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Transforming Science Education through Artificial Intelligence (AI): Opportunities, Challenges, and Implications for Students' Critical Thinking Skills in the Digital Era.

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Abstract

Artificial intelligence (AI) is reshaping science education by expanding access to information, supporting adaptive instruction, enabling simulations, and providing timely feedback. This article examines the opportunities, challenges, and implications of AI integration for students' critical thinking in the digital era. Using a narrative literature review, the study synthesizes foundational scholarship on AI in education, science learning, AI literacy, and critical thinking, alongside recent reviews and international guidance. The synthesis indicates that AI can support critical thinking when it is embedded in inquiry-oriented activities that require students to formulate questions, interpret scientific evidence, compare explanations, identify limitations, and justify conclusions. AI-supported simulations, conversational systems, and feedback tools may make abstract concepts more accessible and provide opportunities for iterative reasoning. However, these benefits are not automatic. Hallucinated information, algorithmic bias, privacy risks, unequal access, academic integrity concerns, and cognitive over-reliance may weaken learning if AI outputs are accepted without verification. The article argues that AI should function as a cognitive partner rather than a substitute for students' intellectual work. Effective integration therefore requires scientific and AI literacy, teacher mediation, transparent assessment, ethical safeguards, and learning tasks that make reasoning visible. A human-centred approach can help science education use AI to strengthen, rather than displace, independent and evidence-based thinking.

Keywords Artificial intelligence; Critical thinking; Digital learning; Science education; Scientific literacy

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INTRODUCTION

Science education is expected to prepare learners to understand natural phenomena, evaluate evidence, solve problems, and make informed decisions in a world increasingly shaped by digital technologies. Artificial intelligence (AI), broadly

understood as computational systems capable of performing tasks associated with human intelligence, is becoming part of this educational landscape. Applications such as intelligent tutoring systems, adaptive learning platforms, automated feedback tools, conversational agents, and AI-supported simulations can influence how scientific knowledge is accessed, represented, discussed, and assessed (Holmes et al., 2019; Zawacki-Richter et al., 2019).

Nevertheless, the educational value of AI cannot be measured simply by the speed or fluency of the answers it produces. Science learning requires students to distinguish claims from evidence, evaluate the reliability of sources, interpret data, recognize uncertainty, and revise explanations when evidence changes. These activities are central to scientific reasoning and critical thinking (National Research Council, 2012; Osborne, 2010). Critical thinking involves purposeful judgment, interpretation, analysis, evaluation, inference, and explanation (Facione, 1990). Therefore, the central educational question is not whether AI can provide answers, but whether interaction with AI encourages students to reason more carefully about those answers.

AI may strengthen students' thinking by making feedback more immediate and by providing prompts that invite comparison, explanation, and reflection. However, the same tools may encourage cognitive offloading if students copy generated responses, accept inaccurate claims, or allow automated systems to determine what counts as a correct explanation. UNESCO (2023) cautions that generative AI can affect privacy, agency, knowledge construction, and the development of higher-order thinking when adopted without appropriate pedagogical and regulatory safeguards. Similar concerns have been raised about the need to preserve human judgement and academic integrity in AI-supported learning (Kasneci et al., 2023; Tlili et al., 2023).

This article examines how AI can transform science education and considers the conditions under which such transformation may support students' critical thinking skills. It focuses on three questions: (1) What opportunities does AI offer for teaching and learning science? (2) What pedagogical, ethical, and practical challenges accompany its integration? and (3) How can science teachers design AI-supported learning so that students remain active evaluators and producers of knowledge? The article argues that AI is most educationally valuable when used as a resource for inquiry and critique, not as an authority whose outputs are accepted without examination.

METHODS

This article employs a narrative literature review to examine the relationship between artificial intelligence, science education, and students' critical thinking. A

narrative approach is appropriate because the topic brings together conceptual foundations, empirical reviews, educational frameworks, and policy guidance from several related fields. Rather than claiming to conduct a systematic review with a reproducible database search and screening protocol, the article offers an interpretive synthesis of selected scholarly publications and authoritative reports relevant to the research questions.

