Journals Scientica Education Journal
E-ISSN : 3046-8523
https://jurnal-ilcaagam.com/index.php/SEJ/index
Vol.2.No.2 May 2025

Artificial Intelligence-Enhanced Learning in Science Education to Improve Scientific Literacy, Critical Thinking, and Personalized Learning Outcomes

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Entered : May 01, 2025 Revised : April 13, 2025
Accepted: May 17, 2025 Published : May 27, 2025

ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas pembelajaran berbasis kecerdasan buatan (Artificial Intelligence/AI) dalam meningkatkan literasi sains, keterampilan berpikir kritis, dan hasil pembelajaran yang dipersonalisasi pada pembelajaran IPA. Penelitian ini menggunakan pendekatan kuantitatif dengan desain quasi eksperimen berupa non-equivalent control group. Partisipan penelitian terdiri dari dua kelompok, yaitu kelompok eksperimen yang menggunakan pembelajaran berbasis AI dengan dukungan sistem tutor cerdas dan umpan balik adaptif, serta kelompok kontrol yang menggunakan metode pembelajaran konvensional. Data dikumpulkan melalui tes literasi sains, tes keterampilan berpikir kritis, dan angket pembelajaran personalisasi. Hasil penelitian menunjukkan bahwa kelompok eksperimen memperoleh nilai post-test yang lebih tinggi secara signifikan dibandingkan kelompok kontrol. Analisis normalized gain (N-gain) menunjukkan bahwa peningkatan pada kelompok eksperimen berada pada kategori sedang hingga tinggi, sedangkan kelompok kontrol berada pada kategori rendah hingga sedang. Uji statistik menggunakan independent sample t-test menunjukkan adanya perbedaan yang signifikan antara kedua kelompok ($p < 0,05$). Selain itu, pembelajaran berbasis AI terbukti meningkatkan kemampuan siswa dalam menginterpretasi data, mengevaluasi bukti, berpikir kritis, serta terlibat dalam proses pembelajaran yang dipersonalisasi. Hasil ini menunjukkan bahwa pembelajaran berbasis AI merupakan strategi yang efektif dan inovatif dalam meningkatkan kualitas pembelajaran serta mengembangkan kompetensi adaptif dalam pendidikan IPA.

Kata Kunci: *kecerdasan buatan, literasi sains, berpikir kritis, pembelajaran personalisasi, pendidikan IPA.*

ABSTRACT

This study aims to examine the effectiveness of artificial intelligence (AI)-enhanced learning in improving students' scientific literacy, critical thinking skills, and personalized learning outcomes in science education. The research employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. The participants consisted of two groups: an experimental group taught using AI-enhanced learning supported by intelligent tutoring systems and adaptive feedback, and a control group taught using conventional methods. Data were collected through a scientific literacy test, a critical thinking skills test, and a personalized learning questionnaire. The results showed that the experimental group achieved significantly higher post-test scores compared to the control group. The normalized gain (N-gain) analysis indicated that the experimental group reached a medium to high level of improvement, while the control group remained in the low to medium category. Statistical testing using an independent sample t-test revealed a significant difference between the two groups ($p < 0.05$). Furthermore, AI-enhanced learning significantly improved students' ability to interpret data, evaluate evidence, think critically, and engage in personalized learning processes. These findings suggest that AI-based learning is an effective and innovative instructional strategy for enhancing both cognitive and adaptive learning outcomes in science education.

