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Generative Artificial Intelligence in Supporting the Transformation of Mathematics Education: An Analysis of Research Trends, Opportunities, Challenges, and Directions for Development

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ABSTRACT

The transformation of mathematics education in the digital age still faces various challenges, such as limitations in personalized learning, the provision of adaptive feedback, educators' readiness to integrate technology, and the lack of a comprehensive synthesis on the development of Generative Artificial Intelligence (GenAI) applications in this field. Therefore, this study aims to analyze research trends, opportunities, challenges, and the direction of GenAI development in supporting the transformation of mathematics education. The study employed a Systematic Literature Review (SLR) method following the PRISMA guidelines. The systematic literature search was conducted through Google Scholar, Scopus, the Directory of Open Access Journals (DOAJ), Elicit, Scite.ai, and SciSpace. A total of 39 studies met the inclusion criteria and were included in the final literature synthesis. The results indicate that research on Generative Artificial Intelligence (GenAI) has seen a significant increase and has shifted from a technology-oriented focus to a pedagogical one. Six main research areas were identified: the use of GenAI in mathematics education (5 studies), pedagogical implementation and teacher support (6 studies), the impact of implementation (8 studies), challenges and ethical issues (8 studies), integration strategies (5 studies), and future research directions (7 studies). GenAI has the potential to enhance personalized learning, adaptive feedback, and learning efficiency; however, its implementation still faces challenges related to ethics, accuracy, teacher readiness, and digital infrastructure. The findings of this study provide a conceptual foundation as well as recommendations for developing pedagogical, ethical, and sustainable GenAI integration strategies in the transformation of mathematics education.

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A. INTRODUCTION

The transformation of mathematics education has become a key requirement in the digital age to address the evolving learning needs of the 21st century. Mathematics education is no longer focused solely on conceptual mastery but is also aimed at developing students' critical thinking skills, mathematical reasoning, problem-solving abilities, creativity, and digital literacy (Engelbrecht & Borba, 2024). However, the implementation of this transformation still faces various challenges, such as limitations in personalized learning, the provision of effective feedback, the availability of adaptive learning resources, and the suboptimal use of technology to support the teaching and learning process (Soboleva et al., 2020). These conditions indicate that the transformation of mathematics education requires technological innovations capable of enhancing the

quality of learning in a more effective, adaptive, and student-centered manner (Saputra et al., 2025).

One of the innovations that has developed rapidly in recent years is Generative Artificial Intelligence (Kanbach et al., 2024). Generative Artificial Intelligence (GenAI) is a branch of artificial intelligence capable of generating various forms of new content, such as text, images, program code, and knowledge representations based on patterns learned from large amounts of data (Banh & Strobel, 2024). Unlike conventional artificial intelligence, which focuses on analysis and prediction, this technology is capable of generating dynamic responses in natural language, compiling learning materials, providing conceptual explanations, offering feedback, and supporting adaptive problem-solving (Ooi et al., 2023). In the context of this study, Artificial Intelligence (AI) is understood as the broader technological field, whereas GenAI refers specifically to AI systems capable of generating new content. Large Language Models (LLMs) are models that support many GenAI applications, while ChatGPT is an example of a conversational application based on an LLM. In contrast, Intelligent Tutoring Systems (ITS) and adaptive learning systems refer to learning-oriented systems designed to provide personalized guidance or adapt learning content and feedback to students' needs**.** These capabilities give Generative Artificial Intelligence the potential to support the transformation of mathematics learning through more interactive, personalized, and flexible learning processes (Awang et al., 2025).

Conceptually, the use of Generative Artificial Intelligence presents both opportunities and challenges for the transformation of mathematics education (Walkington, 2025; Kaya & Yavuz, 2025).. From a pedagogical perspective, this technology has the potential to support personalized learning, accelerate feedback, enrich learning resources, and enhance students' critical thinking, creativity, mathematical reasoning, and problem-solving skills (Ren et al., 2023; Bahroun et al., 2023). However, its implementation also faces various challenges, such as information accuracy, algorithmic bias, data privacy, academic integrity, and the potential for overreliance on technology. Therefore, the effectiveness of Generative Artificial Intelligence is greatly influenced by the quality of instructional design, educators' competencies, AI literacy, and educational policies that support the responsible implementation of technology (Cordero et al., 2025).

