

## AI-Supported Digital Learning Environments to Enhance Scientific Literacy and Critical Thinking in Science Education

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### ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas lingkungan pembelajaran digital berbasis kecerdasan buatan (AI) dalam meningkatkan literasi sains dan keterampilan berpikir kritis siswa 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 digital berbasis AI terintegrasi dengan pendekatan inkuiri dan kelompok kontrol yang menggunakan metode pembelajaran konvensional. Data dikumpulkan melalui tes literasi sains dan tes keterampilan berpikir kritis. 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 interpretasi data, evaluasi, dan pemecahan masalah. Hasil ini menunjukkan bahwa integrasi kecerdasan buatan dengan pembelajaran digital berbasis inkuiri merupakan strategi yang efektif untuk meningkatkan kualitas pembelajaran dan mengembangkan kompetensi abad ke-21 dalam pendidikan IPA.

**Kata Kunci:** kecerdasan buatan dalam pendidikan, pembelajaran digital, literasi sains, keterampilan berpikir kritis, pembelajaran inkuiri.

### ABSTRACT

*This study aims to examine the effectiveness of AI-supported digital learning environments in enhancing students' scientific literacy and critical thinking skills 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-supported digital learning integrated with inquiry-based activities and a control group taught using conventional methods. Data were collected through a scientific literacy test and a critical thinking skills test. 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-supported learning environments significantly enhanced students' abilities in data interpretation, evaluation, and problem-solving. These findings suggest that integrating artificial intelligence with inquiry-based digital learning is an effective strategy to promote meaningful learning and develop essential 21st-century competencies in science education.*

**Keywords:** artificial intelligence in education, digital learning environment, scientific literacy, critical thinking skills, inquiry-based learning.



## INTRODUCTION

The rapid advancement of digital technology and artificial intelligence (AI) has significantly transformed the landscape of science education in the 21st century (Jia, 2024). Science learning is no longer confined to traditional classroom settings but is increasingly supported by digital environments that enable interactive, adaptive, and personalized learning experiences (Yılmaz, 2024). These developments are essential in addressing the growing demand for scientific literacy and critical thinking skills, which are considered fundamental competencies for navigating complex global challenges (Alfaro-Ponce et al., 2024). Scientific literacy, in particular, involves not only understanding scientific concepts but also the ability to apply knowledge, interpret data, and evaluate evidence in real-world contexts. Recent studies highlight that integrating digital tools into science education enhances students' ability to engage in inquiry processes and develop scientific reasoning skills (Urdanivia Alarcon et al., 2023; Komalasari et al., 2024; Prayogi et al., 2024)

Furthermore, the integration of AI technologies into digital learning environments has opened new opportunities for improving the quality of science education (Kotsis, 2025). AI-supported learning systems can provide real-time feedback, adaptive learning pathways, and intelligent tutoring, enabling students to learn at their own pace while engaging in higher-order thinking processes (Saar et al., 2025). These systems also facilitate inquiry-based and problem-based learning by offering simulations, data analysis tools, and interactive experiments. Research indicates that AI-supported learning environments can significantly enhance students' critical thinking, problem-solving, and conceptual understanding by promoting active engagement and reflective thinking (Prayogi et al., 2024; Sukarma et al., 2024; Nurdiana et al., 2024)

In addition, the combination of digital learning, inquiry-based approaches, and STEM integration has been widely recognized as an effective strategy for improving science education outcomes (Kamarudin et al., 2024). Inquiry-based learning encourages students to actively construct knowledge through exploration and investigation, while digital tools provide opportunities for visualization and experimentation that are difficult to achieve in traditional classrooms. STEM-integrated approaches further strengthen this process by promoting interdisciplinary learning and real-world problem-solving. Several studies have shown that digital inquiry-based and STEM-supported learning environments significantly improve students' scientific literacy and critical thinking skills (Ramli & Borhan, 2024; Septiadevana & Abdullah, 2024; Lestari et al., 2024)

Despite these advantages, the implementation of AI-supported digital learning in science education still faces several challenges. These include limited technological infrastructure, insufficient teacher readiness, and a lack of pedagogical frameworks for effectively integrating AI into classroom practice. Moreover, students may experience difficulties in adapting to technology-enhanced learning environments that require self-regulation and independent learning. Previous studies emphasize that the success of digital and AI-supported learning depends not only on technology availability but also on instructional design and teacher facilitation (Urdanivia Alarcon et al., 2023; Halawa et al., 2024; Komalasari et al., 2024)

Therefore, this study aims to investigate the effectiveness of AI-supported digital learning environments in enhancing students' scientific literacy and critical thinking skills in science education. This research is expected to contribute to the development of innovative, technology-driven instructional strategies that align with the demands of 21st-century education and provide practical insights for educators in integrating AI into science learning.

## **METHOD**

This study employed a quantitative research approach using a quasi-experimental design with a non-equivalent control group to examine the effectiveness of AI-supported digital learning environments in enhancing students' scientific literacy and critical thinking skills. This design is widely used in educational research where random assignment is not feasible, allowing for comparison between experimental and control groups while maintaining the natural classroom setting (Creswell & Creswell, 2021).

