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Artificial Intelligence and the Development of Critical Thinking in Science Education: A Systematic Review

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Abstract

The rapid expansion of artificial intelligence (AI) in education has positioned it as a key driver of digital transformation and changes in learning paradigms. This study systematically examines how AI influences the development of critical thinking in science education, focusing on both underlying mechanisms and instructional practices. Guided by the PRISMA framework, a comprehensive search, screening, and synthesis of literature published between 2021 and 2025 in the Web of Science and Scopus databases were conducted, resulting in a final sample of 21 studies. The findings indicate a sustained growth in research within this field, with mixed-methods approaches predominating. At the technological level, generative AI and adaptive learning systems are the most widely applied, while learning analytics systems, predictive AI, explainable AI, and virtual simulation environments are also gaining increasing attention, forming a complementary and evolving technological ecosystem. At the pedagogical level, AI has become increasingly embedded in instructional design, encompassing teaching models, methods, frameworks, and instructional modules, reflecting a trend toward deeper integration. Despite its potential, the application of AI in educational practice faces several challenges, including issues related to output reliability, risks of student overreliance, and limitations in teachers’ professional competencies. These factors may constrain the effectiveness and sustainability of AI in supporting the development of critical thinking in science education.

Keywords: Artificial Intelligence, Science Education, Critical Thinking, Systematic Literature Review

Introduction

In contemporary educational systems, science education has become a critical domain for enhancing students’ scientific literacy, problem-solving abilities, and higher-order thinking skills. As a fundamental component of education, science education encompasses the learning and practice of natural science disciplines, including physics, chemistry, biology, and geography (Antonio & Prudente, 2024; Kaya et al., 2025). Beyond the acquisition of scientific knowledge, science education emphasizes the development of scientific inquiry abilities, evidence-based reasoning, and the capacity to interpret complex phenomena. Through processes such as observation, experimentation, and explanation, students are encouraged to construct knowledge, evaluate evidence, and develop rational and reflective approaches to understanding the world (Osborne, 2023). Therefore, science education has increasingly been recognized not only as a means of knowledge transmission but also as an important context for cultivating the cognitive abilities required to address complex scientific and social challenges.

Among these abilities, critical thinking represents a central educational goal and a key competency for learners in the twenty-first century. Science learning naturally involves processes of inquiry, analysis, argumentation, evaluation, and reflection, which provide important foundations for the development of critical thinking. As highlighted by Vincent-Lancrin (2021), activities such as hypothesis formulation, experimental validation, and data interpretation require learners to analyze information, compare alternative explanations, evaluate evidence, and reflect on their reasoning processes. Consequently, fostering critical thinking through science education has become an important topic in both educational research and broader discussions regarding the development of students' cognitive competencies and scientific literacy.

Meanwhile, the rapid advancement of artificial intelligence (AI) has introduced significant transformations in educational practices and learning environments. As education systems worldwide increasingly embrace digital transformation, AI has emerged as an influential technology capable of reshaping instructional design, learning processes, and assessment practices. In particular, generative AI, adaptive learning systems, intelligent feedback mechanisms, and learning analytics have expanded possibilities for personalized learning and learner-centered instruction. Within science education, AI technologies have been applied to support instructional planning, provide real-time feedback, facilitate scientific inquiry, and create adaptive learning experiences. These applications may contribute to improving learning efficiency while also providing new opportunities for supporting higher-order cognitive development (Mnguni, 2025). For example, Chukwu and Cletus (2025) found that AI-supported learning environments can enhance student engagement and encourage active participation in scientific inquiry and problem-solving activities. Similarly, AI-enabled interactive and data-driven environments can provide cognitive support for analyzing problems, comparing perspectives, and exploring multiple solution pathways, thereby creating favorable conditions for the development of critical thinking skills (Kotsis, 2025; Yadav Phd, 2025).

However, despite the increasing integration of AI into educational contexts, the relationship between AI applications and the development of critical thinking in science education remains theoretically and practically complex. While existing studies have explored the educational benefits of AI, current research findings remain fragmented regarding how different types of AI technologies, instructional strategies, and learning environments contribute to critical thinking development. Specifically, previous studies have primarily examined individual AI applications or specific instructional contexts, making it difficult to develop a comprehensive understanding of the mechanisms through which AI supports critical thinking(Ruff et al., 2024). Moreover, questions remain concerning how AI should be integrated into science education to maximize cognitive benefits while avoiding potential challenges, such as students' overreliance on AI-generated information, limitations in teachers' AI-related competencies, and concerns regarding the reliability of AI outputs(Moemeke, 2024).

These unresolved issues highlight an important research gap in the emerging field of AI-supported science education. Although previous research has provided valuable insights into AI applications and technology-enhanced learning, a systematic synthesis of how AI influences critical thinking development in science education is still insufficient. Without such synthesis, it remains challenging for researchers and educators to identify effective AI-supported pedagogical approaches, understand the underlying mechanisms of cognitive development, and establish evidence-based practices for integrating AI into science learning environments. Addressing this gap is particularly timely given the rapid evolution of AI technologies and the increasing emphasis on cultivating higher-order thinking skills in contemporary education systems.

To address this gap, the present study conducts a systematic literature review to provide a comprehensive synthesis of existing research on the role of AI in supporting critical thinking development in science education. By examining research trends, technological applications, instructional approaches, and associated challenges, this study aims to clarify the current state of knowledge and contribute to ongoing discussions regarding the effective and responsible integration of AI into educational practice. Specifically, this review aims to (1) examine research trends and methodological characteristics in the field, (2) analyze the types and functional roles of AI tools employed in science education, (3) synthesize AI-integrated instructional design approaches that support critical thinking development, and (4) identify challenges associated with the use of AI in fostering critical thinking.

Accordingly, this review addresses the following research questions (RQs):

1. What developmental trends and methodological characteristics characterize current research on AI-supported critical thinking in science education?
2. What types of AI tools are used in science education, and how do they influence the development of critical thinking?
3. Which AI-integrated instructional designs contribute to the development of critical thinking in science education?
4. What challenges are associated with the use of AI to support critical thinking development in science education?

