Jurnal Pendidikan dan Ilmu Fisika (JPIF)
Fakultas Pendidikan Islam dan Keguruan
Universitas Garut
p-ISSN: 2798-9488 e-ISSN: 2798-334X

Enhancing Critical Thinking in Physics Education through AI: A Systematic Literature Review of Trends and Pedagogical Implications

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DOI: https://doi.org/10.52434/jpif.v5i2.43353

Accepted: December 26, 2025 Approved: December 28, 2025 Published: December 29, 2025

ABSTRACT

This study aims to map research trends and analyze the pedagogical role of Artificial Intelligence (AI) in enhancing students' critical thinking skills in physics education. Employing a Systematic Literature Review (SLR) method guided by PRISMA protocols and enriched with bibliometric analysis, this study reviewed Scopus-indexed articles published between 2015 and 2025. Based on 42 mapped articles and an in-depth analysis of 12 key studies, the results indicate a significant trend shift post-2023 toward the use of Generative AI. Key findings reveal that "Role Reversal" pedagogical strategies and the use of "Socratic Tutors" are the most effective approaches for stimulating logical reasoning and scientific argumentation. In conclusion, AI has transformed from a mere visualization tool into a cognitive partner, despite remaining limitations in spatial reasoning. The study's implications recommend the necessity of redesigning physics assessments to focus on critical validation of technological outputs rather than final answers, alongside strengthening ethical literacy to prevent student cognitive dependency.

Keywords: Artificial Intelligence, Critical Thinking, Generative AI, Physics Education, Systematic Literature Review.

Jurnal Pendidikan dan Ilmu Fisika (JPIF)
Vol. 05; No. 02; 2025; 343-354

Meningkatkan Pemikiran Kritis dalam Pendidikan Fisika melalui AI: Tinjauan Literatur Sistematis tentang Tren dan Implikasi Pedagogis

ABSTRAK

Penelitian ini bertujuan untuk memetakan tren riset dan menganalisis peran pedagogis Artificial Intelligence (AI) dalam meningkatkan keterampilan berpikir kritis siswa pada pembelajaran fisika. Menggunakan metode Systematic Literature Review (SLR) dengan protokol PRISMA yang diperkaya analisis bibliometrik, studi ini meninjau artikel terindeks Scopus yang diterbitkan antara tahun 2015 hingga 2025. Dari 42 artikel yang dipetakan dan 12 artikel utama yang dianalisis secara mendalam, hasil menunjukkan adanya pergeseran tren signifikan pasca-2023 menuju penggunaan Generative AI. Temuan kunci mengungkapkan bahwa strategi pedagogis "Pembalikan Peran" (Role Reversal) dan penggunaan "Tutor Socratic" merupakan pendekatan paling efektif untuk menstimulasi penalaran logis dan argumentasi ilmiah. Kesimpulannya, AI telah bertransformasi dari sekadar alat visualisasi menjadi mitra kognitif (cognitive partner), meskipun masih memiliki keterbatasan dalam penalaran spasial. Implikasi studi ini merekomendasikan perlunya redesain asesmen fisika yang tidak lagi berfokus pada jawaban akhir, melainkan pada validasi kritis terhadap luaran teknologi, serta penguatan literasi etika untuk mencegah ketergantungan kognitif siswa.

Kata kunci*: Artificial Intelligence, Berpikir Kritis, Fisika, Generative AI, Systematic Literature Review.*

INTRODUCTION

In the era of Education 5.0, the goal of physics learning has shifted from simply mastering mathematical formulas to developing higher order thinking skills, particularly critical thinking (Alanazi et al., 2024; Haryadi et al., 2021; Sadidah & Irvani, 2021). Physics, with its abstract and complex characteristics, requires students to not only memorize, but also engage in logical reasoning, evidence analysis, and inference (Aisah et al., 2025; Henukh et al., 2024; Tolba & Al-Osaimi, 2023). However, the literature shows that cultivating these skills in conventional learning is often hampered by the limited time teachers have to provide personalized and in-depth feedback to each student (Bhardwaj et al., 2025; Javed, 2023; Qolbi et al., 2024; Vaghela & Parsana, 2024).