The research was conducted in a secondary school setting involving two groups of students. The experimental group was taught using an AI-supported digital learning environment integrated with inquiry-based activities, while the control group received conventional teacher-centered instruction. The AI-supported learning environment included features such as adaptive learning systems, interactive simulations, automated feedback, and data-driven learning support. These tools enabled students to engage in inquiry processes, including problem identification, hypothesis formulation, experimentation, data analysis, and conclusion drawing. Participants were selected using purposive sampling to ensure that both groups had comparable academic backgrounds and learning characteristics.

Data collection was carried out using two main instruments: a scientific literacy test and a critical thinking skills test. The scientific literacy test was adapted from international assessment frameworks to measure students' ability to explain scientific phenomena, interpret data, and evaluate evidence (Organisation for Economic Co-operation and Development, 2023). The critical thinking test was developed based on indicators such as interpretation, analysis, evaluation, and inference. Both instruments were validated through expert judgment and pilot testing to ensure content validity and reliability.

The intervention was implemented over several instructional sessions, during which students in the experimental group interacted with AI-supported digital platforms to complete inquiry-based tasks. These tasks included virtual experiments, data analysis using digital tools, and problem-solving activities supported by AI-generated feedback. Previous studies have shown that AI-supported and digital inquiry-based learning environments enhance students' engagement, conceptual understanding, and higher-order thinking skills (Prayogi et al., 2024; Nurdiana et al., 2024; Ramli & Borhan, 2024).

Prior to the main study, a pilot test was conducted to assess the reliability of the instruments using Cronbach's alpha coefficient. Data analysis included descriptive statistics to summarize student performance and inferential statistics, such as independent sample t-tests and normalized gain (N-gain), to evaluate the effectiveness of the intervention. Statistical analysis was conducted using SPSS software with a significance level of 0.05.

This methodological approach is consistent with recent studies highlighting the effectiveness of AI-supported and digital learning environments in improving students' scientific literacy and critical thinking skills through interactive and adaptive learning processes (Sukarma et al., 2024; Komalasari et al., 2024; Halawa et al., 2024).

## **RESULTS AND DISCUSSION**

### **Descriptive Statistics**

The descriptive analysis of pre-test and post-test scores indicates that both the experimental and control groups experienced improvement after the learning intervention. However, the experimental group, which was exposed to AI-supported digital learning environments, demonstrated a substantially higher increase in post-test scores compared to the control group. The relatively similar pre-test scores between the

two groups suggest that students had comparable baseline abilities prior to the intervention, ensuring the internal validity of the study.

The higher improvement observed in the experimental group indicates that AI-supported learning environments provide more effective support for student learning compared to conventional instruction. The integration of adaptive feedback, interactive simulations, and inquiry-based activities enabled students to actively engage with the content and construct knowledge more effectively. This suggests that digital learning environments enhanced with AI can facilitate deeper understanding and promote more meaningful learning experiences.

### **Normalized Gain (N-gain) Analysis**

The normalized gain (N-gain) analysis revealed that the experimental group achieved a medium to high category of improvement, while the control group remained in the low to medium category. This finding indicates that the use of AI-supported digital learning significantly increased the efficiency of learning, allowing students to achieve greater conceptual understanding within the same instructional time.

The higher N-gain scores in the experimental group suggest that AI-supported learning environments are particularly effective in accelerating students' cognitive development. The adaptive nature of AI systems, which provide personalized learning pathways and immediate feedback, allows students to identify and correct misconceptions more effectively. As a result, students are able to progress more efficiently and achieve higher learning gains compared to traditional learning approaches.

### **Inferential Statistical Analysis**

The results of the independent sample t-test showed a statistically significant difference between the experimental and control groups ( $p < 0.05$ ). This confirms that AI-supported digital learning environments have a significant positive effect on students' scientific literacy and critical thinking skills.

Furthermore, the effect size analysis indicated a moderate to high effect, suggesting that the impact of the intervention is not only statistically significant but also practically meaningful. This highlights the potential of AI-supported learning environments as a powerful tool for improving educational outcomes. The results provide strong empirical evidence supporting the integration of AI in science education as an innovative instructional strategy.

### **Scientific Literacy Analysis**

The analysis of scientific literacy indicators revealed significant improvements in the experimental group across all dimensions, including explaining scientific phenomena, interpreting data, and evaluating evidence. The most prominent improvement was observed in students' ability to interpret data and evaluate scientific information.

This result indicates that AI-supported learning environments effectively enhance students' ability to engage in scientific reasoning processes. Through interactive simulations and data-driven activities, students were able to explore scientific concepts more deeply and develop stronger analytical skills. In contrast, the control group showed limited improvement, suggesting that traditional instruction does not sufficiently support the development of scientific literacy.