Methodology

To systematically examine the impact of artificial intelligence (AI) on the development of critical thinking in science education, this study conducted a comprehensive literature search using two authoritative international academic databases: Web of Science (WoS) and Scopus. These databases are widely recognized for their extensive coverage and high-quality indexed publications, encompassing research in science education, AI applications, and critical thinking, thereby ensuring the representativeness and reliability of the selected literature (Bakhmat et al., 2022).

A structured search strategy was developed based on three core themes: artificial intelligence, science education, and critical thinking. For AI, the search terms included “AI,” “Artificial Intelligence,” “Machine Intelligence,” and “AIED.” For science education, the terms included “science education,” “science learning,” “science teaching,” and “science instruction.” For critical thinking, the terms included “critical thinking” and “think critically.” These keywords were combined using Boolean operators (AND/OR) to ensure that the retrieved studies simultaneously addressed AI applications, science education contexts, and the development of critical thinking.

To capture recent developments in the field, particularly those associated with the rapid emergence of generative AI in education, the search was limited to publications from January 1, 2021, to December 31, 2025. This timeframe ensures that the included studies reflect current trends and emerging practices, thereby enhancing the relevance and timeliness of the review.

Clear inclusion and exclusion criteria were established to guide the screening process. The inclusion criteria were as follows: (1) articles published in English, (2) peer-reviewed journal articles, and (3) studies directly related to AI applications in science education with a focus on critical thinking. The exclusion criteria included conference papers, books, book chapters, and review articles, in order to minimize potential bias arising from variations in review standards and publication quality.

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, rigor, and reproducibility in the review process. In the identification stage, a total of 1,011 records were retrieved from the databases. During the screening stage, 361 articles were retained after applying the predefined inclusion and exclusion criteria, including publication date, language, document type, and peer-review status.

In the eligibility stage, full-text screening was conducted, and studies were excluded for the following reasons: 51 articles with inaccessible full texts, 65 duplicate records, and 224 studies that did not align with the research focus. It should be noted that, in this review, “science education” is strictly defined as education in the natural sciences, including physics, chemistry, biology, and geography. Studies related to computer science education, social science education, and medical or health sciences were excluded due to their distinct disciplinary orientations and were therefore considered outside the scope of this review.

Finally, in the inclusion stage, a total of 21 high-quality peer-reviewed articles were selected for in-depth analysis. The detailed screening process is illustrated in Figure 1.

PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only

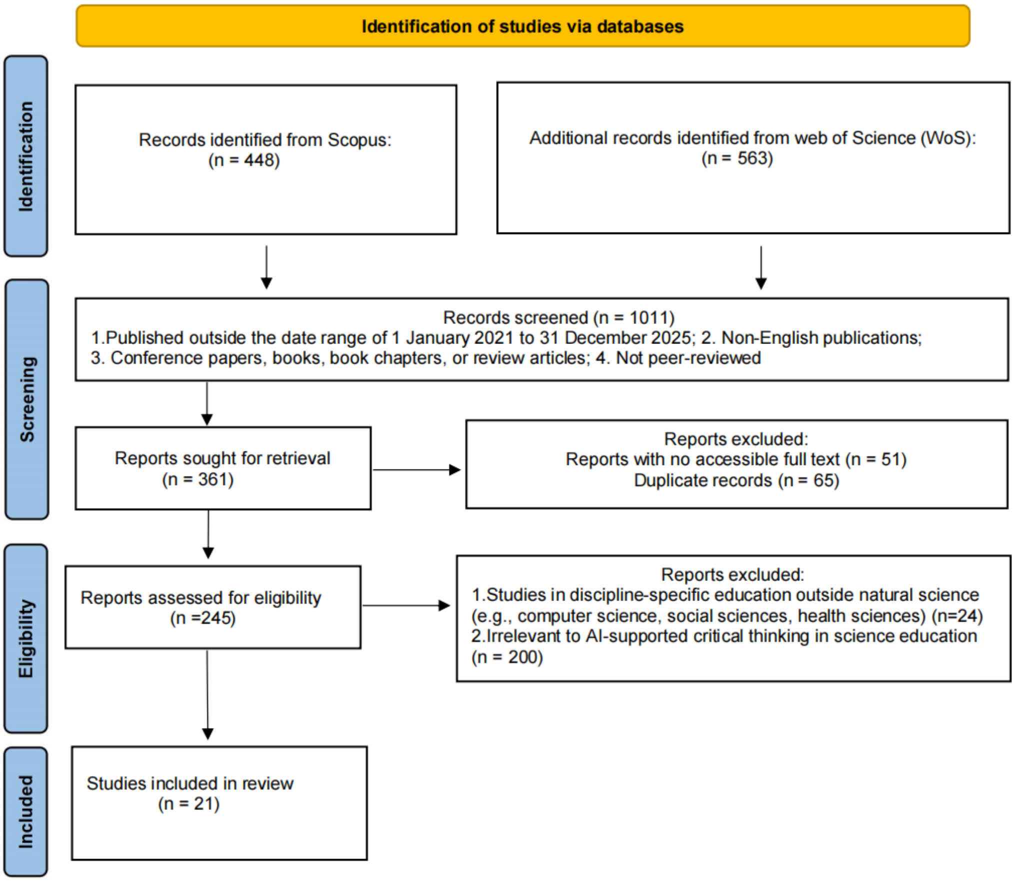

Figure 1. Adapted PRISMA systematic selection process

Results

Developmental Trends and Research Methods of AI-Supported Critical Thinking in Science Education

This study analyzed publications from the Scopus and Web of Science (WoS) databases between 2021 and 2025 that focus on the use of artificial intelligence (AI) to support the development of critical thinking in science education. Overall, the findings reveal a clear and sustained upward trend in the number of relevant studies across both databases. As illustrated in Figure 2, the number of publications indexed in Scopus increased markedly from 14 in 2021 to 238 in 2025, indicating particularly rapid growth. A similar pattern is observed in the Web of Science database, where the number of publications rose steadily from 35 in 2021 to 183 in 2025. These trends suggest that the integration of AI to foster critical thinking in science education has attracted increasing scholarly attention and has emerged as a significant and rapidly developing research focus in recent years.