The integration of digital technology has long been proposed as a solution (Henukh et al., 2025; Paling et al., 2024; Sulastri et al., 2024). However, the last decade (2015-2025) has marked a revolutionary leap with the advent of Artificial Intelligence (AI) in education. Unlike traditional educational technologies (Cao, 2022; Zhang, 2021), modern AI systems (Madanchian et al., 2025; Qazi et al., 2024), ranging from Intelligent Tutoring Systems (Mousavinasab et al., 2021), smart Augmented Reality (Marques et al., 2025), to the latest Generative AI (such as ChatGPT and LLMs), offer unprecedented adaptability. Recent studies highlight AI's potential to provide real-time visualization of abstract concepts and act as a Socratic tutor capable of engaging in dialogue with students.

Although the adoption of AI is rapidly increasing, its impact on critical thinking skills remains a subject of heated academic debate. On the one hand, there are concerns that AI could create cognitive dependency, where students use technology as a shortcut to obtain answers without going through the thinking process (George et al., 2024; Yavich, 2025; Zhai et al., 2024). On the other hand, empirical research is beginning to show that when designed with the right pedagogy, this technology can actually sharpen students' evaluative and argumentative skills (Asad et al., 2021; Jiang et al., 2024; Mejia & Sargent, 2023). Unfortunately, the existing literature review mostly focuses on AI in STEM education in general or only highlights technical efficiency aspects, so that a synthesis that specifically dissects the pedagogical mechanisms of AI in improving specific indicators of critical thinking in physics learning is still limited.

Therefore, this study aims to fill this gap through a Systematic Literature Review (SLR) enriched with bibliometric analysis of Scopus-indexed articles published between 2015 and 2025. This study is designed to answer four key questions: (1) What is the map of research trends and inter-topic relationships in the study of AI and critical thinking in physics education? (3) What are effective pedagogical strategies for transforming AI from a tool of automation to a tool of thinking augmentation?; and (4) What are the challenges and future opportunities in this integration? The results of this review are expected to provide a theoretical and practical framework for physics educators in utilizing AI ethically and constructively.

METHOD

This study uses a Systematic Literature Review (SLR) approach enriched with bibliometric analysis (Adhelacahya, 2023; Henukh et al., 2025). The review procedure is guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure transparency, objectivity, and replicability of the data selection process. The literature search was conducted in the Scopus database, which was selected due to its extensive coverage of high-quality physics education and educational technology journals. The search was limited to articles published in the last decade, namely between January 2015 and December 2025, to capture the latest AI technology trends, ranging from Intelligent Tutoring Systems to Generative AI.

The search strategy uses a combination of keywords linked with Boolean operators (AND, OR). The keywords are organized based on three main domains: (1) AI Technology, (2) Physics Education, and (3) Critical Thinking Skills. The search string used is TITLE-ABS-KEY (("Artificial Intelligence" OR "AI" OR "Machine Learning" OR "Generative AI" OR "Chatbot" OR "Augmented Reality") AND ("Physics Education" OR "Physics Learning" OR "Physics Teaching") AND ("Critical Thinking" OR "Higher Order Thinking Skills" OR "Reasoning" OR "Problem Solving" OR "Argumentation"))

To ensure data relevance, articles were screened based on strict inclusion and exclusion criteria (Table 1). The main focus of the selection was empirical articles that specifically discussed AI interventions in the context of physics and their impact on higher-order cognitive indicators.

