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Human–AI Collaboration in Mathematics Learning: A Systematic Review of Generative AI Integration and Its Implications for Mathematical Thinking

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Keywords:

Human–AI Collaboration, Generative AI, Mathematics Learning, Mathematical Thinking, Systematic Literature Review

Abstract: The rapid advancement of Generative Artificial Intelligence (Generative AI) has transformed mathematics education from the use of technology as a supporting tool toward cognitive collaboration between humans and artificial intelligence. This study aims to identify research trends, forms of Human–AI Collaboration, and their implications for the development of mathematical thinking. The study employed a Systematic Literature Review (SLR) approach following the PRISMA guidelines, with data collected from Google Scholar, Scopus, Scispace, and the Directory of Open Access Journals (DOAJ). The findings indicate that research has evolved from digital technology integration to AI literacy, the TPACK-SAMR framework, adaptive learning, and the implementation of Generative AI and Human–AI Collaboration to enhance mathematical thinking. The review further reveals that Generative AI has the potential to improve mathematical reasoning, representation, and problem-solving through more personalized and collaborative learning. However, its implementation continues to face challenges related to AI literacy, teachers' pedagogical readiness, implementation gaps, and the risk of cognitive offloading. Therefore, developing pedagogical models based on Human–AI Collaboration is essential to foster the sustainable development of students' mathematical thinking.

Kata Kunci:

Human–AI Collaboration, Generative AI, Pembelajaran Matematika, Berfikir Matematis, Systematic Literature Review

Abstrak: *Perkembangan Generative Artificial Intelligence (Generative AI) telah mendorong transformasi pembelajaran matematika menuju kolaborasi kognitif antara manusia dan kecerdasan buatan. Penelitian ini bertujuan mengidentifikasi tren penelitian, bentuk integrasi Human–AI Collaboration, serta implikasinya terhadap pengembangan mathematical thinking. Penelitian menggunakan pendekatan Systematic Literature Review (SLR) berdasarkan pedoman PRISMA dengan sumber data dari Google Scholar, Scopus, Scispace, dan Directory of Open Access Journals (DOAJ). Hasil kajian menunjukkan bahwa fokus penelitian berkembang dari integrasi teknologi digital menuju AI literacy, kerangka TPACK-SAMR, pembelajaran adaptif, serta implementasi Generative AI dan Human–AI Collaboration yang mendukung mathematical thinking. Temuan menunjukkan bahwa GenAI berpotensi meningkatkan kemampuan penalaran, representasi, dan pemecahan masalah matematis melalui pembelajaran yang lebih personal dan kolaboratif. Namun, implementasinya masih menghadapi tantangan berupa literasi AI, kesiapan pedagogis guru, kesenjangan implementasi, dan risiko cognitive offloading. Oleh karena itu, diperlukan pengembangan model pedagogis berbasis Human–AI Collaboration untuk mendukung pengembangan kemampuan berpikir matematis secara berkelanjutan.*

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A. INTRODUCTION

Mathematical thinking is a fundamental competency in twenty-first-century mathematics education, encompassing mathematical reasoning, problem-solving, generalization, mathematical connections, and the construction of logical, evidence-based arguments (Wulandari *et al.,* 2025). This competency not only supports students' academic achievement but also serves as a foundation for developing higher-order thinking skills required to address complex real-world problems (Irawati & Hadi, 2025). In the context of contemporary education, mathematical thinking is widely regarded as a key indicator of successful mathematics learning because it is closely associated with students' ability to understand mathematical concepts, select appropriate problem-solving strategies, and critically evaluate solutions (Siswanto *et al.,* 2024). Furthermore, the rapid advancement of digital technologies and artificial intelligence has created new opportunities to foster mathematical thinking through more adaptive and personalized learning environments (Nuryami *et al.,* 2026).

The rapid advancement of Generative Artificial Intelligence (GenAI) has given rise to a new learning paradigm known as Human–AI Collaboration (Dewantara & Dewi, 2025). This concept refers to the collaboration between humans and artificial intelligence systems in performing various cognitive tasks to support more effective learning processes (Suliyem *et al*., 2024). Within this paradigm, AI no longer functions merely as an information provider but also as a learning partner capable of offering feedback, recommendations, explanations, and alternative solutions to learners (Limbong & Simbolon, 2026). In mathematics education, the integration of GenAI technologies, such as ChatGPT, Gemini, Claude, and various Large Language Models, has the potential to create more adaptive, interactive, and learner-centered learning environments (Abdin *et al.,* 2024). Therefore, Human–AI Collaboration is regarded as an innovative approach that can transform mathematics education by integrating human cognitive abilities with artificial intelligence to create more meaningful and effective learning experiences (Hadian *et al*,. 2026).