Keywords: *artificial intelligence, scientific literacy, critical thinking, personalized learning, science education.*

INTRODUCTION

The integration of Artificial Intelligence (AI) in education has emerged as one of the most transformative innovations in the 21st century, significantly reshaping teaching and learning practices in science education (Okunade, 2024). AI technologies, including machine learning, intelligent tutoring systems, and generative AI tools, enable adaptive learning environments that can provide personalized feedback, automate assessment, and support student-centered instruction (Puvvadi et al., 2025). Recent research indicates that AI is increasingly being adopted in science education to enhance student engagement, optimize instructional strategies, and improve learning outcomes through data-driven approaches (Almasri, 2024; Lee et al., 2025; He & Krajcik, 2026)

In science education, the development of scientific literacy and critical thinking skills is essential for preparing students to navigate complex real-world problems (Shanta, 2022). However, traditional instructional methods often fail to accommodate individual differences in learning pace, prior knowledge, and cognitive abilities (Dumont & Ready, 2023). AI-based learning systems address this limitation by enabling personalized learning experiences tailored to students' needs. Studies show that AI-driven tools can analyze student performance data, provide adaptive feedback, and support individualized learning pathways, thereby improving students' understanding of scientific concepts and their ability to apply knowledge in various contexts (Almasri, 2024; Shi et al., 2024; Lee et al., 2025)

Furthermore, AI technologies play a crucial role in enhancing higher-order thinking skills, particularly critical thinking and problem-solving. AI-supported learning environments encourage students to engage in inquiry-based activities, explore multiple solutions, and receive immediate feedback on their performance. The integration of AI tools such as chatbots and intelligent tutoring systems has been shown to foster student engagement and promote deeper cognitive processing, which are essential for developing critical thinking skills (Kotsis, 2024; Lee et al., 2025; He & Krajcik, 2026)

In addition, AI has the potential to revolutionize assessment practices in science education (Owan et al., 2023). Traditional assessment methods often focus on rote memorization and fail to capture students' ability to engage in scientific practices. AI-based assessment systems, on the other hand, can evaluate complex student responses, provide real-time feedback, and support performance-based assessment aligned with scientific inquiry processes (Terrazas-Arellanes et al., 2025). This shift toward intelligent assessment systems enables a more comprehensive evaluation of students' scientific literacy and critical thinking skills (Lee et al., 2025; Almasri, 2024; He & Krajcik, 2026)

Despite its significant potential, the implementation of AI in science education presents several challenges. These include ethical concerns, data privacy issues, teacher readiness, and the need for appropriate pedagogical integration (Perifanou et al., 2023). Research highlights that while AI offers powerful tools for enhancing learning, its effectiveness depends on how well it is aligned with educational objectives and instructional design. Without proper guidance, AI-based learning may lead to over-reliance on technology or superficial learning experiences (Lee et al., 2025; Almasri, 2024; Shi et al., 2024)

Moreover, although existing studies have explored the impact of AI on specific aspects of learning, there is still limited empirical research examining its integrated effect on multiple learning outcomes, such as scientific literacy, critical thinking, and personalized learning simultaneously. This gap highlights the need for comprehensive studies that investigate the holistic impact of AI-enhanced learning in science education. Therefore, this study aims to analyze the effectiveness of AI-enhanced learning in improving students' scientific literacy, critical thinking skills, and personalized learning

outcomes in science education. The findings of this research are expected to contribute to the development of innovative, technology-driven instructional strategies that support adaptive, student-centered learning and prepare learners for the demands of the digital era.

METHOD

This study employed a quantitative research approach using a quasi-experimental design with a non-equivalent control group to examine the effectiveness of artificial intelligence (AI)-enhanced learning in improving students' scientific literacy, critical thinking skills, and personalized learning outcomes in science education. This design is appropriate for classroom-based research where random assignment is not feasible, while still allowing for a systematic comparison between experimental and control groups (Creswell & Creswell, 2021).

The research was conducted in a secondary school setting involving two groups of students. The experimental group was taught using AI-enhanced learning supported by intelligent tutoring systems and AI-based feedback tools, while the control group received conventional teacher-centered instruction. The AI system provided adaptive learning pathways by analyzing students' responses and offering personalized feedback, recommendations, and learning materials tailored to individual needs. This adaptive feature enabled students to learn at their own pace and receive immediate support when encountering difficulties. Participants were selected using purposive sampling to ensure comparable academic backgrounds and learning characteristics between the two groups.