The literature was selected purposively for its relevance to four themes: (1) applications of AI in teaching and learning; (2) AI integration in science education; (3) definitions and pedagogies of critical thinking and scientific reasoning; and (4) ethical, institutional, and equity-related challenges. The sources include peer-reviewed journal articles, scholarly books, an international science education framework, and UNESCO guidance. Priority was given to foundational works and recent reviews that directly discuss AI-supported learning, generative AI, or science education.

The analysis was conducted through thematic synthesis. First, the selected sources were read to identify recurring claims about AI affordances and limitations. Second, these claims were grouped into instructional opportunities, risks and constraints, and implications for critical thinking. Third, the themes were interpreted in relation to inquiry-based science learning, in which students develop explanations through questions, evidence, reasoning, and communication. Because this is a literature-based conceptual article, it does not report original participant data, experimental effects, or statistical estimates.

The conceptual relationship guiding the discussion can be summarized as follows: AI-supported resources provide information, feedback, adaptive support, and simulations; teacher-designed inquiry tasks determine how students engage with those resources; students' critical thinking is expressed through questioning, evidence evaluation, inference, explanation, and reflection; and ethical safeguards shape the reliability and fairness of the learning environment.

RESULTS AND DISCUSSION

Results

The literature synthesis indicates that AI contributes to science education through several connected functions. These include adaptive explanations, intelligent tutoring, automated feedback, conversational support, data analysis assistance, and interactive simulations. The educational value of these functions depends on the learning objective and on whether students are required to interpret and evaluate the information generated by the system.

Table 1. Opportunities and risks of AI integration in science education

AI application	Potential learning opportunity	Critical-thinking condition
Adaptive tutoring and explanations	Provides differentiated explanations and supports learners at varied levels.	Students compare explanations with textbooks, observations, and scientific evidence.
Generative AI dialogue	Offers questions, examples, alternative hypotheses, and immediate conversational feedback.	Students challenge outputs, request evidence, and identify uncertainty or unsupported claims.
Simulation and visualization	Makes complex or abstract scientific processes more accessible for exploration.	Students interpret variables, distinguish models from reality, and explain limitations.
Feedback and assessment support	Provides formative feedback and helps identify areas requiring revision.	Students judge feedback quality and justify revisions rather than accepting scores automatically.
Data and research assistance	Supports data organization, pattern identification, and preliminary analysis.	Students check calculations, assess data quality, and avoid confusing correlation with causation.

Source: The authors' synthesis of the reviewed literature.

A second result concerns the conditional relationship between AI use and critical thinking. AI tools can provide cognitive scaffolding, but the presence of a tool does not itself demonstrate that higher-order thinking has occurred. Learning tasks must require students to make their reasoning visible. For example, a student who asks an AI system to explain photosynthesis and copies the response has completed an information-retrieval activity. A student who compares the explanation with experimental observations, identifies missing mechanisms, checks terminology, and revises a claim has engaged in deeper scientific reasoning.

Discussion

1. Opportunities for Transforming Science Education

One major opportunity is personalization. Adaptive systems can present explanations, exercises, and feedback that respond to students' progress and learning needs. This may be useful in science, where learners enter classrooms with different levels of prior knowledge and may struggle with abstract concepts. AI-supported tutoring can offer alternative representations and additional practice, while teachers use the resulting information to identify misconceptions. Such support is consistent with broader analyses of AI in education, which describe its potential to support tutoring, assessment, and instructional decision-making (Holmes et al., 2019; Zawacki-Richter et al., 2019).

A second opportunity is the expansion of inquiry. Conversational AI can help students formulate investigable questions, generate competing hypotheses, and consider variables that may influence an experiment. In a biology lesson, for instance, students may ask how light intensity affects plant growth. The AI tool can suggest possible variables and experimental controls, but students should decide which suggestions are scientifically appropriate and design a feasible investigation. This approach positions AI as a brainstorming partner while preserving students' responsibility for methodological decisions.

A third opportunity is the visualization of complex phenomena. Science education often requires learners to reason about processes that cannot be observed directly, such as molecular interactions, planetary motion, or energy transfer. AI-enabled simulations and intelligent learning environments may support exploration by allowing students to manipulate variables and observe modeled outcomes. However, simulations are representations rather than exact copies of reality. Students should therefore discuss assumptions, boundaries, and limitations of the model. The National Research Council (2012) emphasizes the importance of integrating scientific practices with disciplinary core ideas, while Osborne (2010) highlights argumentation as a central dimension of science education.