Various studies have examined the implementation of Generative Artificial Intelligence in mathematics education and have demonstrated its positive potential for improving the quality of learning (Wang & Guo, 2025; Manuel et al., 2025). According to Torre et al. (2026) and Farhah et al. (2025), systematic reviews using the PRISMA methodology found that Generative Artificial Intelligence can support mathematical problem-solving, provide timely feedback, adapt learning to students' needs, and improve access to learning resources. Liu et al. (2026), through a meta-analysis of 22 empirical studies involving 46 independent samples (N = 5,232), reported that the implementation of Generative Artificial Intelligence has a moderate positive effect on mathematics learning outcomes ($g = 0.534$), with the highest effectiveness observed in integration models based on creative transformation and in geometry instruction. These findings indicate that Generative Artificial Intelligence has the potential to enhance the effectiveness of mathematics learning through more adaptive instruction that is responsive to students' needs and supported by learning strategies that foster creativity and the exploration of mathematical concepts (Ma & Zhong, 2025; Guettala, 2024).

Previous research has also shown that the positive impact of Generative Artificial Intelligence is evident not only in improved learning outcomes but also in the development of students' thinking skills (Zhao et al., 2025). The results of meta-analyses

reported by Liu & Zhang (2026) and Fineldi et al. (2026) indicate that strategies for integrating Generative Artificial Intelligence can significantly improve the quality of mathematics learning, particularly through approaches that foster students' creativity. Furthermore, Duong & Vu (2025) found that Generative Artificial Intelligence has a greater impact on cognitive skills (g = 0.596) than on non-cognitive skills (g = 0.320), with the greatest impact on higher-order thinking skills, such as analysis and creation (g = 0.740). These findings indicate that the effectiveness of Generative Artificial Intelligence is influenced by the quality of instructional design, teacher competence, and users' level of AI literacy (Su et al., 2026; Egara, 2024).

In addition to these opportunities, previous research has also revealed a number of challenges in the implementation of Generative Artificial Intelligence in mathematics education. Walkington (2025) notes that a report by the U.S. Department of Education identified various risks, such as algorithmic bias, privacy violations, data oversight, and the system's tendency to generate inaccurate information (hallucinations). Sejun (2025), along with Suresh et al. (2018) reported that although Generative Artificial Intelligence models, such as GPT-4, were able to score 700 out of 800 on the math section of the SAT and a 4 out of 5 on the AP Calculus BC exam, their performance remains limited to problems requiring high-level creative reasoning, as evidenced by a 13% success rate on the Mathematics Olympiad qualifying exam. Su et al. (2026) also found that concerns regarding the accuracy and reliability of Generative Artificial Intelligence outputs were raised in 46.3% of the studies analyzed. These findings underscore the importance of verifying results, strengthening AI literacy, and enhancing the competencies of teachers and students in critically utilizing technology (Daher, 2025).

Based on these findings, a research gap remains in understanding how the growing body of research on Generative Artificial Intelligence can be synthesized specifically in relation to the transformation of mathematics education. Existing studies have largely examined individual benefits, implementation practices, learning outcomes, or specific risks, while a synthesis that connects these dimensions to the broader pedagogical transformation of mathematics education remains limited. In particular, there is a need to clarify how GenAI applications, pedagogical implementation, learning impacts, ethical challenges, integration strategies, and future research directions are interconnected. Therefore, the contribution of this study lies not merely in combining research trends, opportunities, challenges, and future directions, but in synthesizing these dimensions to provide a structured understanding of how GenAI is being positioned and developed within the transformation of mathematics education. This study aims to analyze and synthesize research findings on the use of Generative Artificial Intelligence to support the transformation of mathematics education by identifying research trends, implementation opportunities, challenges, and future directions. The findings of this study are expected to strengthen the conceptual framework, provide recommendations for educators and policymakers, and serve as a reference for future research and the implementation of Generative Artificial Intelligence in mathematics education.

B. METHODS

This study employs the Systematic Literature Review (SLR) method with a thematic analysis approach to identify, evaluate, and synthesize various research findings regarding the use of Generative Artificial Intelligence (GenAI) in the transformation of mathematics education. The SLR method was chosen because it allows the processes of identifying, selecting, evaluating, and synthesizing the literature to be conducted systematically, transparently, and in a replicable manner, thereby yielding findings with

a high level of validity and reliability (Ali, 2020). All stages of the study were designed to identify research trends, opportunities, challenges, and the direction of GenAI development in the transformation of mathematics learning. At the initial stage, Dimensions.ai was used to conduct preliminary bibliometric scoping to identify the volume and publication trends of research related to Generative Artificial Intelligence in mathematics education during the 2017–2026 period. This preliminary scoping was used to provide an overview of the development of the research field and was not used as the sole source for the literature included in the systematic review. For the systematic literature search, scientific articles were identified and accessed through several academic databases and literature discovery platforms, namely Google Scholar, Scopus, the Directory of Open Access Journals (DOAJ), Elicit, Scite.ai, and SciSpace**.** The overall research stages are presented in Figure 1.



