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Artificial Intelligence in Mathematics Education: A Systematic Review of Students' Mathematical Problem-Solving and Self-Directed Learning

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ABSTRACT

Artificial Intelligence (AI) is increasingly integrated into mathematics education to support personalized, adaptive, and student-centered learning. However, evidence concerning its simultaneous contribution to students' mathematical problem-solving skills and self-directed learning remains fragmented. This study aimed to systematically analyze publication trends, forms of AI implementation, contributions to mathematical problem solving and self-directed learning, and research gaps in AI-supported mathematics education. A Systematic Literature Review was conducted following the PRISMA 2020 guidelines. Relevant journal articles published between 2021 and 2025 were retrieved from Scopus, OpenAlex, and Google Scholar using predefined search strings. Studies were selected using the PICOC framework and evaluated through quality assessment based on methodological clarity, the explicit description of AI technologies, and their relevance to the research questions. Of 121 initially identified records, 53 eligible open-access articles were included and analyzed thematically. The findings revealed a substantial increase in publications, from one article in 2021 to 25 articles in 2025. AI chatbots were the most frequently examined technology, followed by other AI-based platforms, adaptive learning systems, intelligent tutoring systems, and machine-learning applications. AI supported mathematical problem solving by providing scaffolding, immediate feedback, strategy guidance, and systematic visualization of solution processes. It also promoted self-directed learning through personalized pathways, flexible access, adaptive feedback, learning-pace regulation, and increased confidence. Nevertheless, only a limited number of studies examined both outcomes simultaneously. Significant challenges included teachers' insufficient digital literacy, unequal access, additional instructional workload, students' overreliance on AI, data-privacy concerns, and algorithmic hallucinations. Future research should develop empirically validated pedagogical models, conduct meta-analyses, and establish ethical guidelines to ensure that AI functions as a safe, inclusive, and sustainable cognitive facilitator in mathematics learning.

ABSTRAK

Integrasi Artificial Intelligence (AI) dalam pembelajaran matematika terus berkembang untuk mendukung pembelajaran yang personal, adaptif, dan berpusat pada siswa. Namun, bukti mengenai kontribusi AI secara bersamaan terhadap kemampuan pemecahan masalah matematis dan kemandirian belajar siswa masih tersebar dan belum disintesis secara komprehensif. Penelitian ini bertujuan menganalisis secara sistematis tren publikasi, bentuk penerapan AI, kontribusinya terhadap kemampuan pemecahan masalah matematis dan kemandirian belajar, serta kesenjangan penelitian dalam pembelajaran matematika berbantuan AI. Penelitian menggunakan metode Systematic Literature Review dengan mengikuti pedoman PRISMA 2020. Artikel jurnal yang diterbitkan pada periode 2021–2025 ditelusuri melalui Scopus, OpenAlex, dan Google Scholar menggunakan kombinasi kata kunci yang telah ditetapkan. Seleksi artikel dilakukan berdasarkan kerangka PICOC dan penilaian kualitas yang mempertimbangkan kejelasan metodologi, bentuk teknologi AI yang digunakan, serta relevansi temuan terhadap pertanyaan penelitian. Dari 121 artikel yang teridentifikasi pada tahap awal, sebanyak 53 artikel akses terbuka memenuhi kriteria dan dianalisis secara tematik. Hasil penelitian menunjukkan peningkatan publikasi yang signifikan, dari satu artikel pada 2021 menjadi 25 artikel pada 2025. Chatbot AI merupakan teknologi yang paling banyak dikaji, diikuti platform berbasis AI lainnya, sistem pembelajaran adaptif, sistem tutor cerdas, dan aplikasi machine learning. AI mendukung pemecahan masalah matematis melalui bantuan bertahap, umpan balik langsung, pengarahan strategi, dan visualisasi proses penyelesaian. AI juga memperkuat kemandirian belajar melalui jalur pembelajaran personal, akses yang fleksibel, umpan balik adaptif, pengaturan kecepatan belajar, dan peningkatan kepercayaan diri. Meskipun demikian, hanya sedikit penelitian yang mengkaji kedua kemampuan tersebut secara bersamaan. Tantangan utama meliputi keterbatasan literasi digital guru, kesenjangan akses, bertambahnya beban pembelajaran, ketergantungan siswa, persoalan privasi data, dan halusinasi algoritmik. Penelitian selanjutnya perlu mengembangkan model pedagogis yang tervalidasi, melakukan meta-analisis, dan merumuskan pedoman etis agar AI berfungsi sebagai fasilitator kognitif yang aman, inklusif, dan berkelanjutan.

