ARTIFICIAL INTELLIGENCE IN MATHEMATICS EDUCATION: INDONESIA'S CURRENT PRACTICES AND ITS ROLE IN DEVELOPING 21ST CENTURY SKILLS AMONG STUDENTS

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis implementasi *Artificial Intelligence* (AI) dalam pembelajaran matematika di Indonesia serta mengkaji perannya dalam mendukung keterampilan abad ke-21, termasuk berpikir kritis, kreativitas, komunikasi, dan kolaborasi. Penelitian ini menggunakan metode *systematic literature review* dengan menganalisis 14 studi yang diidentifikasi melalui penelusuran terstruktur pada basis data akademik, seperti Google Scholar. Data dianalisis menggunakan analisis tematik dan diklasifikasikan berdasarkan kerangka SAMR untuk mengidentifikasi tingkat integrasi pembelajaran. Hasil penelitian menunjukkan bahwa AI diimplementasikan sebagai alat interaktif, terintegrasi dalam model pembelajaran, terintegrasi dalam media pembelajaran, diterapkan dalam sistem adaptif, serta mencakup penggunaan generative AI untuk menghasilkan solusi dan mendukung penalaran. Sebagian besar implementasi berada pada tingkat *augmentation*, di mana AI meningkatkan pembelajaran tanpa secara mendasar mengubah struktur pembelajaran. AI berkontribusi terutama terhadap pengembangan berpikir kritis. Kreativitas berkembang bersamaan dengan berpikir kritis, meskipun kurang mendapat penekanan, sementara komunikasi dan kolaborasi tidak ditemukan sebagai hasil pembelajaran. Selain itu, AI mendukung pemecahan masalah dan penalaran melalui panduan dan umpan balik yang terstruktur, sementara generative AI menunjukkan keterbatasan berupa respons yang tidak konsisten ketika menangani masalah yang kompleks. Penelitian ini berkontribusi dengan memetakan hubungan antara mekanisme implementasi AI, tingkat integrasi, dan pengembangan keterampilan abad ke-21 dalam pembelajaran matematika di Indonesia.

Kata kunci: *artificial intelligence*; pendidikan matematika; integrasi pembelajaran; keterampilan abad ke-21; *systematic literature review*

ABSTRACT

This study aims to analyze the implementation of Artificial Intelligence (AI) for mathematics learning in Indonesia and examine its role in supporting 21st century skills, including critical thinking, creativity, communication, and collaboration. This study employed a systematic literature review by analyzing 14 studies identified through structured searches across academic databases, such as Google Scholar. The data were analyzed using thematic analysis and classified based on the SAMR framework to identify levels of instructional integration. The

findings show that AI is implemented as interactive tools, integrated within instructional models, integrated within learning media, applied in adaptive systems, and includes the use of generative AI for solution generation and reasoning support. Most implementations are at the augmentation level, where AI enhances learning without fundamentally changing instructional structures. AI contributes primarily to the development of critical thinking. Creativity is developed alongside critical thinking, although it is less emphasized, whereas communication and collaboration are absent as learning outcomes. In addition, AI supports problem solving and reasoning through structured guidance and feedback, while generative AI shows limitations in the form of inconsistent responses when addressing complex problems. This study contributes by mapping the relationship between AI implementation mechanisms, levels of integration, and the development of 21st century skills for mathematics learning in Indonesia.
***Keywords**: artificial intelligence; mathematics education; instructional integration; 21st century skills; systematic literature review*

INTRODUCTION

The transformation of the twenty-first century has introduced new challenges for educational systems, particularly in responding to the evolving demands of the future of work. Competencies such as creativity, critical thinking, communication, and collaboration are widely recognized as essential skills for both education and professional environments (Thornhill-Miller et al., 2023). Developing these competencies requires instructional processes that move beyond knowledge transmission, with greater emphasis on problem-solving, interaction, and higher-order thinking (Awang et al., 2025).

These demands influence how learning is designed and implemented, particularly in mathematics education. Mathematics is closely related to the development of critical thinking skills, as mathematics involves reasoning, problem solving, and logical analysis (Fawensi & Susanti, 2025). Learning practices are still dominated by teacher-centered approaches, where students tend to be passive and have limited engagement in learning activities (Susanti et al., 2026). Such conditions indicate the need for instructional approaches that promote active engagement and support the development of conceptual understanding.