AI may also broaden access to feedback. Generative systems can respond to students' explanations and suggest areas for clarification. When used formatively, such feedback can support iterative writing, explanation-building, and reflection. Kasneci et al. (2023) identify potential educational uses of large language models while emphasizing the need to address limitations and risks. The key is to make feedback an object of evaluation: students should determine whether an AI suggestion is relevant, accurate, and supported by evidence.

2. Implications for Students' Critical Thinking Skills

Critical thinking in science involves more than recalling facts. It includes interpreting information, analyzing relationships, evaluating evidence, drawing warranted inferences, explaining conclusions, and reflecting on the reasoning process. Facione (1990) identifies interpretation, analysis, evaluation, inference, explanation, and self-regulation as core dimensions of critical thinking. Ennis (2011) similarly emphasizes reasonable reflective thinking directed toward deciding what to believe or do. These dimensions provide a useful basis for designing AI-supported science activities.

AI can support interpretation when students use it to clarify scientific vocabulary, summarize complex passages, or translate technical explanations into accessible language. It can support analysis when learners compare alternative explanations or examine relationships among variables. It can support evaluation when students verify claims against credible sources, assess the relevance of evidence, and identify possible bias. It can support inference when students use data to develop explanations, provided that they independently examine whether the conclusion follows from the evidence. Finally, it can support self-regulation when students reflect on how AI influenced their decisions and identify where they need further learning.

These benefits depend on active intellectual engagement. Kuhn (1999) argues that developing thinking skills requires opportunities to reason about evidence and arguments. In science classrooms, students should therefore be asked to explain why an AI-generated answer is convincing or unconvincing, identify missing evidence, and revise conclusions when new information becomes available. AI literacy is also important. Long and Magerko (2020) describe AI literacy as a set of competencies that enables people to critically evaluate AI technologies and communicate and collaborate effectively with them. Ng et al. (2021) likewise emphasize the need to conceptualize and develop AI literacy as an educational capability.

A practical strategy is to require an 'AI output audit' in which students identify the main claim generated by an AI tool, verify at least two supporting facts using credible sources, note any uncertainty or error, and write a reasoned judgment. This makes the evaluation of AI output part of the learning objective rather than an optional precaution. It also aligns with the view that scientific literacy includes evaluating evidence and engaging in reasoned decision-making (National Research Council, 2012; OECD, 2019).

3. Challenges and Risks of AI Integration

The first challenge is factual unreliability. Generative AI may produce fluent but inaccurate explanations, fabricated references, incorrect calculations, or misleading

descriptions of scientific processes. This is particularly consequential in science education, where conceptual misunderstandings can affect later learning. Students may mistake linguistic confidence for scientific validity. Teachers should make verification routine and require students to consult authoritative textbooks, peer-reviewed literature, datasets, or primary observations. Almasri (2024) also identifies limitations related to subject-specific understanding, contextual adaptation, and variation in AI system performance.

The second challenge is cognitive over-reliance. If learners use AI to generate complete answers, they may reduce the effort required to formulate questions, organize evidence, and construct explanations. UNESCO (2023) warns that overdependence on generative AI may weaken independent thought and reduce opportunities for learning through direct experience and experimentation. The appropriate response is not necessarily to prohibit AI, but to design tasks in which students must document their own reasoning, explain revisions, and defend conclusions orally or in writing.

The third challenge concerns bias, privacy, and transparency. AI systems may reproduce biases present in training data, provide uneven quality across languages and contexts, or process personal information in ways that are not fully understood by learners. UNESCO (2023) recommends a human-centred approach that protects data privacy and promotes age-appropriate, ethical use. Educational institutions should establish clear rules about which tools may be used, what information must not be entered into them, how AI assistance should be acknowledged, and how outputs are checked.

The fourth challenge is unequal access. Students and schools may differ in internet connectivity, device availability, subscription access, language support, and teacher expertise. If AI-supported learning is available only to well-resourced learners, it may widen existing educational inequalities. AI integration should therefore be accompanied by infrastructure planning, accessible alternatives, professional development, and attention to local language and curriculum needs. Reviews of AI in education note that institutional readiness and educator capacity remain important conditions for meaningful adoption (Crompton & Burke, 2023; Zawacki-Richter et al., 2019).