INTRODUCTION

Mathematics education is fundamentally intended to develop students who not only understand mathematical concepts but also possess the problem-solving skills and self-directed learning needed to meet 21st-century challenges. Mathematical problem solving is a core competency because it involves higher-order thinking processes, including understanding problems, devising solution strategies, applying appropriate procedures, and reflecting on outcomes (Getenet, 2024; Hwang & Tu, 2021). In addition, self-directed learning is an important indicator of instructional success because it reflects students' ability to set learning goals, select strategies, and evaluate their learning independently without excessive reliance on teachers (Han et al., 2024). In modern education, an ideal mathematics-learning environment encourages students to be active, reflective, and responsible for their own learning. Studies of technology-integrated mathematics education support this view by positioning students as the primary agents of learning (Awang et al., 2025; Mohamed et al., 2022).

Although the goals of mathematics education have been clearly established, students continue to face obstacles in developing mathematical problem-solving skills and self-directed learning. In many educational contexts, mathematics instruction remains dominated by procedural approaches and routine exercises. Consequently, students tend to be passive and reliant on teachers' explanations (Soesanto et al., 2022; Supriyadi & Kuncoro, 2023).

This condition limits their ability to solve non-routine problems that require reasoning, strategy exploration, and independent mathematical reflection. Several studies have also shown that students often struggle to manage their own learning processes, including setting goals, monitoring comprehension, and evaluating errors, which indicates limited self-directed learning (Han et al., 2024; Hardika Saputra, 2025). This discrepancy has become increasingly evident as curricula emphasize meaningful learning and higher-order thinking, while current instructional practices have not yet adequately supported these needs.

Advances in digital technology in the Society 5.0 era have changed both student characteristics and the demands of contemporary mathematics education. Students are expected not only to understand mathematical concepts but also to adapt to dynamic, technology-based learning environments that require considerable independence. However, technology integration in mathematics instruction often remains instrumental, with digital media used mainly for presentations or practice exercises rather than to support deep cognitive processes and self-directed learning (Tulak et al., 2024; Yunita & Gunawan, 2025). Consequently, technology has not fully facilitated adaptive and personalized learning despite increasingly diverse student abilities, learning preferences, and learning paces. Students with different learning needs may therefore remain inadequately supported, widening gaps in problem-solving skills and self-directed learning (Tashtoush et al., 2024; Uban Subandi & Supardi US, 2024).

Artificial Intelligence (AI) has emerged as a technological innovation with the potential to address challenges in mathematics education. Unlike conventional educational technologies, AI can support adaptive, interactive, and responsive learning systems tailored to individual student needs. Studies have shown that AI can function as an intelligent tutor, provide automated feedback, and facilitate problem-based learning aligned with students' ability levels (Hwang & Tu, 2021; Wardat et al., 2023). By analyzing learning data, AI can identify error patterns, problem-solving strategies, and levels of conceptual understanding. Consequently, learning can focus not only on final answers but also on students' mathematical thinking processes (Mohamed et al., 2022; Opesemowo & Adewuyi, 2024). These characteristics position AI as a pedagogical tool that may improve the effectiveness of mathematics instruction while supporting the continued development of problem-solving skills and self-directed learning.

Several studies have shown that implementing Artificial Intelligence (AI) in mathematics education can improve students' mathematical problem-solving skills. AI functions as a cognitive tool that helps students understand problem-solving stages sequentially, receive immediate feedback, and explore alternative solution strategies (Chau et al., 2025; Seto et al., 2025). With support from AI systems such as chatbots and AI-based problem-solving applications, students can practice analyzing problems, formulating strategies, and evaluating solutions more systematically (Getenet, 2024; Spreitzer et al., 2024). Thus, AI can serve not merely as an answer-generating tool but also as a medium for developing higher-order mathematical thinking, particularly in problem solving.

Self-directed learning in mathematics refers to students' ability to actively manage their learning by planning, monitoring, and evaluating their mathematical understanding. Integrating Artificial Intelligence (AI) into mathematics instruction can strengthen this ability by providing an adaptive learning environment that responds to individual needs (Soesanto et al., 2022). AI enables students to learn flexibly, access conceptual support independently, and receive immediate feedback without constant teacher intervention (Song et al., 2025). It can also foster independent learning habits by encouraging students to explore solution strategies and learning resources autonomously (Ngoveni, 2025). These findings indicate that AI is not merely a supporting technology but also a medium that can strengthen students' responsibility and self-regulation in mathematics learning.