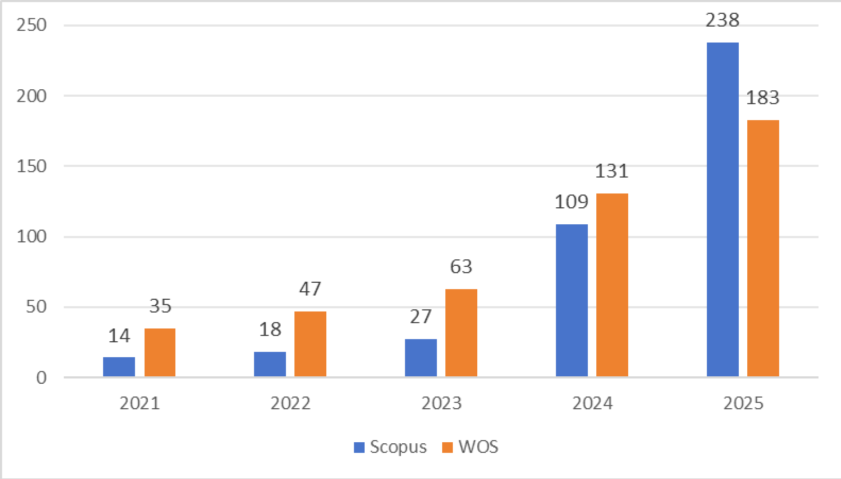

Figure 2. Distribution of the number of articles from 2021 to 2025

Among the studies included in this review, research methodologies demonstrate notable diversity. Of the 21 selected articles, 12 employed mixed-methods approaches, while 4 adopted quantitative methods and 4 utilized qualitative designs. In quantitative studies, quasi-experimental designs were most commonly used, including pretest–posttest designs, control group experiments, and single-group pretest–posttest designs (Archila et al., 2024; Nawafleh & Al-Abbas, 2025; Zorlu, 2025). Data collection instruments typically included standardized critical thinking scales, questionnaires, teacher rating scales, and descriptive assessment tools. In some cases, exploratory data analysis (EDA) was applied to learning behavior data generated by AI-supported systems to examine patterns in the development of students' critical thinking (Marín Díaz, 2025).

Qualitative studies primarily relied on semi-structured interviews, focus group discussions, classroom observations, and case studies for data collection. Analytical approaches commonly included qualitative content analysis and thematic analysis. Some studies also employed self-study methodology, in which researchers reflected on their own instructional practices to examine the impact of AI integration on critical thinking development (Cooper, 2023). In addition, the analysis of students' reflective writings and responses to open-ended questions was frequently used to capture deeper insights into learners' cognitive processes (Archila et al., 2024; Ruff et al., 2024).

In mixed-methods research, quantitative approaches were typically dominant, with qualitative data used to provide explanatory insights into underlying mechanisms (Elshall & Badir, 2025; Zhao et al., 2026). However, some studies adopted a qualitatively driven design supplemented by descriptive statistical analysis to enhance the credibility and robustness of findings (Tang & Putra, 2026). Notably, several studies employed a design-based research (DBR) framework, emphasizing iterative cycles of design, implementation, and refinement of AI-supported instructional interventions in authentic classroom contexts. This approach enables continuous improvement of instructional strategies while systematically evaluating their effectiveness in promoting students' critical thinking (Suyidno et al., 2025).

Differential Effects of AI Tools on the Development of Critical Thinking in Science Education
Based on systematic synthesis and content analysis, this study categorizes AI tools into six types: generative AI, adaptive and personalized learning systems, AI-driven learning analytics and automated feedback systems, data-driven predictive AI, explainable AI (XAI) tools, and AI-supported simulation and virtual laboratory systems. These categories exhibit differentiated functional mechanisms in supporting the development of critical thinking. As summarized in Table 1, AI tools are collectively reshaping pathways for cultivating critical thinking in science education through cognitive support, contextualized learning environments, and data-driven feedback. In doing so, they enhance students' abilities in analytical reasoning, evidence evaluation, and reflective judgment.

Table 1
Different AI Tools in Fostering Critical Thinking

AI Technology application	Tools	Articles	The way it influences critical thinking
Generative AI	1.ChatGPT 2.OpenAI's LLM 3.Large Language Model-Based Dialogue Robots 4.Customized Generative AI Chatbots 5.AI chatbot 6.Jupyter AI 7.Magic School AI platform 8.DST chatbot	(Zorlu, 2025) (Uchida et al., 2025) (Vera et al., 2025) (Zhang et al., 2025) (Elshall & Badir, 2025) (Tang & Putra, 2026) (Zhao et al., 2026) (Archila et al., 2024) (Ruff et al., 2024) (Huang et al., 2025) (Cooper, 2023) (Bitzenbauer, 2023) (KIER et al., 2025) (Baroud et al., 2025) (Holzmann et al., 2025)	Positive Effects: 1. Higher-order cognitive processing: Supports students' analysis, evaluation, and creativity 2. Triggering cognitive conflict: By presenting questionable information, it encourages students to question and verify 3. Development of argumentation skills: Encourages students to analyze, interpret, argue, and refute 4. Metacognitive regulation: Reflection, revision, and continuous inquiry 5. Expansion of Multiple Perspectives: Broadening viewpoints and deepening thinking 6. Collaborative Critical Dialogue: Group discussions and reflection Negative Effects: 1. Risk of Over-Reliance: Weakening of independent thinking and critical integration skills 2. Superficial Thinking Replacing Deep Reasoning: Increased generation of viewpoints but insufficient depth of reasoning
Adaptive & Personalized AI Systems	1.Adaptive Feedback AI 2.Personalized Learning AI 3.AI-enhanced learning platform：Google Classroom 4.AI-assisted web-based expert system and	(Suyidno et al., 2025) (Nawafleh & Al-Abbas, 2025) (Gunawan et al., 2021)	1. Adaptive feedback mechanism: Immediate feedback, error correction, reflection, and evaluation 2. Personalized cognitive support: Customized content and difficulty adjustments that balance cognitive load, maintain an appropriate level of challenge, and promote deep processing 3. Promotion of active construction: Support for exploratory learning and problem-driven tasks to foster active construction and deep understanding.

