	Instructional design, supervision, validation, and pedagogical guidance
Main outcomes	Conceptual understanding, problem-solving, critical thinking, autonomy, and engagement

Emerging Human–AI Pedagogical Models

The synthesis identified four major pedagogical models through which human–AI collaboration is currently emerging in physics education: AI as tutor, AI as cognitive partner, AI as feedback assistant, and teacher-mediated human–AI collaboration. Although experimentation and simulation also appear in the literature, they are better understood as learning contexts in which these four models can operate rather than as completely separate collaboration models.

Table 2. Emerging Pedagogical Models

Model	**Role of AI**	**Role of Student**	**Role of Teacher**	**Dominant Purpose**
AI as Tutor	Explains concepts, gives hints, answers questions	Explores and solves	Monitors learning	Conceptual understanding
AI as Cognitive Partner	Generates alternative reasoning or solutions	Critiques and verifies	Facilitates evaluation	Problem solving and critical thinking
AI as Feedback Assistant	Provides feedback and practice tasks	Revises and reflects	Validates feedback	Formative learning
Teacher-Mediated Collaboration	Provides instructional support	Interacts with AI under guidance	Designs and supervises interaction	Meaningful and responsible AI use

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Among these models, the AI-as-tutor model represents the most direct form of AI-supported learning. Students interact with AI to obtain explanations, examples, hints, or clarification. The cognitive-partner model represents a more advanced form of collaboration because students are required to compare AI-generated reasoning with their own solutions and determine whether the AI response is scientifically appropriate. The feedback model emphasizes continuous revision, while teacher-mediated collaboration places greater emphasis on instructional control and responsible use.

The synthesis therefore suggests that the pedagogical sophistication of AI integration increases when students are required to evaluate rather than simply consume AI-generated information.

Roles of Students, Teachers, and AI

A central finding of the review is that human–AI collaboration involves a redistribution of educational responsibilities rather than the replacement of human participants. AI demonstrates strengths in rapid information generation, explanation, response production, and repetitive feedback. Students remain responsible for interpreting information, applying physics concepts, evaluating solutions, and making learning decisions. Teachers provide pedagogical direction, disciplinary validation, and ethical guidance.

Table 3. Distribution of Responsibilities

Participant	Core Responsibilities
AI	Generate explanations, examples, feedback, questions, and alternative solutions
Students	Reason, solve, question, verify, revise, and reflect
Teachers	Design learning activities, monitor AI use, validate content, and provide guidance

This distribution indicates that effective human–AI collaboration is characterized by complementarity. AI contributes capabilities that can extend learning opportunities, while students and teachers retain functions requiring disciplinary judgment and educational decision-making. Consequently, the most promising pedagogical approaches are not those that maximize AI autonomy but those that establish an appropriate balance between automated assistance and human control.

Learning Outcomes and Pedagogical Benefits

The literature reports several potential benefits of AI-supported physics learning. These include improved conceptual understanding, assistance with physics problem solving, more immediate feedback, increased learning autonomy, and greater opportunities for individualized learning. AI can also provide students with repeated explanations and alternative representations, which may be useful when learners encounter difficulties with abstract physics concepts.

However, the benefits appear to depend strongly on the pedagogical design of AI use. AI-generated answers alone do not necessarily promote deeper learning. More meaningful outcomes are reported or anticipated when students are required to explain their reasoning, compare alternative solutions, identify errors, and reflect on AI-generated information.

Table 4. Major Learning Outcomes

Learning Outcome	Contribution of Human–AI Collaboration
Conceptual understanding	AI provides alternative explanations and examples
Problem-solving ability	Students compare and evaluate AI-supported solution strategies
Critical thinking	Students identify and verify AI-generated claims
Self-regulated learning	AI provides immediate support and opportunities for reflection
Learning engagement	Interactive and individualized learning experiences
Scientific reasoning	Students evaluate explanations against physics principles and evidence

Overall, the findings suggest that the student's cognitive activity remains a crucial factor. AI appears to provide the greatest pedagogical value when it stimulates students' reasoning rather than replacing it.