Although research on Artificial Intelligence (AI) in mathematics education has developed rapidly, relatively few studies have examined its simultaneous contribution to students' mathematical problem-solving skills and self-directed learning. Most studies have emphasized general aspects, such as user perceptions, instructional effectiveness, or overall learning outcomes, without closely linking them to these two variables (Hwang & Tu, 2021). Bibliometric evidence also indicates that research has largely focused on technological trends, whereas systematic syntheses of empirical evidence on higher-order thinking and self-regulation remain limited (Göktepe Yıldız & Göktepe Körpeoğlu, 2025). This concern is reinforced by Rusdial Marta et al. (2025), who reported that AI research in mathematics instruction within the national context remains fragmented and has not been integrated into a comprehensive conceptual framework. Therefore, a Systematic Literature Review (SLR) was needed to map, analyze, and synthesize the role of AI in improving students' mathematical problem-solving skills and self-directed learning.

The novelty of this study lies in synthesizing research on the role of Artificial Intelligence (AI) in mathematics education while examining students' mathematical problem-solving skills and self-directed learning as two interrelated outcomes. Previous studies have shown that AI tools, including algorithm-based problem-solving applications and adaptive learning systems, can help students understand mathematical problem-solving processes in a more structured and sequential manner (Capinding, 2023). Other research has indicated that AI-supported digital learning can strengthen self-regulation and self-directed learning through automated feedback and flexible learning opportunities (Dabingaya, 2022). However, these outcomes have generally been examined separately rather than within a single comprehensive framework. Using an SLR approach, this study therefore integrated empirical findings to identify patterns, trends, and research gaps concerning AI's role in developing both outcomes (Efendi et al., 2024).

Research on Artificial Intelligence in mathematics education has increased substantially over the past five years, although bibliometric studies indicate that it remains dominated by broad analyses of trends, technologies, and user perceptions (Hossein-Mohand et al., 2025). Although AI has frequently been studied in relation to personalization and learning efficiency, its specific contributions to mathematical problem-solving skills and self-directed learning have not been mapped systematically and comprehensively (Göktepe Yıldız & Göktepe Körpeoğlu, 2025). Furthermore, Ngoveni (2025) asserted that AI integration in mathematics education requires synthesis studies that connect empirical findings with meaningful pedagogical implications for developing 21st-century competencies. Accordingly, this study aimed to examine publication trends in AI-based mathematics education from 2021 to 2025, analyze AI's role in improving students' mathematical problem-solving skills and self-directed learning, and identify remaining research gaps. These aims were formulated into four research questions concerning publication trends, AI's role in problem-solving skills, AI's role in self-directed learning, and unresolved research gaps. The findings were expected to provide an empirical synthesis and a conceptual and methodological foundation for future research on AI-based mathematics education.

METHOD

This study used a systematic literature review (SLR), a method that searches scientific databases to collect, select, and analyze findings from studies relevant to a specific topic. An

SLR synthesizes previous research systematically to provide a deeper and more comprehensive understanding of a research problem. Lame (2019) stated that an SLR combines evidence from relevant studies to answer specific research questions through study identification, data collection, and the systematic analysis and integration of findings.

A clear research protocol was required to ensure that the review process was transparent, consistent, and systematic. The protocol guided each stage, from planning and literature searching to reporting the review results, thereby supporting the quality and reliability of the review. This study followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure consistent and structured reporting. Panic et al. (2013) explained that PRISMA refined and replaced the QUORUM guidelines to accommodate developments in reporting systematic reviews and meta-analyses of both observational and experimental studies.

Operationally, the Systematic Literature Review was conducted in five sequential stages: (1) formulating the research questions; (2) searching the literature and collecting data from multiple databases using predefined strategies; (3) selecting studies through a PRISMA flow diagram and the PICOC framework; (4) assessing study quality; and (5) extracting data and synthesizing the findings in depth to answer the research questions.