The rapid development of Artificial Intelligence (AI) has introduced new possibilities for its integration into educational practices. AI has been widely

applied to support teaching and learning. Its applications include adaptive systems, intelligent tutoring systems, and data-driven instructional approaches (Zawacki-Richter et al., 2019). AI-based tools enable personalized learning experiences and provide immediate feedback that supports student engagement and learning progress (Awang et al., 2025). AI also facilitates adaptive learning environments that adjust to students' needs and performance, allowing more flexible and responsive instructional design (Lorenzo-Lledó & Amante Garcia, 2025). These features demonstrate the potential of AI to support more effective and individualized learning processes in mathematics education.

The implementation of AI in Indonesia presents both opportunities and challenges that influence its effectiveness. Students often face limitations related to digital literacy, access to compatible devices, and internet connectivity, which affect their ability to engage in technology-based learning environments in mathematics education (Soesanto et al., 2022). These conditions also suggest that the adoption of AI in learning practices remains limited. Teacher readiness is another determining factor, as the integration of AI depends on teachers' acceptance, attitudes, social influence, and perceived behavioral control in using AI tools (Qudratuddarsi et al., 2025).

Recent research trends indicate increasing attention to the application of AI in mathematics education, particularly in relation to personalization and adaptive learning. The growing number of studies reflects a rising interest in utilizing AI to improve learning outcomes and instructional quality (Utami et al., 2025). Studies in this field have expanded rapidly, with a focus on enhancing student learning and outcomes, although it remains conceptually fragmented and lacks integrative analysis across instructional and learning dimensions (Nanda & Pradhan, 2025). AI is also recognized for its potential to support the development of twenty-first century skills, including critical thinking, creativity, communication, and collaboration, although these skills require structured integration within learning processes and are not consistently developed across studies (Salhab & Aboushi, 2025).

Despite these developments, existing studies in Indonesia still provide limited analysis of AI implementation in mathematics education across multiple

dimensions of learning. Most studies tend to focus on specific outcomes, such as academic performance or system effectiveness, without explicitly examining how AI supports the development of twenty-first century skills within mathematics education. In contrast, several studies in broader educational settings have begun to examine the role of AI in supporting critical thinking, creativity, communication, and collaboration, although these aspects are not always analyzed in an integrated manner. Studies in Indonesia have not sufficiently explored how AI is applied in mathematics education or how it supports the integrated development of these skills. This gap highlights the need for a comprehensive analysis that connects instructional mechanisms, levels of integration, and learning outcomes related to twenty-first century skills in mathematics education.

This study aims to analyze the implementation of AI for mathematics education in Indonesia by examining instructional integration and learning outcomes related to twenty-first century skills. The study is guided by the following research questions: (1) How is AI implemented for mathematics education in Indonesia? (2) How does AI support learning outcomes related to twenty-first century skills?

This study employs a systematic literature review approach to analyze 14 selected studies on AI implementation for mathematics education in Indonesia. Data were collected from scholarly articles indexed in academic databases, including Google Scholar and DOAJ, using keyword combinations on AI, mathematics education, problem solving, and twenty-first century skills. The selected studies were analyzed through thematic coding to identify patterns in instructional mechanisms and learning outcomes.

METHOD

This study employed a systematic literature review to examine Artificial Intelligence (AI) implementation for mathematics education in Indonesia. The study focuses on instructional integration and learning outcomes related to twenty-first century skills.

The data consisted of 14 selected studies examining AI implementation for mathematics education in Indonesia. Supporting studies were used to strengthen theoretical interpretation but were not included in the main dataset.

Data collection was conducted through structured searches in academic databases, including Google Scholar, DOAJ, and other indexed academic databases. The search terms included "Artificial Intelligence," "AI," "mathematics education," "critical thinking," "creativity," "communication," and "collaboration." Inclusion criteria required studies to involve AI implementation and report findings on instructional processes or learning outcomes. Studies not related to mathematics education or not involving AI were excluded.

Data analysis employed thematic analysis. Extracted data were coded to identify patterns in instructional integration and learning outcomes. Themes related to influencing factors and implementation limitations were identified during coding.

The SAMR framework (Substitution, Augmentation, Modification, and Redefinition) was used to classify levels of AI integration in instructional practices (Holmes et al., 2019). The framework differentiates levels of technology integration ranging from substitution to redefinition.