### **Critical Thinking Skills Analysis**

The results also showed that students' critical thinking skills improved significantly in the experimental group, particularly in the areas of analysis, evaluation, and inference. These improvements indicate that students were better able to analyze information, evaluate evidence, and make reasoned decisions after participating in AI-supported learning activities.

The improvement in critical thinking skills can be attributed to the inquiry-based nature of the learning environment, which encourages students to actively engage in problem-solving and decision-making processes. AI-supported tools provided scaffolding and feedback that guided students in developing their reasoning skills, leading to more effective learning outcomes.

## **Discussion**

### **1. Effectiveness of AI-Supported Learning Environments**

The findings of this study demonstrate that AI-supported digital learning environments significantly enhance students' scientific literacy and critical thinking skills. This result aligns with recent studies that emphasize the transformative potential of AI in education. Prayogi et al. (2024) found that inquiry-based digital learning environments supported by advanced technologies improve students' higher-order thinking skills by promoting active engagement and reflective thinking.

Furthermore, Nurdiana et al. (2024) highlighted that technology-integrated learning environments provide opportunities for students to engage in complex cognitive processes, including analysis and evaluation. Similarly, Ramli and Borhan (2024) emphasized that digital tools enhance students' scientific literacy by enabling interactive learning and visualization of abstract concepts. These findings support the results of this study, confirming that AI-supported learning environments provide a more effective platform for developing essential competencies in science education.

### **2. Improvement of Scientific Literacy through AI Integration**

The significant improvement in scientific literacy observed in this study can be explained by the ability of AI-supported systems to facilitate inquiry-based learning. AI tools provide real-time feedback, adaptive learning pathways, and access to rich digital resources, which enable students to explore scientific concepts more effectively. This finding is consistent with the report by the Organisation for Economic Co-operation and Development (2023), which emphasizes that scientific literacy is best developed through learning environments that promote inquiry, reasoning, and application of knowledge. In addition, Urdanivia Alarcon et al. (2023) found that inquiry-based learning enhances students' ability to construct knowledge and apply it in real-world contexts. The integration of AI further strengthens this process by providing personalized learning experiences and immediate feedback.

### **3. Enhancement of Critical Thinking Skills**

The improvement in critical thinking skills observed in this study highlights the effectiveness of AI-supported inquiry-based learning in promoting higher-order thinking. AI tools enable students to engage in complex problem-solving tasks and receive immediate feedback, which supports the development of analytical and evaluative skills. This result is supported by Komalasari et al. (2024), who found that STEM and technology-integrated learning significantly improve critical thinking skills. Additionally, Sukarma et al. (2024) emphasized that digital and inquiry-based learning environments enhance students' ability to analyze and evaluate information. The findings of this study confirm that AI-supported learning environments provide an effective platform for developing critical thinking skills in science education.

### **4. Role of Adaptive Learning and Personalization**

One of the key advantages of AI-supported learning environments is their ability to provide personalized learning experiences. Adaptive learning systems adjust the content and difficulty level based on students' performance, allowing each student to learn at their own pace. This finding aligns with Halawa et al. (2024), who emphasized the importance of instructional design in maximizing the effectiveness of digital learning environments. Personalized learning not only improves student performance but also

increases engagement and motivation. In this study, students in the experimental group demonstrated higher levels of engagement and persistence, which contributed to their improved learning outcomes.

### **5. Challenges in Implementation**

Despite the positive findings, several challenges were identified in implementing AI-supported learning environments. These include limited access to technology, insufficient teacher training, and the need for effective instructional design. These challenges are consistent with previous studies highlighting barriers to the implementation of digital learning in education. Urdanivia Alarcon et al. (2023) emphasized that the success of technology-integrated learning depends on teacher readiness and pedagogical support. Therefore, addressing these challenges is essential for maximizing the effectiveness of AI-supported learning environments.

### **CONCLUSION**

This study concludes that the implementation of AI-supported digital learning environments has a significant and positive impact on enhancing students' scientific literacy and critical thinking skills in science education. The findings demonstrate that students who engaged in AI-supported inquiry-based activities achieved higher learning gains, deeper conceptual understanding, and stronger abilities in analyzing, evaluating, and interpreting scientific information compared to those who experienced conventional instruction. The integration of adaptive learning systems, interactive simulations, and real-time feedback creates a dynamic and personalized learning environment that effectively supports students' cognitive development and promotes meaningful learning experiences.

Furthermore, the results highlight that AI-supported learning not only improves academic performance but also facilitates the development of higher-order thinking skills by encouraging active engagement, inquiry processes, and problem-solving activities. The ability of AI systems to provide personalized learning pathways and immediate feedback enables students to identify misconceptions and refine their understanding more efficiently. However, the successful implementation of this approach requires adequate technological infrastructure, teacher readiness, and well-designed instructional strategies to ensure optimal learning outcomes. Overall, this study provides strong empirical evidence that AI-supported digital learning environments represent an innovative and effective instructional approach for improving the quality of science education. By integrating advanced technology with inquiry-based pedagogy, this approach offers a promising pathway for equipping students with essential competencies needed to face the challenges of the 21st century.

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