Eligibility criteria determined which articles were suitable for further analysis. The criteria consisted of inclusion and exclusion criteria based on the PICOC (Population, Intervention, Comparison, Outcome, and Context) framework. This framework ensured that the selected articles aligned with the study focus and research questions by specifying the population, the form of Artificial Intelligence intervention, the measured outcomes, and the relevant mathematics-education context. Table 1 presents the PICOC framework used to select the articles.

Table 1. PICOC Framework

PICOC Components	Inclusion Criteria	Exclusion Criteria
Population	Students at the elementary, middle-school, high-school, or university level who were involved in mathematics education.	Non-educational contexts (e.g., industry, health, or pure computing).
Intervention	AI implementations, such as adaptive learning systems, intelligent tutoring systems, machine learning, deep learning, or AI-based learning platforms.	Studies that discussed AI only conceptually, without implementation in the learning process.
Comparison	Conventional instruction, non-AI-based technology-enhanced learning, or no comparison group when the research design was noncomparative.	Studies that were entirely technical and lacked a learning context.

Outcome	Improvement in students' mathematical problem-solving skills and/or self-directed learning as a result of using AI in mathematics education.	Studies that did not analyze AI's effects on mathematical problem-solving skills or self-directed learning.
Context	Formal mathematics education; scientific journal articles published from 2021 to 2025; full-text, open-access availability.	Articles outside mathematics education; non-journal publications, editorials, or conference proceedings; articles published before 2021; and articles without open-access full text.

The literature search was conducted systematically using Publish or Perish (PoP) to retrieve article metadata from Scopus, OpenAlex, and Google Scholar. These databases were selected because of their broad literature coverage, relevance to education, and access to open-access articles, enabling the researchers to identify comprehensive and current sources on the application of Artificial Intelligence (AI) in mathematics education.

The search strategy combined keywords with Boolean operators to align the results with the study focus and research questions. The search strings included "artificial intelligence" AND "mathematics education," "artificial intelligence" AND "mathematical problem solving," "artificial intelligence" AND "self-directed learning in mathematics," and "systematic review" AND "artificial intelligence" AND "mathematics education." These combinations were intended to capture a broad range of studies, from general implementations of AI in mathematics education to research specifically addressing mathematical problem-solving skills and self-directed learning.

The search was limited to publications from 2021 to 2025 so that the review represented recent developments in AI research in mathematics education. The selection process was reported using a PRISMA 2020 flow diagram generated with the Shiny app and the PRISMA2020 R package developed by Haddaway et al. (2022). Figure 1 presents the complete study-selection process.

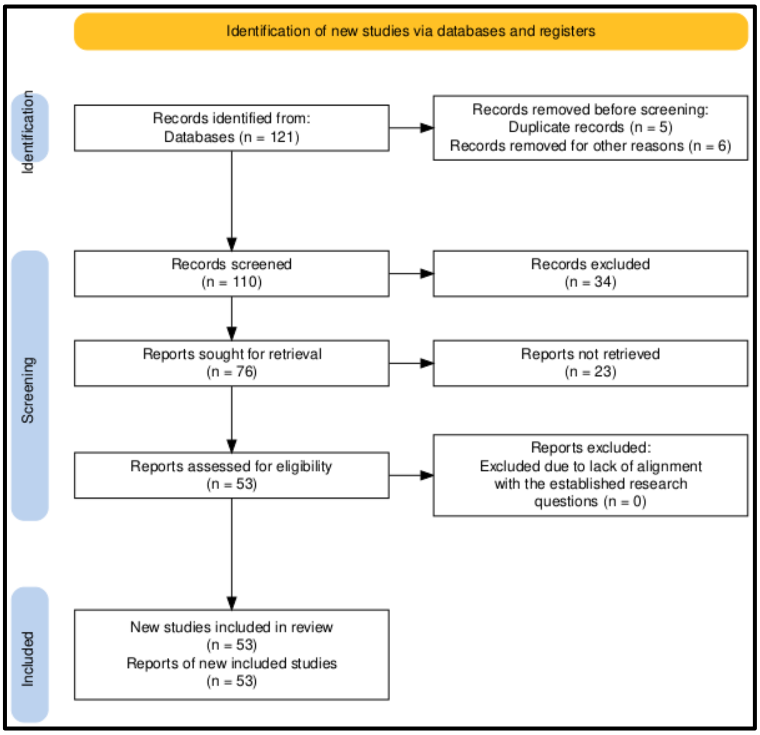

Figure 1. PRISMA Flow Diagram

During identification, searches conducted through Publish or Perish across Scopus, OpenAlex, and Google Scholar yielded 121 articles: 71 from Scopus and OpenAlex combined and 50 from Google Scholar. Five duplicate records and six non-journal records were removed, leaving 110 articles. During screening, 34 articles that did not meet the PICOC criteria were excluded, leaving 76 articles. At the eligibility stage, 23 articles were excluded because full-text open-access versions were unavailable, leaving 53 articles. These 53 articles then underwent quality assessment based on methodological quality, the clarity of the AI technology examined, and the relevance of the findings to the research questions. All 53 articles met the eligibility and quality criteria and were included in the analysis.