	Intelligent Tutoring System		
Learning Analytics & Automated Feedback Systems	1.AI systems providing automated feedback and learning analytics 2.AI-driven interactive video platforms 3.AI-supported lesson planning and inquiry scaffolding tools	(Kunnath & Botes, 2025)	1. Strengthen analysis and reasoning through data-driven feedback 2. Improve the ability to interpret evidence by analyzing learning behaviors 3. Promote reflection and evaluation through real-time diagnostic support 4. Enhance higher-order cognitive engagement through increased interactive participation
Data-Driven Predictive AI	1.Supervised ML(XGBoost) 2.Random Forest 3.Naïve Bayes 4.Fuzzy AI / Fuzzy Clustering	(Marín Díaz, 2025) (Jufrida et al., 2025)	1. Learning Pattern Recognition: Supporting Cognitive Assessment and Targeted Intervention 2. Personalized Task Matching: Enabling Differentiated Support 3. Learning Path Optimization: Enhancing Engagement and Contextual Understanding 4. Targeted Intervention Support: Promoting Deep Understanding and Cognitive Processing
Explainable AI tools	Explainable AI, XAI	(Marín Díaz, 2025)	1. Make the reasoning process transparent to strengthen logical understanding 2. Highlight uncertainty to promote prudent judgment 3. Reflect on the relationship between data and models to enhance critical analysis 4. Improve analytical, reflective, and evaluative skills through transparent decision-making mechanisms
AI-based Simulation & Virtual Lab Systems	AI-based virtual laboratories and simulations AI-powered simulations	(Kunnath & Botes, 2025) (KIER et al., 2025)	1. Strengthen causal analysis and reasoning through dynamic simulation systems 2. Help students analyze simulation data to improve their ability to identify patterns and conduct analysis 3. Enhance problem comprehension and reasoning skills through immersive experimental scenarios

Among these categories, generative AI emerges as the most widely applied tool. Its core mechanism lies in dialogic generation and multi-perspective reconstruction, which provide learners with sustained higher-order questioning and immediate feedback, thereby stimulating reflection, skepticism, and argumentation (Elshall & Badir, 2025; Zorlu, 2025). The iterative interaction cycle of "prompt–response–follow-up" facilitates the development of evidence evaluation, logical reasoning, and metacognitive regulation, ultimately deepening critical thinking (Huang et al., 2025; Zhang et al., 2025). Some studies further suggest that generative AI can function as a "cognitive conflict trigger" by presenting incomplete or potentially misleading information, prompting learners to verify, challenge, and refine their understanding. Through such processes, students enhance their explanatory and reasoning abilities (Archila et al., 2024; Ruff et al., 2024). However, concerns have also been raised that, in the absence of appropriate pedagogical guidance, overreliance on AI may undermine students' independent thinking and critical judgment (Cooper, 2023; Zhao et al., 2026).

Therefore, the educational value of generative AI depends critically on the integration of structured guidance and strategies for its critical use within instructional design.

Adaptive and personalized learning systems represent the second most prevalent category, highlighting their important role in AI-supported instructional regulation. These systems dynamically identify learners' knowledge levels, cognitive pace, and learning preferences, enabling the adjustment of learning pathways and task difficulty. By providing differentiated support and real-time feedback, they strengthen students' reflective capacity and higher-order reasoning, thereby promoting the deeper development of critical thinking (Nawafleh & Al-Abbas, 2025; Suyidno et al., 2025).

Although AI-driven learning analytics and automated feedback systems, data-driven predictive AI, explainable AI tools, and AI-supported simulation and virtual laboratory systems are less frequently reported, their functional contributions remain significant. Learning analytics and automated feedback systems facilitate reflection and evaluation through real-time monitoring of learning processes (Kunnath & Botes, 2025). Data-driven predictive AI supports the development of critical decision-making by enhancing learners' anticipatory thinking and strategic planning (Jufrida et al., 2025). Explainable AI improves algorithmic transparency and fosters critical awareness of AI-generated outputs (Marín Díaz, 2025). Meanwhile, simulation and virtual laboratory systems promote hypothesis testing and evidence-based reasoning by constructing complex and authentic problem scenarios (KIER et al., 2025).

Overall, these diverse AI tools collectively expand the pedagogical pathways for fostering critical thinking in science education.

AI-Integrated Instructional Designs Supporting Critical Thinking in Science Education

The systematic synthesis of the included studies indicates that the application of artificial intelligence (AI) in science education has evolved from a tool-oriented supportive role to a stage of deep integration with instructional design. Existing research primarily addresses this integration through multiple dimensions, including instructional model innovation, framework development, methodological enhancement, and modular design. Overall, AI is increasingly embedded within curriculum structures and instructional processes. Through mechanisms such as intelligent feedback, contextualized scenario generation, and dynamic adaptation, AI effectively supports the development of critical thinking in areas such as problem representation, evidence evaluation, reasoning and argumentation, and reflective regulation. Detailed classifications are presented in Table 2.

Table 2
The way instructional design combined with AI in Fostering Critical Thinking

Instructional design combined with AI		Articles	The way it influences critical thinking
Teaching Model	Project-based learning	(Marín Díaz, 2025) (Jufrida et al., 2025) (Elshall & Badir, 2025) (Ruff et al., 2024) (KIER et al., 2025)	1. Foster students' ability to analyze complex problems and evaluate evidence through real-world project tasks 2. Emphasize information gathering, comparison of alternatives, and the decision-making process to enhance reasoning skills 3. Strengthen critical judgment and self-assessment through project presentations and reflection
	Inquiry-based learning	(Suyidno et al., 2025) (Kunnath & Botes, 2025) (Ruff et al., 2024)	1. Guide students in formulating questions and hypotheses, fostering a spirit of inquiry and critical thinking 2. Develop evidence-based reasoning skills through the process of data collection and interpretation 3. Emphasize the justification and discussion of conclusions to promote the development of logical thinking
	Problem-based learning	(Suyidno et al., 2025) (Zhang et al., 2025) (Vera et al., 2025)	1. Use open-ended questions to drive learning and foster analytical skills 2. Encourage the comparison of multiple options and evidence-based decision-making 3. Enhance argumentation and critical thinking skills through group discussions
	HOTS-based Integrated Science Learning	(Gunawan et al., 2021)	1. Design tasks specifically aimed at higher-order thinking skills such as analysis, evaluation, and creativity 2. Encourage students to interpret scientific phenomena from multiple perspectives 3. Strengthen students' ability to engage in deep reasoning through open-ended questions and complex tasks
	ALACT Reflection model	(Zhao et al., 2026)	1. Foster deep reflection through the cycle of action, reflection, awareness, substitution, and testing 2. Strengthen the ability to analyze learning experiences and identify mistakes