Academic integrity and assessment design also require attention. Traditional assignments that reward only a polished final answer may not reveal whether students understand the science or simply reproduce AI-generated content. Assessment should include process evidence, such as research notes, annotated sources, experiment

records, drafts, oral explanations, and reflections on AI use. Tlili et al. (2023) discuss the opportunities and challenges of ChatGPT in education, including the need to rethink educational practice in response to generative systems. Dwivedi et al. (2023) similarly describe broad implications of generative conversational AI for research, practice, and policy.

4. Pedagogical Strategies for Responsible Integration

First, teachers should align AI use with explicit learning outcomes. If the objective is to develop scientific reasoning, students should not be asked merely to obtain an answer from an AI system. They should formulate questions, evaluate generated explanations, compare claims with evidence, and communicate a justified conclusion. AI should be selected only when it adds value to the intended learning activity.

Second, inquiry-based and problem-based learning can provide a structure for meaningful AI engagement. Students may investigate a local environmental issue, such as water quality or waste management, and use AI to brainstorm variables, clarify concepts, or organize possible explanations. They must then collect or examine evidence, assess the credibility of AI suggestions, and decide which claims are defensible. This makes AI use subordinate to scientific investigation.

Third, teachers should model critical interaction with AI. They can demonstrate how to ask for sources, request alternative explanations, identify uncertainty, and cross-check factual claims. Students should learn that AI-generated references may be inaccurate and that an answer should not be accepted merely because it sounds authoritative. The teacher's role shifts toward designing learning experiences, facilitating dialogue, and helping students evaluate information.

Fourth, assessment should reward reasoning and transparency. Rubrics can assess the quality of questions, use of evidence, evaluation of sources, logical consistency, acknowledgement of uncertainty, and reflection on AI assistance. Students may be asked to submit a short record describing the prompts used, the output they rejected or revised, and the evidence that informed their final conclusion. This approach supports accountability while recognizing that AI is becoming part of contemporary knowledge work.

Finally, institutions should establish human-centred governance. Policies should address privacy, age-appropriate use, accessibility, disclosure, bias, and teacher professional learning. AI literacy should be developed alongside scientific literacy, not treated as a replacement for it. These recommendations are consistent with UNESCO's (2023) guidance and with the broader argument that educational AI should augment human capacities while maintaining human agency (Holmes et al., 2019; Miao &

Holmes, 2023).

5. An Integrative Perspective

The relationship between AI and critical thinking is best understood as conditional rather than automatically positive or negative. AI can extend students' access to explanations, feedback, and representations, but it can also make it easier to avoid intellectual effort. The decisive factor is the quality of the learning design. When tasks emphasize inquiry, evidence evaluation, explanation, and reflection, AI can become a resource for deeper learning. When tasks reward speed, copying, and answer production alone, AI may encourage superficial engagement.

This perspective also clarifies that AI competence and scientific competence should develop together. Students need enough scientific knowledge to recognize implausible outputs and enough AI literacy to understand that system responses are generated through computational processes and may contain errors or bias. In this way, critical thinking is not an optional addition to AI use; it is the central capability that makes AI-supported science learning educationally meaningful.

CONCLUSION

Artificial intelligence offers significant opportunities to transform science education through adaptive explanations, conversational support, simulations, feedback, and assistance with scientific inquiry. These applications can make learning more responsive and provide additional opportunities for students to explore complex concepts. Their contribution to critical thinking, however, depends on how they are integrated into teaching and assessment.

The article concludes that AI is most beneficial when it functions as a cognitive partner rather than a substitute for students' reasoning. Students should be required to question AI-generated claims, verify information, evaluate evidence, recognize uncertainty, and justify their conclusions. At the same time, educators and institutions must address factual unreliability, cognitive over-reliance, bias, privacy, academic integrity, unequal access, and teacher preparedness.

Science teachers are encouraged to integrate AI into inquiry-based and problem-based learning, use assessment practices that make students' reasoning visible, and explicitly teach AI literacy and responsible use. Future empirical research should examine how different AI-supported instructional designs affect specific dimensions of critical thinking across educational levels, science subjects, and diverse Indonesian learning contexts. Such research should use transparent measures and account for students' prior knowledge, access to technology, and levels of AI literacy.

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