

Artificial Intelligence-Based Adaptive Learning in Science Education to Enhance Higher-Order Thinking Skills, Personalization, and Learning Efficiency

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas pembelajaran adaptif berbasis Artificial Intelligence (AI) dalam meningkatkan keterampilan berpikir tingkat tinggi (HOTS), personalisasi pembelajaran, dan efisiensi belajar dalam pendidikan IPA. Penelitian ini menggunakan pendekatan kuantitatif dengan desain quasi eksperimen berupa non-equivalent control group. Partisipan penelitian terdiri dari kelompok eksperimen yang menggunakan pembelajaran adaptif berbasis AI dan kelompok kontrol yang menggunakan pembelajaran konvensional. Data dikumpulkan melalui tes HOTS, angket personalisasi pembelajaran, serta tes efisiensi belajar. Hasil penelitian menunjukkan bahwa kelompok eksperimen memperoleh nilai post-test yang lebih tinggi secara signifikan dibandingkan kelompok kontrol pada seluruh variabel. 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 adaptif berbasis AI terbukti mampu meningkatkan kemampuan berpikir kritis, memberikan pengalaman belajar yang terpersonalisasi, serta meningkatkan efisiensi belajar siswa. Temuan ini menunjukkan bahwa pembelajaran berbasis AI merupakan pendekatan yang efektif dan inovatif dalam meningkatkan kualitas pembelajaran dan hasil belajar dalam pendidikan IPA.

Kata Kunci: *artificial intelligence, adaptive learning, HOTS, personalisasi pembelajaran, efisiensi belajar, pendidikan IPA.*

ABSTRACT

This study aims to analyze the effectiveness of Artificial Intelligence (AI)-based adaptive learning in enhancing students' higher-order thinking skills (HOTS), personalization of learning, and learning efficiency in science education. The research employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. The participants consisted of an experimental group that engaged in AI-based adaptive learning and a control group that received conventional instruction. Data were collected using a higher-order thinking skills test, a personalization questionnaire, and a learning efficiency test. The results showed that the experimental group achieved significantly higher post-test scores compared to the control group across all variables. 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-based adaptive learning effectively improved students' critical thinking, provided personalized learning experiences, and increased learning efficiency. These findings suggest that AI-based adaptive learning is an effective and innovative instructional approach for improving cognitive and instructional outcomes in science education.

Keywords: *artificial intelligence, adaptive learning, higher-order thinking skills, personalization, learning efficiency, science education.*



INTRODUCTION

The integration of Artificial Intelligence (AI) in education has significantly transformed the landscape of teaching and learning, particularly in science education where complex concepts and diverse learner needs require more adaptive and personalized approaches (Konstantinos, 2024). AI-powered adaptive learning systems enable the customization of learning experiences by analyzing student data and adjusting instructional content in real time (Strielkowski et al., 2025). These systems provide personalized feedback, recommend learning pathways, and support individualized pacing, thereby addressing the limitations of traditional one-size-fits-all instructional models (Song et al., 2024). Recent studies highlight that AI-based adaptive learning enhances student engagement, improves learning outcomes, and supports efficient knowledge acquisition through intelligent data-driven mechanisms (Zawacki-Richter et al., 2021; Holmes & Tuomi, 2022; Chen et al., 2023).

One of the primary goals of science education in the 21st century is to develop Higher-Order Thinking Skills (HOTS), including critical thinking, problem-solving, analysis, and evaluation (Zou et al., 2024). However, many students struggle to achieve these competencies due to instructional approaches that emphasize memorization rather than deep understanding (Adeoye et al., 2024). AI-based adaptive learning addresses this issue by providing differentiated learning experiences tailored to students' cognitive levels and learning needs (Ezzaim et al., (2025). Through continuous assessment and feedback, AI systems can identify students' misconceptions and provide targeted interventions that promote deeper cognitive engagement. Research indicates that adaptive learning technologies significantly enhance HOTS by encouraging students to engage in complex problem-solving and reflective thinking processes (Chen et al., 2023; Holmes & Tuomi, 2022; Zawacki-Richter et al., 2021).