DISCUSSION

Current Practices of AI in Indonesian Mathematics Education

Artificial Intelligence in mathematics education operates through instructional mechanisms that shape learning processes and outcomes. The fourteen empirical studies conducted in Indonesia show variation in levels of integration across instructional activities. These variations are classified using the SAMR framework, which distinguishes levels of technology use from substitution to redefinition (Holmes et al., 2019). The classification of these mechanisms across the reviewed studies is presented in Table 1.

Table 1. Classification of AI Mechanisms Based on the SAMR Framework

No	Study	AI Application Type	Instructional Use	SAMR Level
1	Sunarto et al. (2024)	Adaptive Learning System	AI is used to personalize learning	Modification

No	Study	AI Application Type	Instructional Use	SAMR Level
			pathways and support problem-solving through guided analysis and solution development	
2	Fiqri et al. (2025)	Adaptive Learning System	AI is used to personalize learning and provide immediate feedback based on students' learning performance	Augmentation
3	Mardin (2025)	Exploratory Learning Environment	AI is used to provide step-by-step solutions and explanations for solving mathematics problems	Augmentation
4	Arifin et al. (2025)	Adaptive Learning System	AI is used to provide personalized learning recommendations and feedback to support self-regulated learning	Modification
5	Silwana et al. (2025)	Exploratory Learning Environment	AI is used to support conceptual exploration and reflection through interactive question-	Augmentation

No	Study	AI Application Type	Instructional Use	SAMR Level
			and-answer and feedback	
6	Siregar et al. (2025)	Dialogue-Based Tutoring System	AI is used to provide explanations and feedback through interactive question-and-answer during problem-solving	Augmentation
7	Anisyah et al. (2025)	Exploratory Learning Environment	AI is used to provide feedback, analyze errors, and support problem-solving activities in problem-based learning	Augmentation
8	Alansyah et al. (2025)	Exploratory Learning Environment	AI is used to support problem-solving and allow students to access learning resources more flexibly	Modification
9	Qurohman (2024)	Intelligent Tutoring System	AI is used to provide structured, step-by-step support for algebra problem solving	Augmentation
10	Rustiyana et al. (2025)	Adaptive Learning System	AI is used to provide personalized learning pathways, adaptive recommendations, and real-time	Modification

No	Study	AI Application Type	Instructional Use	SAMR Level
			feedback based on student performance	
11	Zein et al. (2024)	Dialogue-Based Tutoring System	AI is used to provide interactive responses and guide students' reasoning through prompting	Augmentation
12	Jufriansah et al. (2026)	Intelligent Tutoring System	AI is used to provide step-by-step solutions and support conceptual understanding through logical reasoning	Augmentation
13	Herwandi et al. (2025)	Adaptive Learning System	AI is used to provide adaptive learning materials and feedback based on students' needs	Modification
14	Elfani et al. (2025)	Adaptive Learning System	AI is used to provide personalized learning, real-time feedback, and adaptive support based on student performance	Modification

Variation in the types of Artificial Intelligence applications used in mathematics education is evident across the reviewed studies. Based on the framework of Holmes et al. (2019), these applications can be categorized into

adaptive learning systems, intelligent tutoring systems, dialogue-based tutoring systems, and exploratory learning environments. Each type reflects distinct functional roles of AI in supporting instructional processes, including personalized learning, structured guidance, interactive dialogue, and exploratory problem-solving support.

Augmentation-level use represents the most dominant form of AI integration in Indonesian mathematics classrooms. AI is primarily used as a problem-solving assistant, explanatory tool, and instructional support medium. Applications such as ChatGPT, Photomath, and Symbolab are employed to generate solutions, provide step-by-step explanations, and deliver immediate feedback. These tools are also integrated to support visualization, interaction, and conceptual understanding within instructional activities, including problem-based learning environments (Anisyah et al., 2025; Fiqri et al., 2025; Mardin, 2025; Qurohman, 2024; Silwana et al., 2025; Siregar et al., 2025; Zein et al., 2024). This pattern indicates a strong orientation toward procedural support and efficiency in solving mathematical problems while also enhancing student engagement and conceptual representation. Several studies suggest that this use supports independent learning; however, reliance on AI-generated responses may reduce students' analytical engagement when reasoning processes are not explicitly guided (Jufriansah et al., 2026).