Numerous studies have demonstrated that the integration of Generative Artificial Intelligence (GenAI) contributes positively to improving the quality of mathematics education (Geovanny *et al.,* 2025). Cuenca *et al.,* (2025) reported that the use of GenAI in mathematical proof construction enables university students to explore diverse problem-solving strategies while fostering deeper reflection on their thinking processes. Similarly, Chen *et al.,* (2025) found that GenAI demonstrates strong capabilities in solving mathematical problems and has considerable potential to support the development of students' mathematical reasoning. Furthermore, a meta-analysis conducted by Syahril *et al.,* (2024) revealed that the use of GenAI has a positive effect on mathematics learning outcomes across different educational levels. These findings suggest that GenAI functions not only as a technology-enhanced learning tool but also as a means of enriching students' cognitive processes and fostering the development of mathematical thinking through more interactive, adaptive, and responsive learning environments (Lee *et al.,* 2025 ; Gqoli & Baidoo, 2025).

Numerous studies have emphasized that the successful implementation of artificial intelligence in mathematics education depends not only on technological sophistication but also on the quality of collaboration established between humans and AI systems (Nguyen, 2025). Trisni and Putri, (2026) reported that networks of AI agents capable of communication and collaboration can assist teachers and students in designing mathematics learning activities that are more complex, authentic, and contextually relevant. Similarly, González-Trejo *et al.,* (2024)

found that the use of GenAI in higher-order mathematical tasks encourages teachers to place greater emphasis on reasoning processes and the development of mathematical thinking rather than merely obtaining correct answers. Other studies have shown that the effectiveness of Human–AI Collaboration is influenced by users' ability to engage with AI critically and reflectively throughout the learning process (Musliha *et al*., 2025). In addition, students' perceptions of the usefulness, ease of use, and suitability of AI technologies for their learning needs constitute important factors influencing the successful integration of AI into mathematics education (Cómo, 2025). This finding is consistent with previous studies highlighting the importance of pedagogical readiness and AI literacy in fostering effective learning interactions (Saputri &Maya, 2026). Overall, these findings indicate that collaborative interactions between humans and AI are essential for optimizing the learning process and enhancing students' mathematical thinking (Nigam & Kushwaha, 2025).

In addition to supporting mathematical problem-solving, the integration of Generative Artificial Intelligence (GenAI) also contributes to the development of students' computational thinking, analogical reasoning, reflective thinking, and critical thinking skills. Murwanto *et al*., (2025) demonstrated that the integration of ChatGPT and GeoGebra enhances computational thinking by providing more interactive and adaptive learning experiences. Furthermore, Aprianto *et al.,* (2025) reported that GenAI assists students in understanding STEM concepts through analogical reasoning that connects new knowledge with their prior knowledge. In addition, Antonio and Vasconcelos, (2023) found that the use of AI in Mathematical Battles with AI activities improves students' verification, evaluation, and critical thinking skills. Other studies have also shown that generative AI enhances students' cognitive engagement by providing rapid and personalized feedback during mathematics learning Muhidin *et al.,* (2025), while also strengthening metacognitive skills by encouraging reflection on problem-solving strategies and processes (Virginayoga *et al.,* 2026). These findings indicate that AI functions not only as an information source but also as a learning partner that supports the comprehensive development of multiple dimensions of mathematical thinking (Gao *et al.*, 2024).