			3. The reflection process promotes metacognition and critical self-assessment
	integrated the ARCS motivational model	(Huang et al., 2025)	1. Enhance students' willingness to think critically through attention-grabbing and relevant design 2. Boost students' confidence in learning, making them more willing to tackle complex reasoning tasks 3. A sense of accomplishment encourages ongoing reflection and evaluation of the learning process
	5Es model	(Cooper, 2023) (Kunnath & Botes, 2025)	1. The Engage phase fosters problem awareness and motivation to think 2. The Explore and Explain phases promote evidence analysis and concept construction 3. The Evaluate phase strengthens reasoning, verification, and critical judgment skills
	blended learning models	(KIER et al., 2025)	1. Online resources support the acquisition and comparison of information from multiple perspectives 2. Digital discussion platforms facilitate argumentation and critical exchange 3. Self-directed learning pathways strengthen reflective thinking and independent judgment
Teaching Framework	deep active learning (DAL) framework	(Archila et al., 2024)	1. Emphasizing active participation and deep cognitive processing 2. Promoting knowledge analysis and integration through complex tasks 3. Strengthening reflective and critical evaluation skills through continuous feedback mechanisms
Teaching Method	Classroom-Integrated Discussion-Based Instructional Design	(Uchida et al., 2025)	1. Promote the comparison of viewpoints and the evaluation of evidence through structured discussions 2. Encourage students to explain their reasoning processes to improve logical expression 3. Strengthen critical thinking skills through a peer-questioning mechanism
	Dialogic Teaching	(Tang & Putra, 2026)	1. Promoting an understanding of diverse perspectives through open dialogue 2. Teachers' probing strategies to reinforce deep reasoning

			3. Cultivating argumentation skills through students' responses and rebuttals
	guided discovery learning (GDL)	(Huang et al., 2025)	1. Explore concepts under the guidance of a teacher 2. Foster analysis and reasoning through guided questions 3. Strengthen the ability to interpret evidence through the discovery process
	think-pair-share method	(Bitzenbauer, 2023)	1. The independent thinking phase facilitates preliminary analysis 2. The peer discussion phase facilitates the testing of ideas 3. The whole-class sharing phase reinforces argumentation and critical expression
	ChatGPT Fact-Check	(Holzmann et al., 2025)	1. Require students to verify AI-generated information to foster evidence-based thinking 2. Compare information from multiple sources to strengthen information evaluation skills 3. Identify errors and biases to develop critical digital literacy
Teaching Module	a computerized instructional module	(Nawafleh & Al-Abbas, 2025)	1. Problem-solving tasks promote logical thinking 2. Immediate feedback promotes reflection 3. An interactive environment promotes active thinking

As shown in Table 3, at the level of instructional models, the integration of AI with project-based learning (PBL) is the most prevalent approach. This model emphasizes the use of AI tools within authentic, real-world project tasks to support students in systematically analyzing complex problems and engaging in logical reasoning, thereby strengthening evidence evaluation, critical judgment, and self-reflection (Jufrida et al., 2025; Marín Díaz, 2025). Inquiry-based learning and problem-based learning also represent prominent approaches, focusing on problem-driven cognitive conflict. With the support of AI-enabled dynamic feedback and resource recommendation, these models guide students toward sustained inquiry and deeper argumentation (Kunnath & Botes, 2025; Suyidno et al., 2025).

In addition, several established instructional models have been systematically integrated with AI technologies, including HOTS-based integrated science learning, the ALACT reflective model, the ARCS motivational model, the 5E instructional model, and blended learning models. These approaches primarily focus on fostering higher-order thinking, developing reflective regulation mechanisms, and enhancing learning motivation. Through structured instructional processes, they contribute to the systematic development of critical thinking (Cooper, 2023; Gunawan et al., 2021; Huang et al., 2025; KIER et al., 2025; Zhao et al., 2026).

At the framework level, AI integration is exemplified by the Deep Active Learning (DAL) framework, which emphasizes student engagement in authentic problem contexts supported by AI-driven data analysis and real-time feedback. This framework promotes active participation, higher-order cognitive engagement, and reflective regulation, thereby facilitating the development of critical thinking (Archila et al., 2024).

At the methodological level, AI is widely embedded in classroom discourse and interactive learning environments. Representative approaches include AI-supported embedded discussion-based instruction, dialogic teaching, guided discovery learning (GDL), the think–pair–share method, and AI-assisted fact-checking activities (e.g., ChatGPT-based verification tasks). These approaches leverage AI to generate questions, present multiple perspectives, and facilitate evidence comparison, thereby encouraging students to engage in argumentation, evidence evaluation, and logical reasoning, ultimately enhancing the depth of their critical judgment (Bitzenbauer, 2023; Holzmann et al., 2025; Huang et al., 2025; Tang & Putra, 2026; Uchida et al., 2025).

Furthermore, some studies have developed AI-supported instructional modules, such as computerized instructional modules, which incorporate structured problem-solving tasks and real-time feedback mechanisms. These modules promote iterative cycles of active thinking and reflection, supporting the progressive development of students' logical reasoning and critical thinking skills (Nawafleh & Al-Abbas, 2025).

Challenges of Using AI to Support Critical Thinking Development in Science Education

The reviewed literature indicates that the use of artificial intelligence (AI) to support the development of critical thinking in science education is accompanied by multidimensional challenges. This study systematically synthesizes these challenges across several key dimensions, including the accuracy and reliability of AI-generated outputs, students' overreliance on technology and associated risks of cognitive weakening, insufficient teacher AI literacy and professional support, difficulties in instructional integration and curriculum implementation, limitations in assessing critical thinking outcomes, technological and infrastructural constraints, and ethical concerns. Overall, the integration of AI into science education for critical thinking development remains constrained by issues requiring systemic coordination and continuous optimization. Detailed findings are presented in Table 3.