Modification-level use is observed in a smaller number of studies where AI is embedded within instructional models commonly applied in Indonesia, particularly problem-based learning and differentiated instruction. In these implementations, AI functions as a scaffold that supports reasoning, error analysis, and iterative problem solving (Alansyah et al., 2025; Elfani et al., 2025; Herwandi et al., 2025; Rustiyana et al., 2025; Sunarto et al., 2024). Instructional activities are redesigned to incorporate AI as part of the learning process. Stronger development of higher-order thinking, especially critical thinking, is observed when AI is integrated within structured pedagogical frameworks rather than used independently.

Redefinition-level implementation is not explicitly observed in the reviewed studies. None of the identified implementations demonstrate AI functioning as a

fully autonomous instructional system that fundamentally transforms learning tasks or replaces existing pedagogical structures. Although adaptive features such as personalized feedback, learning recommendations, and adaptive pacing are present in several studies, these functions remain integrated within existing instructional frameworks rather than establishing entirely new forms of learning experiences. This indicates that Artificial Intelligence integration in Indonesian mathematics education has not yet reached the redefinition level, and remains primarily within augmentation and modification stages.

Generative AI demonstrates varied roles depending on how it is used in Indonesian classrooms. Its use as a solution generator conceptually aligns with substitution and augmentation, while its use as a reasoning support aligns with modification. However, no reviewed studies were explicitly categorized at the substitution level, indicating that even basic AI use in Indonesian mathematics education tends to extend beyond simple replacement of traditional tools. Although generative AI appears to support explanation and exploration, several studies report inconsistent outputs and limited contribution to originality, indicating constraints in supporting higher-order cognitive processes (Jufriansah et al., 2026; Zein et al., 2024).

The overall distribution of AI implementation in Indonesian mathematics education shows a clear dominance of augmentation-level use, with fewer studies reaching modification and no studies achieving redefinition. This distribution indicates that AI adoption in Indonesia remains oriented toward supporting existing instructional practices rather than transforming them. These outcomes are influenced more by the level of instructional integration and pedagogical design than by the type of AI technology used. These findings suggest that the development of AI in Indonesian mathematics education remains in a transitional stage, where technological integration has begun to emerge but has not yet fully reshaped instructional practice.

AI Impact on Mathematics Education and 21st Century Skills in Indonesia

AI demonstrates measurable contributions to mathematics education in Indonesian classrooms, with effects varying according to how it is integrated into instructional processes. Across the reviewed studies, the impact of AI is more

evident in the development of certain twenty-first century skills, particularly critical thinking, while other competencies remain limited or unexamined. These differences are closely related to the role of AI within instruction, where more structured and interactive implementation tends to support higher-order thinking processes. Aside from twenty-first century skills, AI also contributes to other learning outcomes such as problem solving, reasoning, and academic performance, particularly when it is embedded within structured learning activities rather than used as a standalone tool.

Critical thinking in AI-supported mathematics education is primarily developed through the role of AI as a feedback-driven and interactive system rather than as a direct answer provider. Across the reviewed studies, AI facilitates critical thinking when students are required to interpret information, evaluate solution strategies, and reflect on the reasoning process during interaction with the system. This pattern is evident in learning environments where AI provides structured guidance and adaptive feedback, enabling students to engage in analysis, evaluation, and inference as part of the learning process (Elfani et al., 2025; Herwandi et al., 2025; Zein et al., 2024). The role of AI becomes more pronounced in adaptive systems, where continuous feedback and personalized responses require students to compare approaches, identify errors, and construct logical conclusions (Elfani et al., 2025). A similar mechanism is observed in generative AI environments, where interaction with AI-generated responses encourages students to question answer validity, identify inconsistencies, and verify results, thereby directly engaging critical thinking processes (Zein et al., 2024). These findings indicate that the development of critical thinking is determined not merely by the presence of AI, but by how it is positioned as an interactive system that requires active evaluation and reasoning.

Creativity in AI-supported mathematics education emerges through AI as a generative and exploratory system that enables students to construct and refine multiple solution strategies. Across the reviewed studies, creativity emerges when students interact with AI beyond receiving answers, particularly through prompting, exploration, and reinterpretation of generated outputs. This mechanism is evident in the use of ChatGPT as a virtual tutor, where students formulate

prompts, explore alternative responses, and elaborate solutions, leading to measurable improvement in creative thinking (Zein et al., 2024). The generative nature of AI also enables the production of structured explanations that support students in expanding and refining their ideas (Jufriansah et al., 2026). However, creativity development remains dependent on the level of student engagement, as passive reliance on AI-generated answers limits originality and flexibility. These findings indicate that AI supports creativity as an interactive environment for idea development rather than as an independent source of novelty.