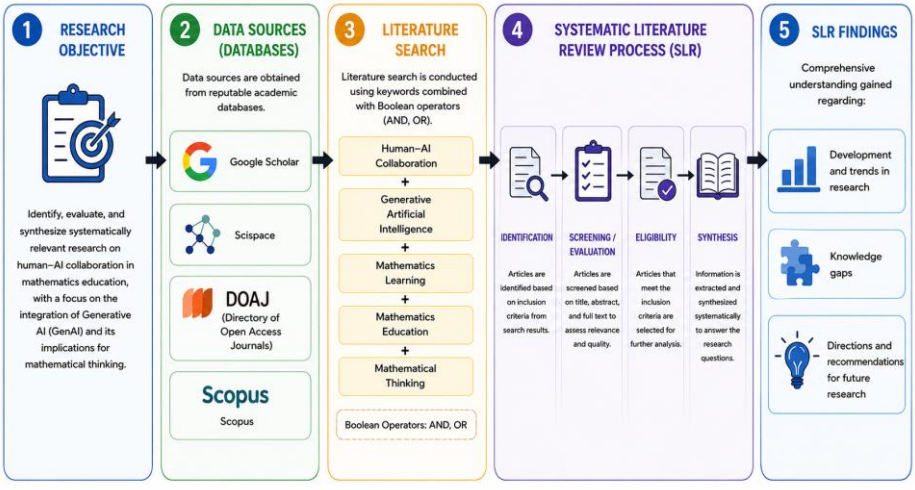
Although research on the application of Generative Artificial Intelligence (GenAI) in mathematics education has grown rapidly, most studies have primarily focused on technological effectiveness, user acceptance, and its impact on students' learning outcomes (Lie *et al.,* 2025). Consequently, the mechanisms through which collaboration between humans and artificial intelligence contributes to the development of mathematical thinking remain insufficiently understood Zhao *et al*., (2025). Moreover, many studies continue to position AI as an instructional support tool, with limited attention given to its role as a cognitive partner in mathematical reasoning, problem-solving, and reflective thinking (Rahman & Mudhsh, 2025). Likewise, systematic reviews synthesizing empirical evidence on the forms of collaboration, interaction patterns, benefits, challenges, and implications of Human–AI Collaboration for mathematical thinking remain relatively scarce (Feng, 2025). In response to these gaps, the present study offers a novel contribution through a comprehensive literature synthesis aimed at mapping research developments, identifying emerging trends and research gaps, and proposing a conceptual framework that explains the role of Human–AI Collaboration in fostering the development of mathematical thinking in the era of artificial intelligence (Mclaughlin *et al.,* 2025).

Based on the identified research background and gaps, this study aims to systematically synthesize empirical findings on Human–AI Collaboration in mathematics education, with a particular focus on the integration of Generative Artificial Intelligence (GenAI) and its implications for the development of mathematical thinking. This review is expected to make a theoretical

contribution by mapping current research trends, identifying existing knowledge gaps, and developing a conceptual framework that explains the relationship between Human–AI Collaboration and artificial intelligence in mathematics education. From a practical perspective, the findings are expected to serve as a reference for researchers, educators, educational technology developers, and policymakers in designing AI implementation strategies that are more effective, ethical, adaptive, and oriented toward strengthening students' mathematical thinking. Furthermore, the findings of this review are expected to contribute to the advancement of mathematics education in the era of digital transformation and artificial intelligence.

B. METHODS

This study employed a Systematic Literature Review (SLR) approach to systematically identify, evaluate, and synthesize research findings on Human–AI Collaboration in mathematics education, with a particular focus on the integration of Generative Artificial Intelligence (GenAI) and its implications for mathematical thinking. The SLR method was selected because it enables researchers to obtain a comprehensive understanding of research developments, emerging trends, knowledge gaps, and future research directions through a systematic and replicable procedure (Page *et al*., 2021). The data sources were obtained from several reputable academic databases, namely Google Scholar, Scispace, the Directory of Open Access Journals (DOAJ), and Scopus. The literature search was conducted using combinations of keywords, including "Human–AI Collaboration," "Generative Artificial Intelligence," "Mathematics Learning," "Mathematics Education," and "Mathematical Thinking," combined with Boolean operators (AND, OR) to retrieve articles relevant to the objectives of this study. The research procedure adopted in this Systematic Literature Review (SLR) is presented concisely and systematically in Figure 1, providing an overview of the research stages undertaken throughout the review process.



Gambar 1. Research Methodology

Figure 1 illustrates the research procedure employed in this Systematic Literature Review (SLR) on Human–AI Collaboration in mathematics education. The review process began with the identification stage, during which relevant articles were collected from various academic databases. This was followed by the literature search stage, in which a combination of keywords aligned with the research focus was used to retrieve studies relevant to the topic. The retrieved articles then underwent a screening process to eliminate duplicate and irrelevant records. During the eligibility stage, the remaining articles were further assessed according to the predefined

inclusion and exclusion criteria, resulting in a set of studies that met the research requirements. The selected articles were subsequently categorized as included studies, after which data extraction was conducted to obtain essential information from each study. The extracted data were then analyzed through thematic analysis and synthesis to identify major themes, research trends, benefits, challenges, and implications. The final stage involved drawing research conclusions based on the findings of the literature synthesis. Through these systematic procedures, this study is expected to produce a comprehensive, transparent, and scientifically rigorous review.