RESULTS AND DISCUSSION

Research on the application of Artificial Intelligence (AI) in mathematics education increased substantially from 2021 to 2025. This growth coincided with the expanding use of digital technology and AI to support adaptive, personalized, and student-centered learning. AI was increasingly viewed not only as a technical tool but also as an integral component of pedagogical innovation, particularly for supporting students' higher-order thinking and independent learning (Badri, 2024; Kuzmenko, 2025).

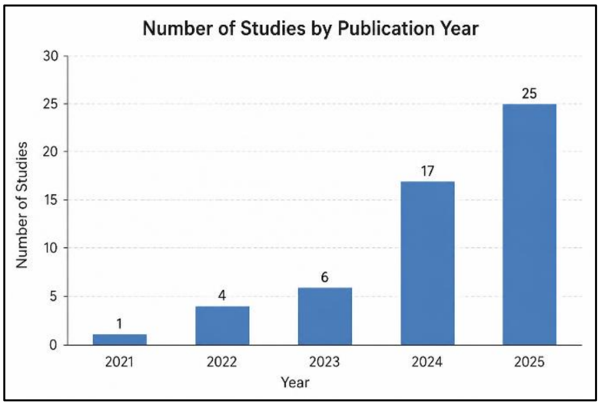

Figure 2. Publication Trends in AI Research in Mathematics Education, 2021–2025

Figure 2 shows that the number of publications on AI in mathematics education increased sharply, from one article in 2021 to four in 2022 and six in 2023. The number rose to 17 in 2024 and peaked at 25 in 2025. This pattern indicates growing scholarly attention to AI as a major research topic (Hossein-Mohand et al., 2025; Sutomo & Turmudi, 2025). A descriptive analysis was also conducted to map the demographic and methodological characteristics of the 53 reviewed articles. Table 2 presents the characteristics of 10 representative articles.

Table 2. Characteristics of 10 Representative Articles

Author and Year	Country	Instrument	AI Type	Main Findings
Chau et al., 2025	Vietnam	Transcripts of student–chatbot interactions	AI chatbots	Developed an AI-chatbot-based mathematics learning model that enhanced problem-solving competence, critical thinking, and self-directed learning through adaptive pathways and real-time personalized feedback.
Rizos et al., 2024	Greece	Interviews, worksheet tasks, and electronic questionnaires	*Generative AI (ChatGPT-3.5)*	Personalized worksheets created with ChatGPT increased active engagement, conceptual understanding (e.g., square roots and irrational numbers), and students' sense of security and confidence, including among learners with dyslexia and ASD.
Kulkarni et al., 2025	India	Pretest and posttest ability measures and feedback surveys	AI-powered educational game using the Minimax	Improved mathematics test scores by an average of 6.03 points and helped maintain attention and concentration on mathematical concepts.

Author and Year	Country	Instrument	AI Type	Main Findings
			algorithm	
Anjos et al., 2024	Brazil	Semi-structured interviews using a report-aloud protocol and descriptive gesture analysis	*Generative AI (ChatGPT)*	Integrating ChatGPT as a simulation and sociotechnical medium deepened conceptual understanding and supported modeling and problem-solving skills.
Song et al., 2025	Malaysia	Standardized pretests and posttests, questionnaires, and semi-structured interviews	AI-powered mathematics tools / adaptive learning platforms	AI improved overall mathematical performance and problem-solving skills. The tools supported personalized learning and immediate feedback, although technical and data-privacy concerns remained.
Kuzmenko, 2025	Russia	Online questionnaires	AI-based mathematical problem-solving tools and virtual assistants (e.g., MathGPT, ChatMathGPTPro, and neural networks)	Seventy percent of mathematics teachers reported readiness to use AI, but actual adoption ranged from 13% to 40% because of fragmented understanding, limited skills, and device constraints.
Capinding, 2023	Philippines	Written pretests and posttests and Likert-scale questionnaires	AI-powered mathematics application (Photomath)	Photomath improved self-directed learning, interest, and academic performance in precalculus.