Table 1. Inclusion and Exclusion Criteria

Criteria	*Inclusion*	*Exclusion*
Document Type	*Journal Articles (Research Articles) and indexed Conference Proceedings.*	*Books, Book Chapters, Editorials, Opinions, White Papers, and unpublished Theses/Dissertations.*

Criteria	*Inclusion*	*Exclusion*
Publication Year	*Publications published between January 2015 – 2025.*	*Publications published before 2015.*
Language	*English*	*Languages other than English*
Subject / Context	*Physics Education at Secondary School (High School) or Higher Education (University) levels.*	*General Science education, Chemistry, Biology, Mathematics, or Engineering without an explicit focus on Physics content.*
Intervention (AI)	*Generative AI, Chatbots, Intelligent Tutoring Systems, Machine Learning, Adaptive Learning*	*Non-AI educational technologies*
Research Outcome	*Studies discussing the impact, role, or correlation of AI on higher-order thinking skills (Critical Thinking, Reasoning, Argumentation, Problem Solving).*	*Studies focusing solely on technical software development without pedagogical trials, or studies only measuring lower-order cognitive learning outcomes.*

The data selection process was carried out through three systematic stages based on the PRISMA protocol, beginning with the identification of documents from the Scopus database, elimination of duplicates, and screening of titles and abstracts. The eligibility evaluation stage resulted in a total of 42 articles that were eligible for bibliometric analysis to map global research trends. From this data set, further selection was carried out, prioritizing articles with explicit pedagogical interventions and significant empirical findings, resulting in 12 main articles selected for in-depth analysis.

RESULT AND DISCUSSION

Research Trends and Bibliometric Maps

Analysis of 42 selected articles shows a significant surge in publications related to AI and physics in the period 2023-2025, which correlates closely with the launch of the Generative AI model. The keyword map results from the data obtained are shown in Figure 1.

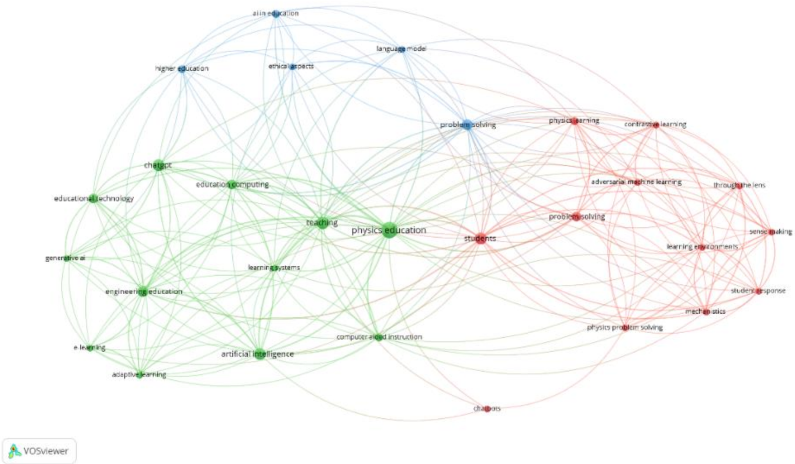

Figure 1. Network Visualization of Co-occurrence Keywords Research Trends in AI and Critical Thinking Skills in Physics Education (Source: Scopus Database, 2015-2025).

Network visualization using VOSviewer identifies the formation of intellectual clusters that connect the domains of technology and pedagogy. The map shows that the keywords “Artificial Intelligence” and “Physics Education” have the largest nodes with strong link strength to “Critical Thinking,” “Problem Solving,” and “Reasoning.” This confirms that academic discourse has moved beyond the use of technology as a mere presentation tool toward the integration of AI as a cognitive instrument. This finding is in line with the theory of Cognitive Apprenticeship, in which AI is positioned as an “expert partner” that provides scaffolding for students in solving complex physics problems. The density of the relationship between “AI” and “Reasoning” specifically indicates that the current research focus is on how intelligent algorithms can stimulate students' logical reasoning processes, rather than simply providing automatic answers.

From a temporal perspective (overlay visualization), there is a very significant shift in trends for the period 2023-2025. Research prior to 2023 tended to be dominated by the topics of “Machine Learning” and “Augmented Reality,” which focused on concept visualization and student performance prediction. However, the emergence of the ‘latest’ indicator color (bright yellow) for the keywords “Generative AI,” “Large Language Models,” and “ChatGPT” signifies a radical technological disruption. This surge correlates directly with the findings of Tong et al. (2024) and Werdhiana et al. (2025), who note that the reasoning capabilities of large language models (LLMs) have opened up new opportunities for Socratic dialogue simulations and automated diagnostic tests in physics education. This shift indicates that the physics research community is rapidly responding to the emergence of GenAI as a potential tool for training higher-order thinking skills (HOTS).