This study adopted a Systematic Literature Review (SLR) approach with inclusion criteria comprising research articles published between 2021 and 2026 that examined the integration of Generative Artificial Intelligence (GenAI), artificial intelligence, or Human–AI Collaboration within the context of mathematics education. Eligible studies were required to be published in peer-reviewed national or international journals, available in full-text format, and written in either Indonesian or English. The exclusion criteria included duplicate articles, conference proceedings, editorials, books, theses, dissertations, and research reports that had not undergone peer review, as well as studies that were not directly related to mathematics education or mathematical thinking, or that did not provide sufficient methodological information and research findings. The literature selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, consisting of the identification, screening, eligibility, and inclusion stages. Data extracted from the selected studies were analyzed using thematic analysis and qualitative descriptive analysis to identify research patterns, themes, trends, benefits, challenges, and the implications of Human–AI Collaboration for the development of mathematical thinking. The extracted data were further classified according to research characteristics, research design, study participants, types of AI technologies employed, and the principal findings of each study. To ensure the validity and reliability of the review, the selection and data extraction processes were conducted systematically based on predefined criteria, accompanied by consistency checks and comprehensive documentation of each stage of the review. Furthermore, the application of the PRISMA protocol and the use of multiple reputable academic databases were intended to enhance the transparency, credibility, and reproducibility of the study findings

C. RESULTS AND DISCUSSION

To obtain a comprehensive understanding of the development of Human–AI Collaboration in mathematics education, the selected studies were reviewed based on several key criteria: (1) research focus or field of study, (2) forms of artificial intelligence integration in learning, (3) pedagogical frameworks employed, (4) impacts on the learning process and learning outcomes, and (5) the challenges and implications identified. Through this literature synthesis, the present study identified emerging trends in AI integration within education, its contributions to the development of mathematical thinking, and the various challenges associated with the implementation of Human–AI Collaboration. These review criteria enabled a more systematic mapping of research directions, the relationships among the investigated variables, and the research gaps that warrant further investigation in the context of mathematics education. A summary of the literature review findings, including the research field, authors, and the main research variables of each selected study, is presented in Table 1 as the basis for the analysis and synthesis of the research findings.

Table 1. Synthesis of Research Focus and Research Variables in Human–AI Collaboration Studies in Mathematics Education

No	Research Area/Focus	Author(s)	Main Research Variables
1	AI Integration in the STEAM Curriculum	Soomro & Soomro (2025)	AI Integration, STEAM Curriculum, Inclusive Learning, Problem Solving, Systemic Thinking
2	AI Literacy in Primary Education	Yeter et al. (2024)	AI Literacy, Educational Policy, AI Implementation, Elementary Education
3	AI Integration In Teacher Education	Kohnke & Zou (2025)	Artificial Intelligence Integration, TPACK, SAMR, Teacher Education
4	AI-Driven Flipped Classroom	Suvendu & Sikdar (2024)	AI-Driven Learning, Flipped Classroom, Personalized Learning, Student Engagement
5	Development of the TPACK Framework in the AI Era	Gatete (2025)	Extended TPACK, Digital Transformation, AI Pedagogy
6	Human–AI Collaboration in Mathematics Education (SLR Synthesis)	Synthesis from Soomro & Soomro (2025), Kohnke & Zou (2025), Gatete (2025), Suvendu & S. (2024), and Yeter et al. (2024)	Human–AI Collaboration, Generative AI, Mathematical Thinking, Mathematical Reasoning, Mathematical Representation, Problem Solving
7	Challenges in AI Implementation in Education	Synthesis from Yeter et al. (2024), Kohnke & Zou (2025), and Gatete (2025)	AI Literacy, Pedagogical Readiness, Policy–Practice Gap, Cognitive Offloading
8	Pedagogical Implications of Human-AI Collaboration	Synthesis from Kohnke & Zou (2025), Gatete (2025), and Suvendu & Sikdar. (2024)	AI-Based Pedagogy, AI-TPACK, Human–AI Interaction, Mathematics Learning

Based on the literature mapping presented in Table 1, the analysis and discussion in this study are organized around three major themes emerging from the synthesis process: trends in the integration of Human–AI Collaboration, its impact on the development of mathematical thinking, and the pedagogical challenges and implications for mathematics education.