Communication and collaboration are not represented as measured competencies in AI-supported mathematics education within Indonesian classrooms, indicating a clear gap in current implementation. Across the reviewed studies, instructional activities are predominantly structured around individual interaction between students and AI systems, where the focus is placed on receiving feedback, solving problems, and refining answers independently rather than engaging in peer discussion or collective knowledge construction. This pattern limits opportunities for students to articulate mathematical ideas, negotiate meaning, and develop shared understanding through social processes. The absence of collaborative structures suggests that current implementations prioritize cognitive outcomes over communicative and social dimensions, resulting in an imbalance in the development of twenty-first century skills.

Aside from twenty-first century skills, AI contributes to problem-solving ability by functioning as a system that provides structured guidance, interactive feedback, and opportunities for iterative refinement during the solution process. This contribution is reflected in AI-based learning environments that present problems through clear and sequential solution steps, allowing students to follow procedures and improve the accuracy of their answers (Qurohman, 2024). The role of AI is further strengthened when it operates as an interactive learning tool, where students can ask questions, receive explanations, and revise their responses during learning activities, leading to improved problem-solving performance compared to conventional instruction (Siregar et al., 2025). In learning settings that integrate AI within problem-based activities, such integration supports students in accessing information and exploring solution strategies, contributing to higher achievement

in mathematical problem solving (Alansyah et al., 2025). These findings indicate that AI enhances problem-solving ability primarily through procedural guidance and feedback mechanisms, while more advanced strategies depend on how AI is embedded within instructional design.

Overall, AI-supported mathematics education in Indonesia shows stronger and more consistent development in critical thinking, partial support for creativity, and limited attention to communication and collaboration as integral components of twenty-first century skills.

Limitations of AI Integration in Mathematics Education

The effectiveness of AI in mathematics education is influenced by how it is positioned within instructional processes rather than by the technology itself. Evidence across the reviewed studies shows that AI can support higher-order thinking when it functions as an interactive system that provides feedback, adaptation, and opportunities for evaluation, particularly in adaptive and deep learning-based environments that encourage students to analyse solutions and construct logical arguments (Elfani et al., 2025). In contrast, when AI is primarily used as a solution provider, students tend to rely on generated answers, which is associated with lower analytical thinking performance (Mardin, 2025). Generative AI systems also present limitations, including inconsistent responses and variability in answer quality, especially when addressing more complex problems (Jufriansah et al., 2026; Zein et al., 2024). These findings indicate that AI contributes positively when it supports reasoning processes, but may reduce cognitive engagement when it replaces students' active reasoning processes.

CONCLUSION

Artificial Intelligence (AI) plays a significant role in Indonesian mathematics education, with its impact determined by how it is integrated into instructional processes rather than by the technology itself. The findings show that AI is implemented through various instructional mechanisms, including its use as interactive tools, integration within instructional models, learning media, and adaptive systems that support feedback and personalization. These mechanisms are applied at different levels of integration, with most implementations concentrated

at the augmentation level, indicating that AI is primarily used to support existing instructional practices rather than transform them.

The impact of AI is most evident in the development of higher-order thinking, particularly critical thinking, which consistently emerges across studies when AI functions as an interactive system that supports reasoning, evaluation, and feedback. Creativity is present but not consistently developed, as it depends on the extent to which students engage with AI in exploratory and generative ways. Communication and collaboration are not represented as explicit learning outcomes, indicating that AI-supported mathematics education in Indonesia remains focused on individual interaction between students and AI systems.

In addition to twenty-first century skills, AI supports improvements in problem solving and reasoning, particularly through structured guidance and iterative feedback. However, these outcomes are closely related to the level of instructional integration, with stronger effects observed when AI is embedded within structured learning models rather than used as a standalone tool.

Overall, the implementation of AI in Indonesian mathematics education reflects a pattern in which technological integration supports cognitive development but has not yet extended to social and interactive dimensions of learning. This imbalance indicates the need for more integrative instructional approaches that position AI not only as a cognitive support tool but also as a means to facilitate communication and collaboration in mathematics education.

This study is limited by the scope of the selected literature and the variability of research designs and findings, which may influence the generalizability of the results. Therefore, future research is recommended to examine a broader range of studies and further investigate how AI can be effectively integrated to support communication and collaboration in mathematics education.

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