Table 3
Challenges of AI in Supporting Critical Thinking

Dimension	Manifestations	Article
The reliability of AI output and the quality of information	1. AI may generate incorrect information, false citations, flawed reasoning, or "hallucinations" 2. The output text may appear reasonable but be difficult to identify as incorrect	(Zorlu, 2025) (Zhang et al., 2025) (Elshall & Badir, 2025) (Archila et al., 2024) (Ruff et al., 2024) (Cooper, 2023) (Bitzenbauer, 2023) (Baroud et al., 2025) (Holzmann et al., 2025)
Students' excessive reliance on AI and the risk of cognitive weakening	1.Students may place excessive trust in AI-generated results, leading them to verify evidence less frequently 2. It may reduce cognitive effort and the motivation for independent thinking 3. It may lead to metacognitive laziness, cognitive atrophy, and superficial learning	(Zorlu, 2025) (Vera et al., 2025) (Zhang et al., 2025) (Kunnath & Botes, 2025) (Elshall & Badir, 2025) (Zhao et al., 2026) (Huang et al., 2025) (Cooper, 2023) (Bitzenbauer, 2023) (KIER et al., 2025) (Baroud et al., 2025)
Teachers' AI teaching capabilities and teaching support are insufficient	1. Teachers lack AI training and practical experience 2. There are psychological and technical barriers to using AI 3. Teachers find it difficult to effectively utilize AI to guide their teaching	(Gunawan et al., 2021) (Vera et al., 2025) (Jufrida et al., 2025) (Kunnath & Botes, 2025)
There are difficulties in teaching integration and curriculum implementation	1. The structured integration of AI into formal curricula is limited 2. Complex AI tools are difficult to translate into classroom practice	(Marín Díaz, 2025) (Huang et al., 2025)
The cultivation effect and evaluation mechanism of critical thinking are insufficient	AI's methods for assessing critical thinking are still not fully developed	(Uchida et al., 2025)
Technical and infrastructure limitations	1. Unstable internet connection and insufficient equipment 2. Limited functionality in the free version 3. Technical difficulties in integrating AI	(Kunnath & Botes, 2025) (Huang et al., 2025)
Ethical issues	Ethical risks and insufficient guidelines for use	(Vera et al., 2025) (Cooper, 2023) (KIER et al., 2025)

As shown in Table 4, the most frequently reported challenges center on two primary issues: the reliability and quality of AI-generated information, and the risk of students' overdependence on AI leading to cognitive disengagement. On the one hand, generative AI may produce factual inaccuracies, logical inconsistencies, or oversimplified explanations, often creating an illusion of correctness. This can mislead students into assuming that the provided information is accurate and reliable, potentially resulting in misconceptions and inappropriate application during processes of understanding, transfer, and reasoning (Cooper, 2023; Ruff et al., 2024; Zorlu, 2025). On the other hand, excessive reliance on AI tools may foster cognitive passivity, reducing students' active inquiry and deep processing. As a result, learning may remain at the level of surface acceptance and outcome acquisition, thereby weakening essential critical thinking skills such as analysis, reasoning, and reflection (Baroud et al., 2025; Kunnath & Botes, 2025; Vera et al., 2025).

In addition, the effective implementation of AI in science education is constrained by insufficient teacher preparedness and ethical considerations. Many educators have yet to develop adequate AI literacy and the pedagogical capacity required to meaningfully integrate AI functionalities with the cultivation of higher-order thinking (Gunawan et al., 2021; Jufrida et al., 2025). Ethical issues, including data privacy and academic integrity, further complicate the responsible use of AI in educational contexts (KIER et al., 2025).

Moreover, challenges persist in the integration of AI into instructional practices, curriculum implementation, and the assessment of critical thinking outcomes. Existing frameworks and application pathways remain underdeveloped and lack systematic coherence, indicating a need for further refinement (Marín Díaz, 2025; Uchida et al., 2025). Finally, limitations related to technological infrastructure and access may exacerbate practical barriers to implementation, particularly in resource-constrained educational settings (Huang et al., 2025).

Discussion

Implications of Developmental Trends and Research Methodologies

From an overall developmental perspective, the rapid increase in publications between 2021 and 2025 indicates that research on AI-supported critical thinking in science education is transitioning from an exploratory phase to a stage of rapid expansion. This trend largely reflects the deepening application of AI technologies in education. In particular, the rapid advancement of intelligent learning systems, adaptive learning platforms, and generative AI tools has enabled researchers to more directly investigate the role of AI in fostering higher-order cognitive skills (Zhao et al., 2026).

Moreover, the consistent growth patterns observed across both Scopus and Web of Science suggest that this research topic has gained sustained and widespread attention within the international academic community. This trend not only highlights the increasing integration of AI into educational practice but also underscores its potential to support the development of critical thinking and other key twenty-first-century skills (Celik et al., 2024). Consequently, it provides a strong foundation for further expansion and deeper exploration in this field.

In terms of methodological distribution, research on AI-supported critical thinking in science education is characterized by the dominance of mixed-methods approaches, alongside the parallel development of quantitative and qualitative studies. This pattern reflects a dual emphasis within the field: on the one hand, the need to measure the effectiveness of instructional interventions, and on the other, the importance of understanding learning processes and underlying cognitive mechanisms. The widespread adoption of mixed methods suggests an increasing recognition that reliance on quantitative indicators alone is insufficient to capture the complexity of critical thinking development in AI-mediated learning environments. Instead, qualitative evidence is essential for contextualizing and explaining quantitative findings, thereby enabling a more comprehensive and coherent evidence base.

Notably, some studies have incorporated design-based research (DBR) frameworks, which emphasize iterative cycles of design, implementation, and refinement within authentic classroom settings, alongside continuous evaluation of their impact on students' critical thinking (Suyidno et al., 2025). This methodological shift indicates that the field is moving beyond early-stage validation of AI tools toward the reconstruction of instructional models and the optimization of pedagogical practices. It also suggests that future research is likely to place greater emphasis on long-term classroom implementation and the systematic integration of pedagogy and technology.

Overall, the increasing methodological diversity not only reflects the inherent complexity of the research topic but also signals a broader shift from isolated experimental studies toward more contextualized, process-oriented, and longitudinal investigations. Future research should therefore maintain empirical rigor while strengthening multi-source data integration, longitudinal designs, and systematic instructional interventions in authentic educational settings. Such efforts will further enhance the explanatory power of research findings and their practical relevance for science education.