1. Trends and Patterns of Human–AI Collaboration Integration in Mathematics Education

The findings of the literature synthesis indicate that the integration of Human–AI Collaboration in education has evolved from the mere use of digital technologies toward a more adaptive, collaborative, and artificial intelligence-driven approach. Although not all studies were conducted specifically within the context of mathematics education, the conceptual patterns identified demonstrate the transferability of AI integration principles across various educational domains, including STEAM education, digital pedagogy, and AI literacy. Soomro and Soomro, (2025), through the INSPIRE Model, demonstrated that integrating AI into the STEAM curriculum promotes more inclusive and contextualized

learning. The model further emphasizes that AI can function as a catalyst for strengthening twenty-first-century competencies, including problem-solving and systems thinking, both of which are closely associated with mathematics education (Aisyah, 2025).

Suvendu and Sikdar, (2024) argued that AI integration has increasingly shifted toward AI-driven flipped classrooms, a learning model that utilizes AI for content personalization, learning analytics, and enhanced student engagement. These findings indicate a transition from conventional instruction to data-driven adaptive learning. Consistent with this perspective, Yeter *et al.,* (2024) found that AI implementation in primary education remains largely dominated by top-down policy initiatives and has not yet been fully integrated into classroom practice. This finding suggests that AI adoption in education is still at an early stage, resulting in a gap between policy directions and their actual implementation in teaching and learning processes.

Based on these findings, three major trends in the development of Human–AI Collaboration can be identified: the integration of STEAM-based curricula, the development of AI-driven adaptive learning, and the strengthening of AI literacy as a pedagogical foundation. Nevertheless, most existing studies remain focused on conceptual perspectives and the general implementation of AI in education. Consequently, empirical evidence specifically explaining patterns of human–AI collaboration in mathematics education remains limited. This highlights the need for further research exploring how AI integration can be effectively implemented in mathematics education and how such collaboration contributes to the development of students' mathematical thinking.

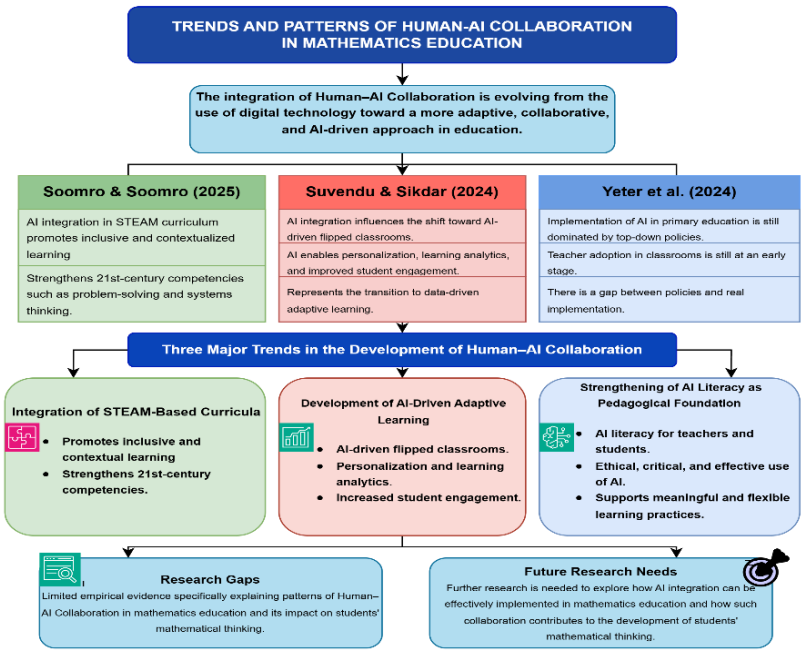


Figure 2. Trends of Human–AI Collaboration in Mathematics Education

Figure 2 demonstrates that Human–AI Collaboration in mathematics education is evolving toward adaptive, personalized, and AI-supported learning. Three dominant trends emerge, namely STEAM integration, AI-driven adaptive learning, and AI literacy development. Despite these advances, empirical research on the impact of Human–AI Collaboration on

students' mathematical thinking remains limited, highlighting the need for further investigation

2. The Impact of Generative AI on the Development of Mathematical Thinking in Collaborative Learning

Although most studies do not explicitly focus on mathematics education, the conceptual evidence indicates that Generative AI has significant implications for developing higher-order thinking skills that constitute the core of mathematical thinking, including reasoning, representation, and problem-solving. Kohnke and Zou, (2025) emphasized that AI implementation in education should be guided by the TPACK and SAMR frameworks to ensure that AI functions not merely as a technological substitute but also as a means of fundamentally transforming the learning process. Within mathematics education, this approach suggests that AI can strengthen mathematical reasoning and facilitate students' conceptual understanding rather than simply providing automated answers.