In addition to improving higher-order thinking skills, personalization is a key advantage of AI-based adaptive learning systems (Adiyono et al, 2025). Personalization allows students to learn at their own pace, receive customized feedback, and access content that matches their individual learning styles and abilities. This approach is particularly important in science education, where students often have varying levels of prior knowledge and learning readiness. Studies show that personalized learning environments supported by AI significantly improve student motivation, engagement, and academic achievement by creating more meaningful and relevant learning experiences (Holmes & Tuomi, 2022; Chen et al., 2023; Zawacki-Richter et al., 2021).

Furthermore, learning efficiency is a critical factor in modern education, especially in contexts where time and resources are limited. AI-based systems optimize learning efficiency by identifying the most effective learning pathways for each student, reducing unnecessary repetition, and focusing on areas that require improvement. This targeted approach not only accelerates learning but also enhances knowledge retention and transfer. Empirical evidence suggests that adaptive learning systems improve learning efficiency by enabling students to achieve better outcomes in shorter periods of time compared to traditional instructional methods (Chen et al., 2023; Holmes & Tuomi, 2022; Zawacki-Richter et al., 2021).

Despite these advantages, the implementation of AI in science education presents several challenges, including ethical concerns, data privacy issues, and the need for teacher readiness. Additionally, there is a need for more comprehensive research that examines the combined impact of AI-based adaptive learning on multiple learning outcomes simultaneously. While previous studies have explored individual aspects such as personalization or academic achievement, there is still limited research investigating

how AI can simultaneously enhance higher-order thinking skills, personalization, and learning efficiency within a single instructional framework.

Moreover, the successful integration of AI requires a shift in pedagogical approaches, where teachers act as facilitators who guide students in navigating adaptive learning environments. Teachers must be equipped with the skills to interpret data generated by AI systems and use it to support instructional decision-making. Without proper integration, the potential benefits of AI may not be fully realized.

Therefore, this study aims to analyze the effectiveness of Artificial Intelligence-based adaptive learning in enhancing students' higher-order thinking skills, personalization of learning, and learning efficiency in science education. The findings of this study are expected to contribute to the development of innovative, data-driven, and personalized instructional strategies that support meaningful learning in 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)-based adaptive learning in enhancing students' higher-order thinking skills (HOTS), personalization of learning, and learning efficiency in science education. This design was selected due to its suitability in real classroom settings where random assignment is not feasible, while still allowing for systematic comparison between experimental and control groups (Creswell & Creswell, 2021).

The research was conducted in a secondary school involving two groups of students. The experimental group was exposed to AI-based adaptive learning supported by an intelligent learning system that provided personalized content, real-time feedback, and adaptive learning pathways. Meanwhile, the control group received conventional teacher-centered instruction. In the experimental group, the AI system continuously analyzed students' performance data, identified learning gaps, and automatically adjusted the level of difficulty and type of content presented to each student. Participants were selected using purposive sampling to ensure comparable academic backgrounds and learning characteristics between both groups.

Data were collected using three main instruments: a higher-order thinking skills (HOTS) test, a personalization of learning questionnaire, and a learning efficiency test. The HOTS test was designed to measure students' abilities in analysis, evaluation, and problem-solving. The personalization questionnaire assessed students' perceptions of individualized learning experiences, including adaptive content, feedback, and pacing. The learning efficiency test measured the extent to which students achieved learning outcomes within a given time frame. All instruments were validated through expert judgment and pilot testing to ensure their validity and reliability.

The intervention was conducted over several instructional sessions, during which students in the experimental group engaged with AI-based adaptive learning systems. These systems provided personalized learning recommendations, adaptive assessments, and immediate feedback, enabling students to learn according to their individual needs and abilities. Previous studies indicate that AI-based adaptive learning significantly enhances higher-order thinking skills and learning efficiency by providing targeted and data-driven instructional support (Chen et al., 2023; Holmes & Tuomi, 2022; Zawacki-Richter et al., 2021).