Differential Effects of AI Tools on the Development of Critical Thinking in Science Education

This study reveals that different types of AI tools exhibit both functional differentiation and synergistic effects in supporting the development of critical thinking in science education. This finding suggests that the role of AI in education is evolving from a single instructional aid toward a multidimensional cognitive support system (Liu, 2025). Various AI technologies are increasingly embedded in the learning process through mechanisms such as cognitive scaffolding, learning pathway regulation, data-driven feedback, and contextualized scenario construction. Together, these functions form an integrated technological ecosystem that supports the development of critical thinking. This multi-path development trend indicates that AI applications in education are shifting beyond improving the efficiency of knowledge transmission toward fostering deeper cognitive engagement and processing (Shahzad et al., 2025).

Among these technologies, the prominent use of generative AI is particularly noteworthy. Its dialogic interaction mechanism creates continuous cognitive challenges and dynamic feedback loops within the learning process. This iterative pattern of "ongoing prompting–immediate response–subsequent refinement" inherently strengthens learners' argumentation and reflective practices (Ocak et al., 2025). Unlike traditional digital learning tools, which primarily focus on information delivery or answer provision, generative AI directly engages with learners' reasoning processes and judgment formation, making it one of the most promising tools for supporting higher-order cognition (Zhao et al., 2026). However, the findings also indicate that the effectiveness of generative AI is highly contingent upon pedagogical guidance. In the absence of well-structured tasks and teacher facilitation, learners may become overly reliant on AI-generated outputs, thereby weakening their independent reasoning and argumentation processes (Zoelfakar & Ibrahim, 2026). Thus, the educational value of generative AI depends less on the technology itself and more on the extent to which instructional design incorporates strategies for critical use and reflective engagement.

Beyond generative AI, the widespread use of adaptive and personalized learning systems further demonstrates how AI influences the developmental pathways of critical thinking through learning process regulation. By dynamically aligning task difficulty with learners' cognitive needs, these systems maintain an optimal level of challenge, thereby providing essential cognitive support for complex reasoning and deep thinking (Hariyanto et al., 2025). This finding aligns with (Juniayanti & Dewi, 2025), who highlights the positive role of AI in regulating cognitive load, thereby facilitating deeper information processing and understanding.

Although learning analytics systems, predictive AI, explainable AI, and virtual simulation systems appear less frequently in the reviewed studies, their functional orientations highlight the diverse mechanisms through which AI contributes to critical thinking development. These tools operate at different levels of the learning process, collectively enabling multiple pathways for fostering critical thinking in science education. As noted by (Obaje, 2025), AI is no longer merely embedded as a technological tool within instructional processes; rather, it actively stimulates learners' cognitive processing and metacognitive regulation across multiple dimensions. This shift reflects a broader paradigm transition from "supporting learning" to "enhancing thinking."

Overall, the findings suggest that AI is reshaping the development of critical thinking in science education through diverse technological pathways. The focus is gradually shifting from technology-supported knowledge acquisition toward the construction of intelligent learning environments centered on cognitive processes. Future research should further investigate the combined use of different AI tools in authentic classroom settings, their long-term effects on learning outcomes, and the role of teacher facilitation in optimizing their impact.

Pedagogical Mechanisms and Implications of AI-Integrated Instructional Designs for Supporting Critical Thinking in Science Education

The findings of this study indicate that the application of artificial intelligence (AI) in science education is undergoing a shift from "tool-based support" to "deep integration with instructional design." This transition suggests that AI is no longer merely an external resource for information access or learning assistance, but is increasingly embedded as a core component within curriculum structures, learning tasks, and classroom interactions. Existing studies demonstrate integration across multiple dimensions, including instructional models, pedagogical frameworks, teaching methods, and instructional modules. This reflects a broader movement from isolated technological interventions toward the systematic reconstruction of teaching and learning processes. Fundamentally, this shift indicates that the role of AI in classroom practice is evolving from enhancing immersive learning environments to fostering deeper cognitive processing and higher-order thinking (Ilgun Dibek et al., 2025).

At the level of instructional models, the integration of AI with project-based learning, inquiry-based learning, and problem-based learning suggests a growing emphasis on embedding critical thinking within authentic problem-solving contexts. By incorporating intelligent support and dynamic feedback into complex tasks, AI enables sustained engagement in evidence evaluation, logical reasoning, and reflective revision. This trend highlights that the value of AI extends beyond the provision of learning resources; it lies in its capacity to sustain learners' cognitive engagement through structured task design, thereby transforming the development of critical thinking from episodic training into a continuous learning process (Shahzad et al., 2025).

At the levels of pedagogical frameworks and instructional methods, AI integration is reshaping patterns of classroom interaction. AI-supported data analytics, real-time feedback, and multi-perspective information generation are transforming classroom discourse from one-way knowledge transmission into iterative, dialogic processes of argumentation (Zhao et al., 2026). The incorporation of AI into dialogic teaching, guided discovery learning, and embedded discussion-based approaches further demonstrates its role in strengthening argumentation-centered practices of critical thinking. These approaches encourage learners to engage in the comparison of multiple perspectives, the construction of coherent reasoning chains, and the dynamic revision of explanatory frameworks.

In addition, the development of AI-supported instructional modules highlights how structured learning sequences, staged cognitive tasks, and continuous feedback mechanisms can be systematically integrated and dynamically regulated. Such designs enable coherent progression across instructional stages and promote the coordinated development of learners' critical thinking. As noted by (Saar et al., 2026), the deep integration of AI and instructional design is increasingly significant for the construction and optimization of overall teaching systems, with a growing emphasis on the continuous operation and dynamic refinement of instructional processes, ultimately contributing to the development of higher-order thinking skills.

Overall, the deep integration of AI and instructional design is advancing the development of critical thinking by reconstructing learning contexts, optimizing instructional structures, and strengthening cognitive support mechanisms. Future research should further examine the synergistic relationships between AI and diverse instructional models and methods, with particular attention to developing coherent, sustainable, and scalable frameworks for implementation.