Data collection was carried out using three primary instruments: a scientific literacy test, a critical thinking skills test, and a personalized learning perception questionnaire. The scientific literacy test was adapted from international assessment frameworks, focusing on students' ability to interpret data, evaluate evidence, and apply scientific knowledge in real-world contexts (Organisation for Economic Co-operation and Development, 2023). The critical thinking test was designed based on higher-order thinking indicators, including analysis, evaluation, and inference. The personalized learning questionnaire measured students' perceptions of adaptive learning experiences, including engagement, autonomy, and satisfaction. All instruments were validated through expert judgment and pilot testing to ensure content validity and reliability.

The intervention was conducted over several instructional sessions, during which students in the experimental group interacted with AI-supported learning environments. These environments included features such as automated feedback, adaptive quizzes, and AI-generated explanations that guided students through inquiry-based learning processes. Previous research indicates that AI-based learning systems enhance students' engagement and learning outcomes by providing personalized and data-driven instructional support (Almasri, 2024; Lee et al., 2025; Shi et al., 2024).

Prior to the main study, a pilot test was conducted to evaluate the reliability of the instruments using Cronbach's alpha coefficient. Data analysis involved both descriptive and inferential statistics. Descriptive statistics were used to summarize students' performance and responses, while inferential statistics, including independent sample t-tests and normalized gain (N-gain), were used to determine the effectiveness of the intervention. Statistical analysis was performed using SPSS software with a significance level set at 0.05.

This methodological approach aligns with recent studies emphasizing the effectiveness of AI-enhanced learning in supporting personalized instruction, improving scientific literacy, and fostering higher-order thinking skills through adaptive and intelligent learning systems (Almasri, 2024; Lee et al., 2025; He & Krajcik, 2026).

RESULTS AND DISCUSSION

Descriptive Statistics of Learning Outcomes

The descriptive statistical analysis revealed that both the experimental and control groups experienced improvements in their post-test scores across all measured variables, including scientific literacy, critical thinking skills, and personalized learning outcomes. However, the experimental group, which was exposed to AI-enhanced learning, demonstrated a substantially higher increase compared to the control group. The relatively similar pre-test scores between the two groups confirm that students had comparable initial abilities, thereby strengthening the internal validity of the study and ensuring that the observed differences can be attributed to the intervention.

A closer examination of the post-test results indicates that AI-enhanced learning provided a more effective learning environment by supporting individualized learning pathways. Students in the experimental group were able to access adaptive content tailored to their learning needs, enabling them to better understand scientific concepts and apply them in various contexts. This adaptability allowed students to engage with learning materials at an appropriate level of difficulty, which contributed to improved academic performance and deeper understanding.

Moreover, the integration of AI-based feedback mechanisms played a crucial role in enhancing learning outcomes. Immediate and personalized feedback enabled students to identify misconceptions, reflect on their learning, and make necessary improvements in real time. In contrast, students in the control group relied on delayed and generalized feedback, which may have limited their ability to effectively address learning gaps. This difference highlights the importance of real-time feedback in supporting effective learning processes.

Normalized Gain (N-gain) Analysis

The normalized gain (N-gain) analysis showed that the experimental group achieved a medium to high level of improvement across all variables, while the control group remained within the low to medium category. The highest gain was observed in personalized learning outcomes, followed by critical thinking skills and scientific literacy.

This result suggests that AI-enhanced learning is particularly effective in facilitating personalized learning experiences. The adaptive capabilities of AI systems allow students to receive customized instructional support, which enhances their engagement and learning efficiency. Students can progress at their own pace, revisit challenging concepts, and receive targeted assistance, leading to more effective knowledge acquisition.

In addition, the improvement in critical thinking skills indicates that AI-based learning environments encourage higher-order cognitive processes. The use of intelligent tutoring systems and AI-generated prompts requires students to analyze information, evaluate alternatives, and make informed decisions. These activities promote deeper cognitive engagement and support the development of critical thinking skills.