These findings are further supported by Gatete, (2025), who argued that digital transformation requires an expanded TPACK framework capable of adapting to the rapid advancement of AI technologies. This finding implies a changing role for teachers in mathematics education, shifting from knowledge transmitters to facilitators who guide interactions between students and AI systems in constructing mathematical understanding. Furthermore, Yusuf, (2025) reported that AI-supported flipped classroom models enhance student engagement by promoting more independent and structured learning experiences. In the context of mathematical thinking, this approach has the potential to facilitate concept exploration, the development of problem-solving strategies, and students' reflection on their own thinking processes during learning (Saputra *et al*., 2025).

Overall, the impact of Generative AI on mathematical thinking can be summarized into three primary dimensions: enhancing flexibility in conceptual representation, strengthening reasoning processes through human–AI interaction, and improving problem-solving abilities through more adaptive learning environments. However, the majority of available studies remain conceptual and primarily focus on pedagogical frameworks and general technology integration. Therefore, further empirical research is required to investigate the influence of Generative AI on specific components of mathematical thinking, including mathematical reasoning, mathematical representation, and problem-solving, in order to achieve a more comprehensive understanding of the effectiveness of human–AI collaboration in mathematics education.

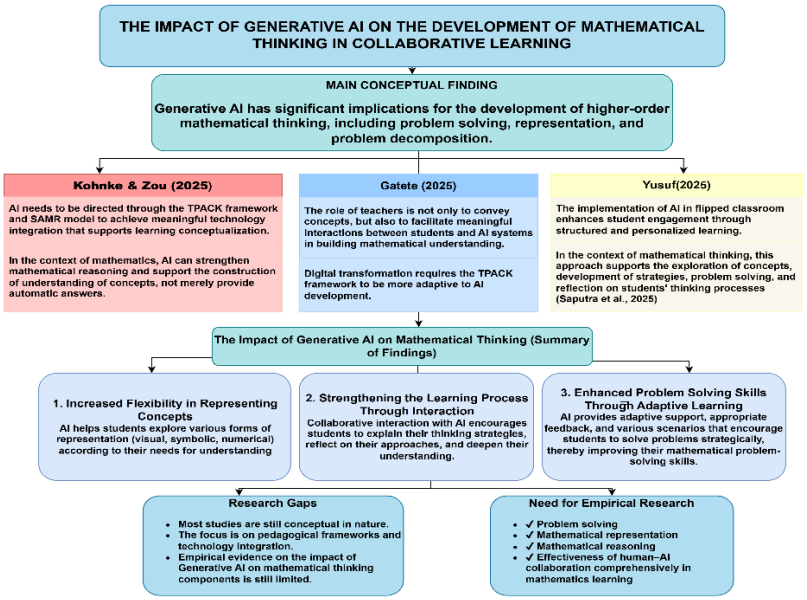


Figure 3. Impact of Generative AI on the Development of Mathematical Thinking

Figure 3 summarizes the impact of Generative AI on the development of mathematical thinking in collaborative learning. The synthesis indicates that Generative AI enhances concept representation, collaborative learning processes, and problem-solving skills through adaptive and interactive learning environments. However, limited empirical evidence highlights the need for further research to examine its effectiveness in improving students' mathematical thinking in mathematics education.

3. Challenges, Research Gaps, and Pedagogical Implications of Human–AI Collaboration in Mathematics Education

The literature synthesis indicates that although Human–AI Collaboration has considerable potential to support educational transformation, its implementation continues to face significant challenges, particularly within formal education. Adinda and sahrul, (2026) identified a substantial gap between AI literacy policies and their implementation at the elementary school level. These findings suggest that the readiness of educational systems to adopt AI remains uneven in terms of infrastructure, human resource competencies, and policy support. Consequently, AI integration in teaching and learning, including mathematics education, is likely to exhibit varying levels of implementation quality across regions, institutions, and educational levels.