Challenges and Research Gaps

Despite its potential, human–AI collaboration in physics learning presents several challenges. The most prominent concerns involve the accuracy of AI-generated physics explanations and calculations, student overreliance on AI, insufficient AI literacy, difficulties in assessing

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AI-assisted work, and the need for teacher supervision. These challenges are particularly important in physics because an apparently convincing AI response may contain conceptual, mathematical, or scientific errors.

Table 5. Challenges and Research Gaps

Challenge	Research Gap / Future Direction
AI inaccuracies	More studies should examine physics-specific accuracy
Student overreliance	Investigate strategies that preserve independent reasoning
Limited AI literacy	Develop AI-literacy models for physics learners
Teacher preparedness	Examine teacher competencies for AI-mediated physics instruction
Assessment difficulties	Develop assessment approaches compatible with AI-supported learning
Limited empirical evidence	Conduct longer-term and larger-scale studies
Ethical and equity concerns	Examine access, privacy, academic integrity, and responsible use

The synthesis also reveals an important research gap: much of the existing literature focuses on what AI can do, while fewer studies systematically investigate how students, teachers, and AI should share cognitive and pedagogical responsibilities. Evidence concerning long-term learning, classroom implementation, and teacher-mediated collaboration also remains limited. These gaps provide a strong rationale for developing a human-centered framework for AI integration in physics education.

Summary of Findings

Taken together, the findings indicate that human–AI collaboration in physics learning is evolving from simple technological assistance toward more complex pedagogical relationships. The emerging evidence can be summarized as:

AI provides support → Students interact and evaluate → Teachers guide and validate → Physics learning is enhanced.

The review therefore suggests that the central issue is not whether AI should be used in physics education, but how AI can be integrated without weakening students' independent reasoning or teachers' pedagogical authority. The most promising direction is a human-centered model in which AI augments, rather than replaces, the cognitive and pedagogical contributions of students and teachers.

DISCUSSION

The findings indicate that human–AI collaboration in physics education is developing beyond the conventional use of technology as a supplementary instructional tool. The reviewed literature demonstrates a movement toward interactive arrangements in which AI contributes explanations, feedback, alternative solutions, and learning resources, while students and teachers retain important cognitive and pedagogical responsibilities. This finding supports the argument that the educational value of AI depends not simply on its technical capabilities but on how those capabilities are embedded within instructional design. Qian (2025) similarly emphasizes that generative AI in education is increasingly being considered in relation to learner autonomy, creativity, and higher-order cognitive processes rather than merely task automation. Thus, the present review suggests that the emerging direction in physics education is toward augmentation of human learning rather than substitution of human reasoning.

The emergence of AI as an intelligent tutor demonstrates one of the most accessible forms of human–AI collaboration. AI can provide students with explanations, examples, hints, and responses to questions at the point of need. This function is particularly valuable in physics because students often experience difficulty connecting abstract concepts with mathematical representations and physical phenomena. However, the findings also indicate that tutoring becomes pedagogically stronger when AI provides scaffolding instead of complete solutions. Students need opportunities to formulate questions, attempt solutions, and evaluate explanations. Consequently, AI tutoring should be designed as an interactive process rather than a mechanism for delivering ready-made answers. This interpretation is consistent with recent evidence showing that generative AI can provide useful tutoring support in physics while still requiring human oversight because of possible inaccuracies in generated responses (Moundridou *et al.*, 2026).

The AI-as-cognitive-partner model represents a more advanced form of collaboration and may have particular significance for physics education. In this model, students do not simply accept AI-generated solutions but compare them with their

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own reasoning and evaluate their scientific validity. This process creates opportunities for critical thinking because students may need to identify incorrect assumptions, mathematical errors, incomplete explanations, or inappropriate applications of physical laws. Such interaction changes the function of AI from an answer provider into a source of alternative reasoning. The pedagogical importance of this model lies precisely in the possibility that AI errors can become learning opportunities when students are required to detect and explain them. From this perspective, productive AI use is characterized not by the accuracy of every AI response but by the quality of the human reasoning that follows interaction with the AI system.