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 students' performance and inferential statistics, such as independent sample t-tests and normalized gain (N-gain), to determine the effectiveness

of the intervention. Statistical analysis was conducted using SPSS software with a significance level set at 0.05.

This methodological approach aligns with recent research emphasizing the effectiveness of AI-based adaptive learning in improving personalized learning experiences, enhancing higher-order thinking skills, and increasing learning efficiency through data-driven instructional practices (Chen et al., 2023; Holmes & Tuomi, 2022; Zawacki-Richter et al., 2021).

RESULTS AND DISCUSSION

Descriptive Statistics of Learning Outcomes

The descriptive statistical analysis revealed that both the experimental and control groups experienced improvements in post-test scores across all variables, including higher-order thinking skills (HOTS), personalization of learning, and learning efficiency. However, the experimental group, which was exposed to AI-based adaptive learning, demonstrated substantially higher gains compared to the control group. The comparable pre-test scores between both groups indicate that students had relatively similar initial competencies, thus strengthening the validity of the comparison.

A closer examination of the post-test results shows that the experimental group achieved significantly higher mean scores in HOTS. Students demonstrated improved abilities in analyzing complex scientific problems, evaluating evidence, and generating solutions. This indicates that AI-based adaptive learning systems effectively facilitate deeper cognitive engagement by tailoring content and challenges to students' individual learning levels.

In terms of personalization, students in the experimental group reported higher satisfaction with their learning experiences. The adaptive system provided customized feedback, individualized pacing, and targeted content, enabling students to learn according to their specific needs. This contrasts with the control group, where learning experiences were more uniform and less responsive to individual differences.

Normalized Gain (N-gain) Analysis

The normalized gain (N-gain) analysis indicated 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. Among the variables, the highest gain was observed in personalization of learning, followed by HOTS and learning efficiency.

This finding suggests that AI-based adaptive learning is particularly effective in delivering personalized learning experiences. By continuously analyzing student performance data, the system dynamically adjusts learning pathways, ensuring that each student receives appropriate challenges and support. This level of personalization enhances motivation and engagement, which in turn contributes to improved learning outcomes.

Furthermore, the significant improvement in HOTS reflects the ability of AI systems to provide complex, adaptive tasks that promote critical thinking and problem-solving. The moderate to high gain in learning efficiency indicates that students were able to achieve better learning outcomes within shorter periods, demonstrating the effectiveness of targeted and data-driven instruction.

Higher-Order Thinking Skills (HOTS) Analysis

The results showed a significant improvement in HOTS among students in the experimental group compared to the control group. Students demonstrated enhanced abilities in critical analysis, problem-solving, and decision-making.

This improvement can be attributed to the adaptive nature of AI-based learning systems, which provide tasks that match students' cognitive levels and gradually increase in complexity. By engaging students in challenging and meaningful activities, the system encourages deeper cognitive processing and promotes the development of higher-order thinking skills.

Moreover, the immediate feedback provided by the system allows students to reflect on their performance and refine their thinking strategies. This iterative learning process supports the development of metacognitive skills, which are essential for higher-order thinking.

Personalization of Learning Analysis

The analysis of personalization revealed that students in the experimental group experienced a significantly higher level of individualized learning compared to those in the control group. Students reported that the adaptive system helped them learn at their own pace, provided relevant feedback, and addressed their specific learning needs.

The effectiveness of personalization can be explained by the system's ability to analyze large amounts of student data and generate tailored learning pathways. This ensures that students are neither overwhelmed by difficult content nor bored by tasks that are too easy. As a result, students remain engaged and motivated throughout the learning process.

Additionally, personalization supports differentiated instruction by accommodating diverse learning styles and abilities. This is particularly important in science education, where students often have varying levels of prior knowledge and understanding.