Author and Year	Country	Instrument	AI Type	Main Findings
Wardat et al., 2024	United Arab Emirates (Abu Dhabi)	Likert-scale questionnaires	General AI systems and applications, including intelligent tutoring systems, adaptive learning systems, and robotics	Teachers viewed AI as an effective tool for facilitating instruction, increasing motivation, and improving individual performance. However, implementation required substantially more effort and workload than traditional methods.
Seto et al., 2025	Indonesia	Mathematical problem-solving test based on Polya's indicators and observation sheets	AI application (Mathos AI)	Mathos AI improved students' mathematical problem-solving scores from an average of 75 to 100 and supported problem comprehension, solution planning, systematic procedures, and answer checking.
Saputra, 2025	Indonesia	Document analysis	Chatbots	Chatbots improved conceptual understanding and self-directed learning and helped students manage their learning time through real-time feedback and flexible access.

The 10 representative articles in Table 2 revealed several patterns. Geographically, the studies were conducted in diverse countries, including Indonesia, Malaysia, and the Philippines, and most examined AI applications at the elementary and secondary school levels. Methodologically, quantitative and mixed-methods designs were common, and mathematical ability tests and questionnaires were the primary data-collection instruments. These characteristics indicate a strong emphasis on empirically evaluating AI's effects on students.

The increase in publications coincided with the development of diverse AI technologies in mathematics education. AI was no longer limited to simple algorithm-based systems but included technologies capable of interacting with students naturally, adaptively, and contextually, such as large-language-model-based chatbots and adaptive learning systems (Almarashdi et al., 2024; Sánchez-Ruiz et al., 2023). To map this technological diversity, the 53 articles were grouped according to the type of AI intervention. The extracted data were recapitulated and categorized using Microsoft Excel, and the resulting distribution is presented in Figure 3.

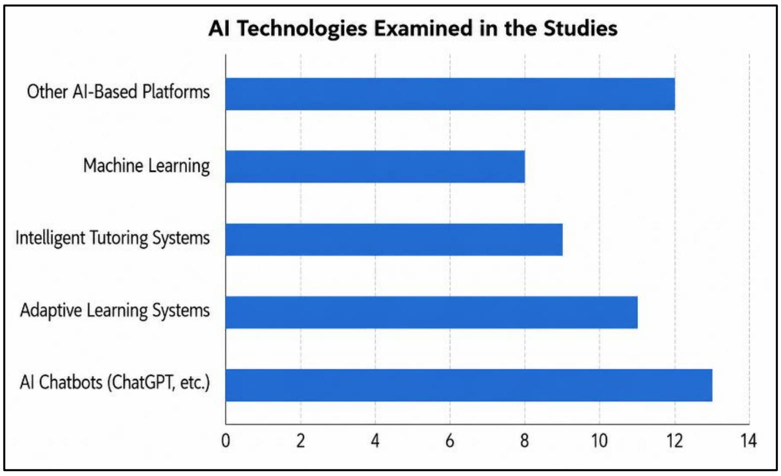

Figure 3. Distribution of AI Technologies in Mathematics Education

As shown in Figure 3, AI chatbots, including ChatGPT, were the most frequently studied technology (13 articles), followed by other AI-based platforms (12 articles) and adaptive learning systems (11 articles). Intelligent tutoring systems (9 articles) and machine learning (8 articles) were examined less frequently. The prominence of chatbots and interactive platforms indicates a shift toward AI systems that interact directly and naturally with students (Anjos et al., 2024; Dinta et al., 2023; Korkmaz Guler et al., 2024). The studies were also classified by their focal mathematical variables to clarify the pedagogical direction of these interventions.