Meskipun tren teknologi meningkat pesat, analisis peta juga mengungkap adanya kesenjangan (gap) pada klaster etika dan evaluasi kritis. Node yang berkaitan dengan "Ethical Issues" atau "AI Literacy" tampak belum sebesar node teknologi, padahal literatur terbaru menekankan risiko "halusinasi AI" yang dapat menyesatkan siswa. Hal ini memperkuat argumen Al-Kamzari et al. (2025) mengenai perlunya menyeimbangkan adopsi teknologi dengan pengembangan disposisi berpikir kritis siswa agar tidak terjebak pada kepercayaan buta terhadap mesin. Oleh karena itu, peta bibliometrik ini menyarankan arah penelitian masa depan yang tidak lagi hanya bertanya "apakah AI efektif?", melainkan "bagaimana strategi pedagogis (seperti role reversal) dapat memitigasi risiko ketergantungan kognitif pada AI?".

Classification of AI Technology in Physics Education

Based on content analysis of the reviewed literature, the integration of artificial intelligence in physics education is no longer dominated by a single type of technology, but rather shows diversification of tools specific to students' cognitive needs. These technologies can be classified into three main categories that play distinctive roles in supporting critical thinking skills, as follows.

1. Generative AI and Large Language Models (GenAI/LLMs)

This category experienced the most massive surge in adoption after 2023. Technologies such as ChatGPT (OpenAI), Gemini (Google), and Copilot (Microsoft) are used not only as search engines, but also as “dialogic partners.” Studies show that GenAI has a unique capacity for natural language reasoning. Tufino et al. (2025) utilized this capability to create a Socratic AI Tutor that is able to guide students through the concepts of electromagnetism using tiered questions rather than direct answers. In addition, GenAI is also used as a diagnostic testing tool, as Werdhiana et al. (2025) did in measuring student reasoning on static fluid material using a two-tier test that was automatically analyzed by AI. The main advantage of GenAI lies in its ability to facilitate argumentation and text evaluation skills.

2. AI-Integrated Augmented Reality (AI-AR)

Unlike text-based GenAI, AI integration in Augmented Reality focuses on visuospatial reasoning. In physics, many concepts are abstract and invisible (such as magnetic fields or waves), which often hinder critical thinking. Suyidno et al. (2025) developed AR and AI-based renewable energy learning media that not only visualize the energy conversion process but also provide adaptive responses to student interactions. A similar approach was applied by Xolboyev et al. (2025) to electromagnetic wave material, where immersive visualization helped students analyze phenomena that cannot be observed directly, thereby strengthening the bridge between abstract theory and concrete understanding.

3. Intelligent Tutoring Systems (ITS) and Adaptive Learning

The third category is intelligent learning systems that focus on personalized scaffolding. Abdulayeva et al. (2025) highlight that these systems work by recording students' learning data trails to provide materials or challenges that match their zone of proximal development (ZPD). In the context of critical thinking, ITS plays a role in detecting patterns of logical fallacies or student misconceptions in real-time, then providing specific interventions without waiting for human instructors. Teodoro et al. (2025) also note the use of Qualitative Reasoning (QR) in this system to help students understand the behavior of complex physical systems through cause-and-effect simulations.

A summary of the classification of technologies and their main pedagogical functions is presented in Table 2.

Table 2. Matrix of AI Technology Classification and its Role in Critical Thinking

Technology Category	***Example Platform/Tool***	***Main Function in Physics***	***Contribution to Critical Thinking***	***Representative Article***
Generative AI (LLMs)	*ChatGPT, Gemini, Copilot*	*Socratic Dialogue, Problem Creation, Misconception Detection*	*Trains argumentation, information evaluation, and verbal reasoning*	*(Rico-Gutierrez, 2025; Tufino & Gregorcic, 2025)*
AI-Enhanced AR	*Mobile AR Apps, Smart Glasses*	*Visualization of Abstract Phenomena (Clustering, Medan)*	*Trains spatial analysis, inference of visual evidence, and contextual connections*	*(Suyidno et al., 2025; Xolboyev et al., 2025)*
Intelligent Tutoring (ITS)	*Adaptive Platforms, Auto-Grading Systems*	*Personalizes Content, Provides Real-time Feedback*	*Provides scaffolding (design) when facing logical deficiencies*	*(Teodoro & Freire, 2025; Verawati & Nisrina, 2024)*