The findings further demonstrate that teacher mediation remains essential even when AI systems become increasingly sophisticated. Teachers determine learning objectives, select appropriate AI-supported activities, monitor students' interactions, verify scientific information, and establish boundaries for responsible AI use. This finding challenges the assumption that increasingly capable AI systems will necessarily reduce the importance of teachers. Instead, the teacher's role appears to become more focused on instructional design, evaluation, and facilitation. Mishra *et al*. (2024) similarly emphasize that effective AI integration requires teachers to develop not only technological knowledge but also pedagogical and professional judgment. In physics education, this responsibility is particularly important because AI-generated content must be evaluated according to disciplinary principles, mathematical consistency, and scientific evidence.

Another important finding concerns the relationship between AI use and student agency. The reviewed literature suggests that AI can support conceptual understanding, problem solving, feedback, self-regulated learning, and engagement, but these benefits are strongly influenced by how actively students participate in the learning process. When students use AI to obtain immediate answers, the technology may increase efficiency without necessarily producing deeper understanding. Conversely, when students use AI to generate alternatives, challenge explanations, receive feedback, revise their work, and reflect on their reasoning, AI can potentially strengthen learning autonomy and metacognitive engagement. This distinction suggests that future physics pedagogy should emphasize AI-supported inquiry and reflection, rather than unrestricted AI-assisted answer generation.

Finally, the review identifies several unresolved issues that should shape future research. Concerns about inaccurate AI-generated content, student dependence, assessment integrity, unequal access, privacy, and insufficient AI literacy indicate that technological adoption alone cannot guarantee educational improvement. More importantly, empirical research on long-term human–AI collaboration in authentic physics classrooms remains limited. Future studies should therefore investigate not only whether AI improves test performance but also whether it influences students' scientific reasoning, conceptual transfer, problem-solving processes, and ability to work independently. Research should also examine how teachers can design effective human–AI learning environments and how assessment can evaluate students' reasoning when AI assistance is permitted. Overall, the evidence supports a human-centered pedagogical model in which AI functions as a flexible cognitive and instructional resource, students remain active learners and evaluators, and teachers retain responsibility for pedagogical and disciplinary judgment.

CONCLUSION

This systematic literature review examined the emerging forms of human–AI collaboration in physics learning, with particular attention to the pedagogical roles of AI, students, and teachers. The synthesis indicates that AI is increasingly moving beyond its role as a conventional instructional technology and becoming an interactive component of physics learning. Four major pedagogical models were identified: AI as an intelligent tutor, AI as a cognitive partner, AI as a feedback assistant, and teacher-mediated human–AI collaboration.

The findings suggest that the greatest pedagogical potential occurs when AI augments rather than replaces human reasoning. AI can provide explanations, alternative solutions, feedback, learning resources, and analytical support, while students remain responsible for questioning, reasoning, evaluating, and reflecting on AI-generated information. Teachers continue to play an essential role in designing learning activities, monitoring AI use, validating scientific content, and maintaining pedagogical and ethical standards.

The review also indicates that human–AI collaboration can support several dimensions of

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physics learning, including conceptual understanding, problem solving, critical thinking, self-regulated learning, scientific reasoning, and learner engagement. However, these benefits cannot be assumed simply from the presence of AI. The effectiveness of AI-supported physics learning depends on the quality of pedagogical design and the extent to which students remain cognitively active.

Several challenges remain, particularly concerning inaccurate AI-generated physics content, student overreliance, limited AI literacy, assessment integrity, teacher preparedness, privacy, and unequal access to AI technologies. These challenges demonstrate the need for responsible and carefully mediated implementation rather than unrestricted adoption.

Overall, this review proposes a human-centered approach to AI integration in physics education, in which AI serves as a cognitive and instructional resource, students remain active learners and evaluators, and teachers retain responsibility for pedagogical and disciplinary judgment. Future research should move toward longitudinal and classroom-based investigations that examine not only academic achievement but also students' scientific reasoning, independence, metacognitive development, and ability to critically evaluate AI-generated knowledge. Such research will be important for developing sustainable pedagogical models in which artificial intelligence strengthens, rather than diminishes, the human dimensions of physics learning.

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Publisher: SARC Publisher

Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:
Panjaitan, M. B. & Panjaitan, B. "Human–AI Collaboration in Physics Learning: A Systematic Literature Review of Emerging Pedagogical Models." *Sarcouncil Journal of Education and Sociology* 5.9 (2026): pp 1-12.

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