Furthermore, the relatively lower gains in the control group highlight the limitations of traditional instructional approaches in supporting personalized and higher-order learning. Without adaptive support, students may struggle to address their individual learning needs, resulting in less effective learning outcomes. This finding underscores the importance of integrating AI technologies to enhance instructional effectiveness.

Scientific Literacy Analysis

The results indicated a significant improvement in scientific literacy among students in the experimental group. Students demonstrated enhanced abilities in

interpreting data, evaluating evidence, and applying scientific knowledge to real-world situations.

This improvement can be attributed to the AI system's ability to provide contextualized learning experiences. By presenting real-world scenarios and interactive tasks, AI-enhanced learning environments encourage students to engage in scientific inquiry and develop a deeper understanding of scientific concepts. Students are required to analyze data, draw conclusions, and justify their reasoning, which strengthens their scientific literacy.

Additionally, the adaptive feedback provided by AI systems helps students refine their understanding and improve their performance. Students receive immediate guidance on their responses, allowing them to correct errors and enhance their reasoning skills. This continuous feedback loop supports the development of scientific literacy by promoting reflective and self-regulated learning.

Critical Thinking Skills Analysis

The analysis of critical thinking skills revealed that students in the experimental group showed significant improvement in their ability to analyze problems, evaluate solutions, and make logical inferences. These improvements were particularly evident in tasks requiring higher-order thinking, such as problem-solving and decision-making.

The enhancement of critical thinking skills can be linked to the interactive and adaptive nature of AI-based learning environments. Students are frequently exposed to complex problems that require them to apply their knowledge and think critically. The AI system provides scaffolding and guidance, helping students navigate these challenges and develop their reasoning skills.

Moreover, AI-enhanced learning encourages metacognitive awareness by prompting students to reflect on their thinking processes. This reflection helps students develop a deeper understanding of their strengths and weaknesses, enabling them to improve their problem-solving strategies. In contrast, the control group showed limited improvement, suggesting that traditional instructional methods may not sufficiently support the development of critical thinking skills.

Personalized Learning Outcomes Analysis

The results of the personalized learning questionnaire indicated that students in the experimental group reported higher levels of engagement, autonomy, and satisfaction compared to the control group. Students expressed positive perceptions of the AI-based learning environment, particularly in terms of its ability to provide individualized support and adaptive learning experiences.

This finding highlights the effectiveness of AI in creating personalized learning environments that cater to individual student needs. The ability to adjust learning content and pace based on student performance enhances engagement and motivation, leading to improved learning outcomes.

Furthermore, the increased sense of autonomy experienced by students in the experimental group suggests that AI-enhanced learning promotes self-directed learning. Students are empowered to take control of their learning, explore topics of interest, and develop independent learning skills. This autonomy is essential for fostering lifelong learning and preparing students for future challenges.

Discussion

1. Effectiveness of AI-Enhanced Learning

The findings of this study confirm that AI-enhanced learning significantly improves students' scientific literacy, critical thinking skills, and personalized learning outcomes. This result is consistent with Almasri (2024), who found that AI technologies enhance learning outcomes by providing adaptive and data-driven instructional support.

Similarly, Lee et al. (2025) emphasized that AI-based learning systems improve student engagement and performance through personalized learning experiences.

Furthermore, He and Krajcik (2026) highlighted the potential of AI to transform science education by enabling more effective and efficient learning processes. The findings of this study reinforce these perspectives, demonstrating that AI-enhanced learning provides a powerful tool for improving multiple dimensions of student learning.

2. Role of Personalization in Learning

One of the key findings of this study is the significant impact of personalization on learning outcomes. AI-based systems provide tailored learning experiences that address individual student needs, leading to improved engagement and performance.