Technology Category	*Example Platform/Tool*	*Main Function in Physics*	*Contribution to Critical Thinking*	*Representative Article*
Machine Learning & NLP	*Automated Essay Scoring*	*Student Response Analysis*	*Measures students' progress in quantitative thinking*	*(Dorris et al., 2024; Kieser et al., 2023)*

Thematic Analysis of the Role of AI in Critical Thinking

To complement the macro bibliometric analysis, this study conducted an in-depth content analysis of 12 selected articles identified as having the highest relevance (high impact). These articles were selected through a rigorous selection process with the following criteria: (1) empirically applying AI interventions in physics classes, and (2) explicitly measuring or discussing the impact of these interventions on specific indicators of critical thinking, such as reasoning, argumentation, and analytical skills. Based on a synthesis of the findings, the main literature was classified into three thematic domains: Pedagogical Strategies, Comparative Analysis of Reasoning, and Ethical Challenges. A summary of the main articles and their focus of study is presented in Table 3.

Table 3. Classification of AI's Role in Critical Thinking in Physics

Thematic Category	*Author(s) (Year)*	*Study Focus / Intervention*	*Key Findings Related to Critical Thinking (CT)*
Pedagogical Strategies	*(Rico-Gutierrez, 2025)*	*Role Reversal (Students teach AI)*	*Strengthening conceptual understanding and CT through correcting AI's mistakes.*
	(Tufino & Gregorcic, 2025)	*Socratic AI Tutor*	*Guiding conceptual reasoning through a question-and-answer dialogue.*
	(Suyidno et al., 2025)	*AI-Augmented Reality Integration*	*Enhancing 5C skills by visualizing abstract concepts in concrete forms.*
	(Dahlkemper et al., 2023)	*"Spot the Bot" Activity*	*Training students to evaluate the scientific accuracy of AI's responses.*
	(Huang et al., 2025)	*IT-CSTP Learning Model*	*Integrating chatbots for cultivating scientific thinking.*
Reasoning Comparison (AI vs. Students)	*(Sirnoorkar et al., 2024)*	*Sensemaking Analysis*	*Comparing the sensemaking process between AI and students in optics.*
	(Mansyur, 2025)	*Two-Tier Diagnostic Test*	*Measuring AI's reasoning performance on static fluid misconceptions.*
	(Zollman et al., 2023)	*Mechanistic Reasoning*	*Testing AI's reasoning consistency with variations of physics problems.*
	(Polverini & Gregorcic, 2024)	*Visual (Spatial) Reasoning*	*Identifying AI's weaknesses in spatial tasks (right-hand rule).*
Challenges & Ethics	*(Al-Kamzari & Alias, 2025)*	*Implementation Challenges Review*	*Highlighting risks of dependency that may hinder CT.*
	(Gumilar et al., 2025)	*Argumentation Assessment*	*Testing AI's validity in assessing the quality of students' socio-scientific arguments.*

Thematic Category	*Author(s) (Year)*	*Study Focus / Intervention*	*Key Findings Related to Critical Thinking (CT)*
	(Khodadad, 2025)	*Academic Integrity*	*Recommending balancing AI efficiency with independent reasoning development.*

Table 3 shows a significant paradigm shift. Whereas educational technology was previously positioned as a delivery tool, recent research places AI as the object of evaluation. The findings of Rico-Gutiérrez et al. (2025) on the Role Reversal strategy provide empirical evidence that placing students in the role of "teachers" for AI is far more effective in stimulating metacognition than traditional learning models. When students are asked to correct AI's incorrect answers (hallucinations), they are forced to mobilize their deep understanding of physics concepts to construct logical counterarguments. This is in line with the "Spot the Bot" activity proposed by Dahlkemper et al. (2023), which emphasizes that the imperfections of AI are actually a pedagogical asset for training students' intellectual skepticism.