Mochtar and qurotul, (2024) highlighted the risk of excessive dependence on AI technologies, which may reduce the reflective roles of both teachers and students during the learning process. In the context of mathematics education, this issue is particularly important because mathematical thinking requires active cognitive engagement, including reasoning, analysis, and problem-solving, which cannot be entirely replaced by AI systems. Consistent with these findings, Susanto *et al.,* (2026) further emphasized that digital transformation requires a reinterpretation of pedagogical frameworks capable of accommodating the complexity of AI integration in education. Without an appropriate pedagogical framework, AI integration risks resulting only in superficial digitalization of learning rather than producing meaningful improvements in the quality of teaching and learning.

Based on the overall findings, the primary challenges in implementing Human–AI Collaboration extend beyond technological aspects to include pedagogical readiness, AI literacy, and the capacity of educational institutions to integrate AI effectively. These findings also reveal existing research gaps that require further investigation, particularly regarding the development of Human–AI collaborative learning models capable of sustaining students' mathematical reasoning processes. Accordingly, several pedagogical implications can be identified, including the need to strengthen AI literacy among mathematics teachers, develop learning models that position AI as a learning partner supporting students' thinking processes, and expand the integration of the TPACK–SAMR framework to facilitate the critical, reflective, and sustainable implementation of AI-based learning.

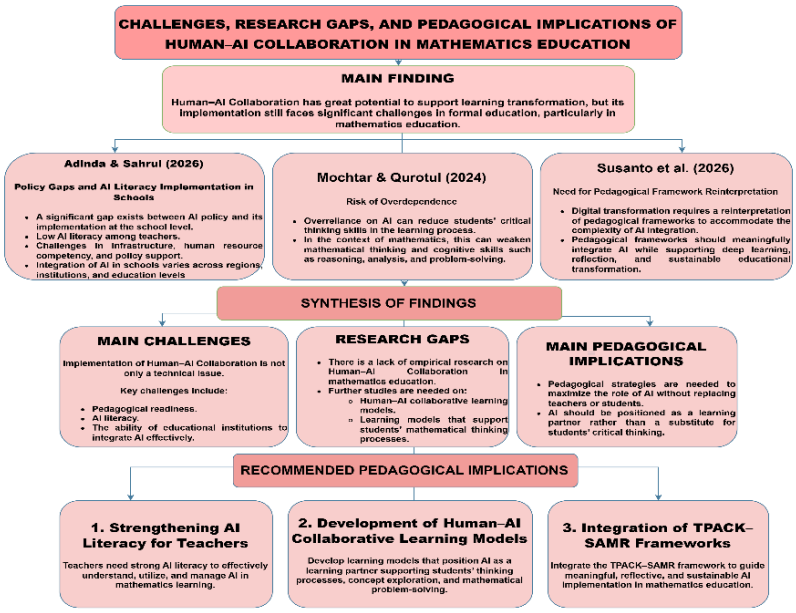


Figure 4. Challenges and Pedagogical Implications of Human–AI Collaboration in Mathematics Education

Figure 4 summarizes the key challenges, research gaps, and pedagogical implications of Human–AI Collaboration in mathematics education. Although AI has significant potential to enhance teaching and learning, successful implementation requires stronger AI literacy, pedagogically sound learning models, and effective integration frameworks. The limited empirical evidence identified in the literature highlights the need for further research to support meaningful and sustainable Human–AI Collaboration in mathematics education.

To provide a clearer illustration of the evolution of research focus and the relationships among the themes identified in the literature, the synthesized research trends on Human–AI Collaboration in mathematics education during the 2021–2026 period are visualized in the form of a conceptual map presented in Figure 2.