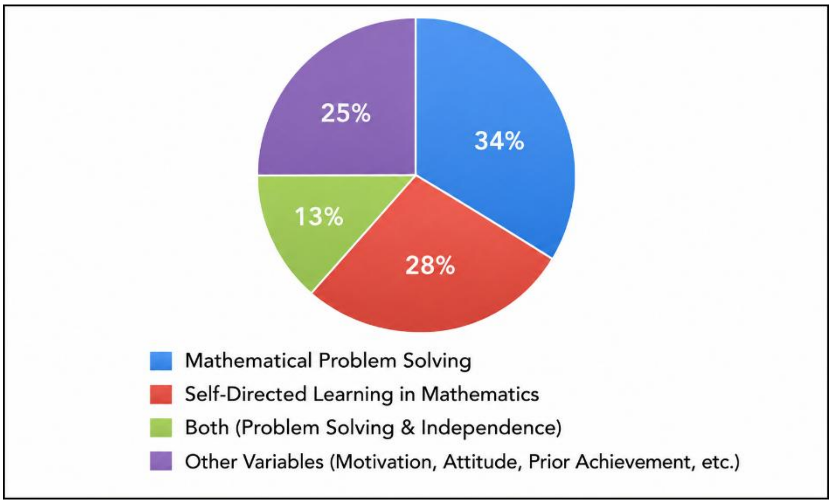

Figure 4. Focus Variables in AI Research on Mathematics Education

Figure 4 shows that mathematical problem-solving skills were the most common focus (18 articles), followed by self-directed learning in mathematics (15 articles). Only seven articles examined both variables simultaneously, while the remaining 13 focused on outcomes such as motivation, attitudes, general achievement, and mathematical beliefs. This pattern indicates that, although AI has been widely used to support cognitive outcomes, the combined development of problem-solving skills and self-directed learning has not yet become a major research focus (Hanan & Sugiman, 2025; Winanti, 2025; Yuntaro & Yudhanegara, 2024).

Overall, the findings confirm that AI research in mathematics education has developed rapidly in publication volume, technological diversity, and learning outcomes examined. Nevertheless, substantial opportunities remain to investigate how AI can simultaneously improve mathematical problem-solving skills and students' self-directed learning. This issue is examined further in the following subsection.

The extracted data indicated that AI's role in mathematics education depended substantially on the type of technology implemented. To answer the research questions concerning mathematical problem-solving skills and self-directed learning, the findings were organized into a conceptual synthesis of the relationships among these variables, as presented in Table 3.

Table 3. Conceptual Synthesis of AI's Role in Students' Mathematical Learning

AI Technology Category	Impact on Mathematical Problem-Solving Skills	Impact on Self-Directed Learning	Supporting Research
Generative AI & Chatbots	Supports the planning of problem-solving strategies through scaffolding and immediate dialogic feedback.	Promotes independence through flexible learning time and may reduce mathematics anxiety by allowing students to ask questions without fear of judgment.	(Chau et al., 2025; Saputra, 2025; Anjos et al., 2024; Rizos et al., 2024; Spreitzer et al., 2024)
Adaptive Learning Systems (ALS) and Intelligent Tutoring Systems	Personalizes problem difficulty in real time to match each student's initial cognitive capacity.	Supports self-directed learning through adaptive pathways that allow students to regulate their own learning pace.	(Han et al., 2024; Song et al., 2025; Dabingaya, 2022; Niño-Rojas et al., 2023)
AI-Powered Applications and Gamification	Visualizes problem-solving stages systematically, from understanding the problem to checking the solution.	Strengthens intrinsic motivation, self-reliance, and persistence when students encounter difficult mathematical problems.	(Seto et al., 2025; Capinding, 2023; Kulkarni et al., 2025; Winanti, 2025)

The synthesis in Table 3 revealed a consistent pattern in how AI interventions affected students' cognition and self-regulation. AI chatbots were particularly beneficial during the initial stages of mathematical problem solving. Rather than merely providing final answers, chatbots integrated with active learning approaches served as virtual tutors that offered scaffolding and guided students' reasoning (Anjos et al., 2024; Chau et al., 2025). Adaptive learning systems (ALS) were also associated with stronger self-directed learning. Several studies (Han et al., 2024; Song et al., 2025) showed that personalized learning pathways enabled students to regulate their pace and exercise greater control over their learning.

The synthesis also identified contradictions and implementation challenges. Teachers and students recognized AI's potential to improve mathematical performance, but classroom adoption continued to face substantial barriers. Studies by Kuzmenko (2025) and Tashtoush et al. (2024) found that teacher readiness lagged behind technological development because of limited digital literacy and the additional workload involved in designing AI-based learning.

The review further showed that most studies examined mathematical problem solving and self-directed learning separately (see Figure 4). Important pedagogical risks also remained underexplored, including overreliance on AI, which may weaken students' long-term mathematical intuition, and misconceptions caused by hallucinated outputs from generative AI when solving advanced mathematical problems. Future research should therefore develop pedagogical models that position AI not merely as a problem-solving aid but as a tool for balancing analytical skill development with students' self-directed learning.