Furthermore, the transition from AI as a "answering machine" to a "thinking partner" is clearly evident in the development of Socratic AI Tutor by Tufino et al. (2025). Unlike search engines that stifle curiosity with instant answers, this system is designed to maintain students' "cognitive tension" through multi-level questions. This indicates that the future of AI in physics education lies not in automating answers, but in automating the scaffolding process that guides students in constructing their own knowledge.

Comparative Reasoning: The Limits of AI in Physics "Sensemaking"

Although AI performs well in standard tasks, analysis in Category 2 reveals a gap in reasoning quality between AI and humans. Sirnoorkar et al. (2024) found that although AI is capable of producing correct mathematical solutions, it often fails in the process of sensemaking, that is, linking mathematical symbols to real-world physical meanings. AI tends to operate at the level of symbolic manipulation, while students excel at constructing situational mental models.

The limitations of AI are becoming increasingly apparent in the visual-spatial domain. A study by Polverini et al. (2025) highlights that Large Language Models (LLMs) experience significant difficulties in tasks that require spatial reasoning, such as applying the "right-hand rule" in electromagnetism. This finding is crucial for physics educators: it marks an area where human intervention is irreplaceable. Physics teachers need to be aware that AI may be verbally "fluent" (able to explain Ampere's law beautifully), but spatially "blind" (unable to determine the direction of a magnetic field in a 3D diagram). Therefore, visual-based assessments and physics lab work remain vital components that cannot be entirely delegated to AI.

Ethical Implications: Avoiding the Illusion of Competence

The next discussion raised the issue of "competence illusion" identified by Al-Kamzari et al. (2025). Easy access to coherent AI explanations can make students feel that they "understand" simply because they read neat texts, even though they have not experienced the cognitive struggle necessary for long-term memory. Khodadad et al. (2025) warn that without proper pedagogical regulation, AI integration risks producing graduates who are skilled at using tools (tool-savvy) but weak in fundamental science. Therefore, the main recommendation from this synthesis is the need for a physics curriculum that integrates “AI literacy,” where students are taught when to use AI as an accelerator and when to leave it behind to train their independent thinking muscles.

CONCLUSION

This study concludes that the integration of Artificial Intelligence (AI) in physics education has undergone a fundamental transformation over the last decade (2015–2025), shifting from functioning merely as passive visualization tools to becoming active cognitive partners. Bibliometric analysis confirms a significant surge in research trends post-2023, where the focus has shifted toward utilizing Generative AI and Large Language Models (LLMs) to stimulate reasoning. Pedagogically, the review of key literature identifies that the effectiveness of AI in enhancing critical thinking skills lies not in technological sophistication alone, but in the implementation strategy. The "Role Reversal" strategy and the use of "Socratic Tutors" have proven to be the most potent approaches for training scientific skepticism and argumentation skills, effectively transforming the risk of AI hallucinations into constructive learning opportunities.

The primary implication of these findings for physics education practice is the necessity for a redefinition of assessment and instructional design. Teachers can no longer rely on tasks that solely demand final answers, as AI can resolve these with ease. Instead, educators need to design activities that require students to validate, critique, and refine AI-generated outputs. However, this study also highlights crucial limitations of AI regarding spatial reasoning and real-world contextual sensemaking. This underscores that while AI can serve as an accelerator for verbal-logical reasoning, physical laboratory experiences and human intervention remain irreplaceable for building a comprehensive and phenomenon-based understanding of physics concepts.

Based on the identified gaps, future research is recommended to move beyond short-term effectiveness studies toward longitudinal studies that measure the long-term impact of AI dependency on students' metacognition. The research community is also encouraged to explore the development of Hybrid-AI models specifically designed to bridge AI's weaknesses in visual-spatial reasoning. Finally, integrating ethical frameworks and "AI Literacy" into the physics curriculum is an urgent priority to prevent the "illusion of competence," ensuring that students grow into critical thinkers capable of leveraging technology without losing their intellectual independence.

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