Discussion of the Challenges in Employing AI for Critical Thinking Development in Science Education

The synthesis of this study indicates that, although artificial intelligence (AI) demonstrates considerable potential in supporting the development of critical thinking in science education, its practical implementation remains constrained by multiple interrelated factors. These challenges extend beyond technical limitations and involve issues related to the quality of AI-generated information, learners' cognitive processes, teachers' professional capacities, and broader institutional and ethical contexts.

One of the most prominent challenges identified in the literature concerns the reliability and quality of AI-generated outputs. While generative AI is capable of producing well-structured and linguistically coherent explanations, its content may still include factual inaccuracies, oversimplified reasoning, or flawed inferences (Bitzenbauer, 2023). This "superficially plausible but potentially flawed" information can create an illusion of credibility, thereby reducing students' attention to evidence verification and reasoning processes. If learners uncritically accept AI-generated responses as authoritative, the learning process may shift from scientific inquiry toward mere answer acquisition, ultimately undermining the development of critical thinking (Martinez et al., 2025). Therefore, the educational value of AI depends not only on the accuracy of its outputs but also on whether instructional design positions these outputs as objects of critique, verification, and reflection.

Another widely recognized challenge is students' overreliance on AI tools. Existing research suggests that when AI significantly reduces the cognitive effort required for information retrieval, explanation generation, and problem solving, learners may develop dependency and cognitive passivity, which in turn weakens their capacity for independent thinking and judgment (Vera et al., 2025). The key issue, therefore, is not whether AI should be used, but how instructional strategies can balance the reduction of mechanical cognitive load with the preservation of meaningful cognitive engagement and inquiry processes.

Furthermore, this study highlights the critical role of teachers' AI literacy and pedagogical integration capacity in shaping the effectiveness of AI-supported critical thinking development. Many educators have yet to develop systematic competencies in applying AI within instructional contexts, making it challenging to align technological functionalities with inquiry-based learning and cognitive development goals (Celik et al., 2022). Studies by (Kim et al., 2022; Yue et al., 2022) further emphasize that the educational value of AI depends on teachers' ability to transform technological applications into cognitively engaging activities that promote argumentation, comparison, and reflection. In this regard, teachers' professional judgment and instructional design expertise remain central determinants of whether AI can effectively support the development of critical thinking (Alqarni, 2025).

In addition, limited integration of AI within curriculum structures and the lack of robust assessment mechanisms for evaluating critical thinking constrain its educational potential. These limitations hinder the effective use of AI in supporting inquiry-based learning and complex problem-solving. Future educational practice should therefore prioritize deeper integration of AI into curriculum design and the development of more comprehensive assessment frameworks capable of capturing students' reasoning processes and cognitive development.

Other factors, such as cognitive load, also impose constraints on AI-supported learning environments. Moreover, ethical concerns—including data privacy, academic integrity, and unequal access to technological resources—may affect both the responsible use and equitable implementation of AI in educational settings. As noted by (Criado et al., 2025; Ni & Hassan, 2024), the integration of AI for critical thinking development is not solely a pedagogical issue but also involves broader considerations related to policy, ethical governance, and resource allocation.

Accordingly, the effective realization of AI's educational potential depends on the establishment of robust institutional and technological support systems. Future research and practice should prioritize improving the reliability of AI outputs and strengthening cognitive support mechanisms, while simultaneously enhancing teachers' AI competencies, refining ethical frameworks, and advancing curriculum integration, assessment practices, and technological infrastructure. Such coordinated efforts are essential to fully leverage AI in fostering higher-order thinking in science education.

Limitations and Conclusion

Limitations

This study has several limitations. First, in the literature selection process, conference papers, books, book chapters, and review articles were excluded, and only peer-reviewed journal articles published in English were included. While this approach helps ensure research quality and comparability, it may have led to the omission of relevant studies published in other formats or languages, thereby limiting the comprehensiveness of the review.

Second, the time frame of the included literature was restricted to publications from January 1, 2021, to December 31, 2025. Although this delimitation allows for a focused examination of recent developments during the rapid advancement of AI technologies, it may exclude earlier foundational studies, thus constraining the representation of the long-term evolution of the field.

Finally, this review focused exclusively on science education within the natural sciences, including physics, chemistry, biology, and geography. Studies related to computer science education, social sciences, and medical or health sciences were not included. While this disciplinary focus enhances the consistency of the analysis, it may limit the generalizability of the findings to broader educational contexts.

Conclusion

This systematic review demonstrates that artificial intelligence is becoming a key driver in reshaping the development of critical thinking in science education. Over the past five years, research in this field has grown rapidly, with mixed-methods approaches dominating and quantitative and qualitative paradigms developing in parallel. Future research should further enhance explanatory depth through multi-source data integration, longitudinal research designs, and systematic investigations conducted in authentic classroom contexts.

At the level of technological application, different types of AI tools exhibit both functional differentiation and synergistic effects in supporting critical thinking development. Generative AI and adaptive personalized learning systems are the most widely used, while learning analytics, predictive AI, explainable AI, and virtual simulation systems are gaining increasing attention. Overall, AI is reshaping the cultivation of critical thinking through multiple technological pathways, shifting its role from supporting knowledge acquisition to facilitating cognitive processes. Future studies should explore the combined use of multiple AI tools, their long-term effects on learning outcomes, and the role of teacher regulation.

In terms of pedagogical integration, AI is most commonly combined with project-based and inquiry-based learning models and is increasingly embedded within instructional frameworks, curriculum modules, and teaching methodologies. This trend indicates a transition from tool-level application toward the reconstruction of instructional systems. Future research should therefore focus on the synergistic mechanisms between AI and diverse instructional designs, aiming to develop coherent, stable, and scalable implementation frameworks.

Despite its potential, the application of AI continues to face several challenges, including issues related to output reliability and information quality, students' overreliance on AI, insufficient teacher AI competence, underdeveloped ethical frameworks, limited curriculum integration and assessment mechanisms, and constraints in technological infrastructure. Future research and practice should prioritize improving the reliability of AI systems and strengthening cognitive support mechanisms, while simultaneously enhancing teacher professional capacity, ethical governance, curriculum integration, and assessment practices. Such coordinated efforts are essential to fully realize the potential of AI in supporting the development of higher-order thinking in science education.

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