Although research on Artificial Intelligence (AI) in mathematics education continues to expand, several substantive gaps remain. First, most studies have focused on established AI applications, such as chatbots, intelligent tutoring systems, and recommendation systems, while gamified AI has received comparatively little attention. AI integrated into game mechanisms may foster self-directed learning from an early age by making mathematical problem-solving activities more engaging and challenging. Kulkarni et al. (2025) indicated that evidence on how gamified AI supports independence and active engagement, particularly at the elementary level, remains limited.

In addition, AI research in mathematics education has largely been conducted separately from other disciplines. In practice, AI operates in interdisciplinary contexts, particularly within STEM and across the curriculum. The limited number of studies examining how AI supports self-directed learning during mathematical problem solving integrated with science, technology, or language indicates a gap between current research and the demands of complex, contextual, real-world problem solving (Rahmanita Zakaria, 2024; Tassilova et al., 2025).

A further gap concerns the specificity of the AI tools examined. Many studies have discussed AI broadly, while highly specialized tools such as GeoGebra Discovery have received limited attention. Automated reasoning tools of this kind may support independent exploration, mathematical reasoning, and autonomous geometric proof. The limited literature connecting these tools with self-directed learning indicates an underexplored research area (Martínez-Zarzuelo et al., 2025).

Research has also focused mainly on implementing technology rather than optimizing learning outcomes for independent use. Although prototypes such as AI4Math have demonstrated the potential to accelerate learning, few studies have examined how students can use such systems independently without extensive teacher supervision (Cunska, 2022; Tulak et al., 2024). This gap is reinforced by evidence that teachers' readiness to integrate AI varies and is often unsupported by clear pedagogical guidance; consequently, AI has not yet fully strengthened students' self-directed learning (Devi et al., 2025; Kuzmenko, 2025).

Furthermore, the challenge of AI implementation lies not only in the availability of technology but also in selecting the most appropriate tools from the growing range of options. This situation reveals a gap between technological innovation and educators' practical ability to select AI tools that align with the goal of independent mathematics learning (Sari & Mahmud, 2024). Moreover, generative AI tools such as GPT are still often positioned as sources of instant answers. Research is therefore needed to develop their role as learning assistants that foster self-regulation and independence rather than merely increasing task-completion efficiency (Buton et al., 2025).

Finally, ethical issues, accessibility, and educational context remain important research gaps. AI's potential to strengthen self-directed learning has not been fully realized because of disparities in access and implementation constraints across educational settings. Although research on AI in advanced mathematics at the higher-education level is growing, comparable studies focused on self-directed learning in elementary and secondary education remain limited (Kohnke & Zaugg, 2025; Suryadi, 2025). Further research is therefore needed to map AI's role in supporting self-directed learning in ways that are contextual, inclusive, and oriented toward improved learning outcomes.

CONCLUSION

Based on the systematic review of 53 relevant articles, this study reached several conclusions that addressed the research questions. Publications on Artificial Intelligence (AI) in mathematics education increased markedly from 2021 to 2025, with AI chatbots and adaptive learning systems dominating the literature, particularly at the elementary and secondary school levels. Regarding cognitive outcomes, AI played an important role in improving students' mathematical problem-solving skills by functioning as a virtual tutor that provided scaffolding from problem comprehension to the planning of solution strategies. AI also contributed to self-regulation and self-directed learning. Personalized learning pathways and adaptive feedback enabled students to regulate their learning pace, increase their self-confidence, and reduce mathematics anxiety.

Despite these positive contributions, the review identified several research gaps and limitations. Key gaps included teachers' digital literacy, which has not kept pace with advances in AI, and the limited number of empirical studies examining problem solving and self-directed learning simultaneously. This review was limited to open-access articles indexed in Scopus, OpenAlex, and Google Scholar and published from 2021 to 2025, which may have excluded relevant studies available through subscription databases or other sources. In addition, substantial methodological heterogeneity among the reviewed studies restricted the analysis to a thematic conceptual synthesis. Future research should broaden database coverage, conduct statistical meta-analyses to estimate AI's effectiveness, and develop pedagogical guidelines that position AI not merely as a technical aid but as a facilitator of independent and sustainable mathematics learning.

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