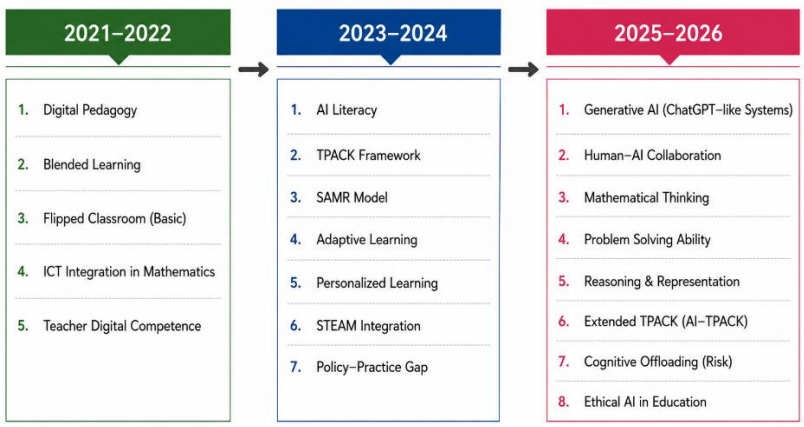


Figure 5. Mind Map Evolution of Research Trends on Human–AI Collaboration in Mathematics Learning (2021–2026)

Figure 5 illustrates the evolution of research trends related to Human–AI Collaboration in mathematics education during the 2021–2026 period. In the initial phase (2021–2022), research primarily focused on the integration of digital technologies into teaching and learning, encompassing digital pedagogy, blended learning, flipped classrooms, the integration of Information and Communication Technology (ICT) in mathematics education, and the enhancement of teachers' digital competencies. During the 2023–2024 period, the research focus shifted toward the application of artificial intelligence in education, as reflected by increasing attention to AI literacy, the adoption of the TPACK and SAMR frameworks, adaptive learning, personalized learning, STEAM integration, and the policy–practice gap. Subsequently, in the 2025–2026 period, research evolved toward more complex themes, including Generative AI and Human–AI Collaboration, which were closely associated with the development of mathematical thinking, problem-solving skills, reasoning and representation, the development of the Extended TPACK (AI-TPACK) framework, as well as growing concerns regarding cognitive offloading and the ethical implications of AI use in education.

From an interpretative perspective, the evolution of the research variables presented in the figure indicates a paradigm shift from technology-enhanced learning toward learning environments that position artificial intelligence as a cognitive partner in the learning process. During the 2021–2022 period, technology primarily functioned as a learning support tool (technology as a tool). In contrast, throughout the 2023–2024 period, artificial intelligence increasingly emerged as a means of supporting personalized and adaptive learning through strengthened AI literacy and the implementation of relevant pedagogical frameworks. This transformation reached a more advanced stage during the 2025–2026 period, when AI was no longer viewed merely as an instructional tool but rather as a collaborative partner (AI as a collaborative partner) capable of facilitating mathematical reasoning, representation, and problem-solving processes. These findings suggest that future research should extend beyond technological advancement and place greater emphasis on developing pedagogical designs that effectively optimize human–AI collaboration to enhance mathematical thinking while simultaneously minimizing students' potential cognitive dependency on AI systems.

D. CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this Systematic Literature Review (SLR), it can be concluded that the integration of Generative Artificial Intelligence (GenAI) in mathematics education has experienced significant development, marked by a shift in the role of technology from merely serving as a learning support tool to fostering cognitive collaboration between humans and artificial intelligence. This evolution is reflected in the changing research focus: during the 2021–2022 period, studies primarily emphasized the integration of digital technologies and the enhancement of teachers' digital competencies; in 2023–2024, the focus shifted toward strengthening AI literacy, adopting pedagogical frameworks such as TPACK and SAMR, and promoting adaptive learning; while in 2025–2026, research increasingly concentrated on the implementation of Generative AI and Human–AI Collaboration to enhance mathematical thinking. The synthesized evidence indicates that artificial intelligence has considerable potential to improve mathematical reasoning, mathematical representation, and problem-solving skills by facilitating more personalized, adaptive, and collaborative learning experiences. Nevertheless, the implementation of Human–AI Collaboration continues to face several challenges, including the gap between policy and practice, limited AI literacy, variations in teachers' pedagogical readiness, and the risk of cognitive offloading, which may reduce students' cognitive engagement. Therefore, the successful integration of Generative AI in mathematics education depends not only on technological capabilities but also on pedagogical designs that position AI as a learning partner capable of supporting knowledge construction and fostering the optimal development of students' mathematical thinking.

Future research should therefore focus on the development and empirical validation of Human–AI Collaboration models to comprehensively examine the impact of Generative AI on multiple dimensions of mathematical thinking, including mathematical reasoning, representation, and problem-solving skills. In addition, further studies should explore AI-based pedagogical designs that effectively optimize collaborative interactions between humans and artificial intelligence while minimizing the potential risk of students' cognitive dependency throughout the mathematics learning process.

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