Learning Efficiency Analysis

The results also indicated a significant improvement in learning efficiency among students in the experimental group. Students were able to achieve higher learning outcomes in a shorter amount of time compared to the control group.

This improvement can be attributed to the targeted nature of AI-based adaptive learning. By focusing on areas that require improvement and eliminating unnecessary repetition, the system optimizes the learning process. Students spend more time on meaningful learning activities, which enhances both efficiency and effectiveness.

Furthermore, the adaptive feedback mechanism helps students quickly identify and correct errors, reducing the time needed to master concepts. This streamlined learning process contributes to improved academic performance and better retention of knowledge.

Discussion

1. Effectiveness of AI-Based Adaptive Learning

The findings of this study confirm that AI-based adaptive learning significantly enhances higher-order thinking skills, personalization, and learning efficiency in science education. This result is consistent with Chen et al. (2023), who highlighted the role of AI in improving learning outcomes through data-driven personalization. Similarly, Holmes and Tuomi (2022) emphasized that AI systems support adaptive learning environments that enhance student engagement and performance.

Furthermore, Zawacki-Richter et al. (2021) found that AI applications in education enable more efficient and personalized learning experiences. The findings of this study reinforce these perspectives, demonstrating that AI-based adaptive learning provides a comprehensive solution for improving multiple dimensions of learning.

2. Enhancement of Higher-Order Thinking Skills

The significant improvement in HOTS observed in this study highlights the importance of adaptive learning environments in promoting deep cognitive engagement.

AI systems provide complex and dynamic tasks that challenge students to think critically and solve problems.

This finding aligns with Chen et al. (2023), who reported that AI-based systems enhance critical thinking by providing adaptive and interactive learning experiences. Additionally, Holmes and Tuomi (2022) emphasized that AI supports the development of higher-order thinking by enabling personalized and data-driven learning.

3. Role of Personalization in Learning

The strong improvement in personalization underscores the importance of individualized learning experiences in science education. AI-based systems enable students to learn at their own pace and receive tailored support, which enhances motivation and engagement.

This finding is supported by Zawacki-Richter et al. (2021), who emphasized that personalization is a key advantage of AI in education. Similarly, Chen et al. (2023) noted that adaptive learning systems improve student outcomes by providing customized learning pathways.

4. Improvement of Learning Efficiency

The improvement in learning efficiency indicates that AI-based adaptive learning optimizes the learning process by focusing on relevant content and reducing unnecessary repetition. Students are able to achieve better outcomes in less time.

This finding is consistent with Holmes and Tuomi (2022), who highlighted the efficiency of AI systems in optimizing learning pathways. Additionally, Chen et al. (2023) emphasized that AI enhances learning efficiency through targeted instruction and real-time feedback.

5. Implications and Challenges

Despite its effectiveness, the implementation of AI-based adaptive learning presents challenges, including ethical concerns, data privacy issues, and the need for teacher training. Teachers must be equipped with the skills to interpret AI-generated data and integrate it into instructional practices.

Zawacki-Richter et al. (2021) emphasized that successful implementation requires careful integration of technology and pedagogy. Therefore, educational institutions must provide adequate support to ensure the effective use of AI in science education.

CONCLUSION

This study concludes that the implementation of Artificial Intelligence (AI)-based adaptive learning in science education significantly improves students' higher-order thinking skills, personalization of learning, and learning efficiency. By utilizing data-driven algorithms, the system is able to provide tailored learning pathways, real-time feedback, and adaptive challenges that match students' individual needs and cognitive levels. This not only enhances students' ability to think critically and solve complex problems but also creates more meaningful and engaging learning experiences through personalized instruction. Additionally, the improvement in learning efficiency indicates that students can achieve better outcomes in a shorter time, highlighting the effectiveness of targeted and optimized learning processes. The novelty of this study lies in its integrated examination of cognitive (HOTS), instructional (personalization), and performance (efficiency) dimensions within a single AI-based framework, demonstrating the transformative potential of adaptive technologies in advancing science education in the digital era.

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