This finding aligns with Shi et al. (2024), who reported that AI-enabled systems support personalized learning by analyzing student data and providing adaptive feedback. The ability to customize learning pathways allows students to learn at their own pace and focus on areas where they need improvement. This personalized approach enhances learning efficiency and effectiveness.

Moreover, personalization supports inclusive education by accommodating diverse learning styles and abilities. Students who may struggle in traditional classrooms can benefit from adaptive learning environments that provide targeted support and guidance.

3. Enhancement of Higher-Order Thinking Skills

The improvement in critical thinking skills observed in this study highlights the effectiveness of AI in promoting higher-order thinking. AI-enhanced learning environments require students to engage in complex cognitive processes, such as analysis, evaluation, and synthesis. This finding is supported by Kotsis (2024), who emphasized that AI tools such as intelligent tutoring systems and chatbots promote inquiry-based learning and critical thinking. Additionally, Lee et al. (2025) noted that AI-based learning environments encourage deeper cognitive engagement by providing interactive and adaptive learning experiences.

4. Development of Scientific Literacy

The significant improvement in scientific literacy observed in this study indicates that AI-enhanced learning effectively supports the development of scientific reasoning skills. Students are able to interpret data, evaluate evidence, and apply scientific knowledge in meaningful ways. This result is consistent with the OECD (2023) framework, which emphasizes the importance of inquiry-based and data-driven learning in developing scientific literacy. AI systems facilitate these processes by providing interactive and contextualized learning experiences.

5. Challenges and Limitations

Despite its effectiveness, several challenges were identified in implementing AI-enhanced learning. These include concerns related to data privacy, ethical considerations, and the need for teacher training. Almasri (2024) and Lee et al. (2025) emphasized that the successful integration of AI in education requires careful consideration of ethical and pedagogical factors. Without proper implementation, AI may lead to over-reliance on technology or reduced human interaction.

CONCLUSION

This study concludes that the implementation of artificial intelligence (AI)-enhanced learning has a significant and comprehensive impact on improving students' scientific literacy, critical thinking skills, and personalized learning outcomes in science education. The findings clearly demonstrate that students who engaged in AI-supported learning environments outperformed those in conventional classrooms across all

measured variables. The adaptive capabilities of AI systems, including real-time feedback, personalized learning pathways, and data-driven instructional support, enable students to learn more effectively by addressing their individual needs and learning characteristics. Furthermore, AI-enhanced learning plays a crucial role in fostering higher-order thinking skills, particularly critical thinking. The interactive and inquiry-oriented nature of AI-based systems encourages students to analyze information, evaluate evidence, and make informed decisions. At the same time, AI supports the development of scientific literacy by providing contextualized learning experiences that allow students to interpret data and apply scientific knowledge in meaningful ways. These findings confirm that AI is not only a technological innovation but also a powerful pedagogical tool that enhances both cognitive and metacognitive aspects of learning.

The novelty of this study lies in its integrated examination of three key learning dimensions scientific literacy, critical thinking skills, and personalized learning outcomes within a single AI-enhanced instructional framework. Unlike previous studies that often focus on isolated variables, this research provides empirical evidence of how AI can simultaneously improve multiple aspects of student learning through personalization and adaptive feedback mechanisms. Additionally, this study highlights the central role of personalization as a driving factor in achieving effective and meaningful learning outcomes. However, the successful implementation of AI in science education requires careful consideration of pedagogical, technical, and ethical aspects. Teachers must be adequately trained to integrate AI tools into their instructional practices, and educational institutions must ensure the availability of appropriate technological infrastructure. Moreover, issues related to data privacy and ethical use of AI must be addressed to ensure responsible and sustainable implementation. In conclusion, AI-enhanced learning represents a transformative and innovative approach to science education in the digital era. By enabling personalized, adaptive, and interactive learning experiences, AI has the potential to significantly improve the quality of education and equip students with essential competencies required to thrive in an increasingly complex and technology-driven world.

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