Figure 1. Flowchart of the Systematic Literature Review Research Procedure

As shown in Figure 1, the study began with problem identification to determine research gaps, followed by the establishment of research objectives, the development of keywords, and the formulation of a literature search strategy for the literature sources used in the systematic review. The search strategy was conducted using relevant keywords in the title, abstract, and keyword fields of the records where these fields were available**.** Next, the process of identifying and selecting articles was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which include the stages of identification, screening, eligibility, and inclusion (Parums, 2021). These stages aim to ensure that only articles meeting all eligibility criteria are included in the synthesis process. The literature was then selected based on the following inclusion criteria: (1) scientific articles published between 2017 and 2026, (2) articles that had undergone a peer-review process, (3) articles that explicitly discussed the use of Generative Artificial Intelligence in the transformation of mathematics education, (4) articles available in full text, and (5) articles written in Indonesian or English. Exclusion criteria included duplicate articles, conference proceedings, books, theses, dissertations, articles that were not available in full, and studies that did not align with the focus of this study.

Articles that met all the criteria were then extracted to obtain information regarding the authors, year of publication, research objectives, research focus, research methods, research subjects, research instruments, and key findings. The data were then analyzed using thematic analysis through the stages of coding, categorizing, comparing, and synthesizing to identify the main themes that describe research trends, opportunities, challenges, and the direction of GenAI development in the transformation of mathematics learning. In addition, bibliometric mapping was conducted using VOSviewer software to visualize the relationships between keywords, topic developments, and research trends. The results of the analysis were then synthesized into research findings that served as the basis for formulating the study's results, conclusions, and implications. To ensure the validity and reliability of the research results, all stages of the SLR were carried out systematically in accordance with the PRISMA guidelines, applying inclusion and exclusion criteria consistently, and performing source triangulation through cross-verification against various relevant scientific articles.

C. RESULT AND DISCUSSION

A literature search using the Dimensions.ai database yielded an initial total of 30,404 publications relevant to the research topic. The selection process was conducted in stages based on predetermined criteria, including filtering for open-access articles, which yielded 11,452 publications; selection based on publication type, resulting in 8,754 scientific articles; and limiting the publication years to the 2017–2026 period, resulting in 6,393 articles that met the research criteria. The reduction in the number of publications at each stage indicates that the selection process was conducted systematically to obtain high-quality, relevant literature aligned with the study's focus on the use of Generative Artificial Intelligence to support the transformation of mathematics learning. The results of the literature selection at each stage are presented in Figure 2.



Figure 2. Trends in Research Publications on Generative Artificial Intelligence in Mathematics Education, 2017–2026

Source: Data processed from Dimensions AI (https://app.dimensions.ai), accessed on September 5, 2026. *Data for 2026 is year-to-date, so the figures do not yet reflect the total number of publications for the entire year.

Based on Figure 2, the number of publications on Generative Artificial Intelligence (GenAI) in support of mathematics education transformation shows a steadily increasing trend over the 2017–2026 period. At the beginning of the period (2017–2022), the

number of publications remained relatively low and fluctuated, ranging from 23 to 158 articles per year. Entering 2023, the number of publications began to rise to 250 articles (3.91%), then experienced a very significant surge in 2024 to 1,055 articles (16.50%) and peaked in 2025 at 2,580 articles (40.38%). Meanwhile, in 2026, there were 1,926 articles (30.12%). This figure is still year-to-date and therefore does not yet represent the total number of publications for the entire year. Overall, 87% of the analyzed publications were published during the 2024–2026 period, indicating a concentration of research activity on Generative Artificial Intelligence in mathematics education during this period. This increase reflects researchers' growing attention to the potential of Generative Artificial Intelligence in supporting the transformation of mathematics education through more adaptive learning, personalized instruction, the provision of automated feedback, and the development of students' mathematical thinking skills.

To gain insight into the intellectual structure and main themes of the research, a keyword co-occurrence analysis was conducted using VOSviewer software. This analysis maps the relationships between keywords based on the frequency of their simultaneous occurrence (co-occurrence), thereby identifying research themes, interconnections between topics, and the direction of research on the use of Generative Artificial Intelligence to support the transformation of mathematics learning. The visualization results yielded five interconnected main clusters, as shown in Figure 3.

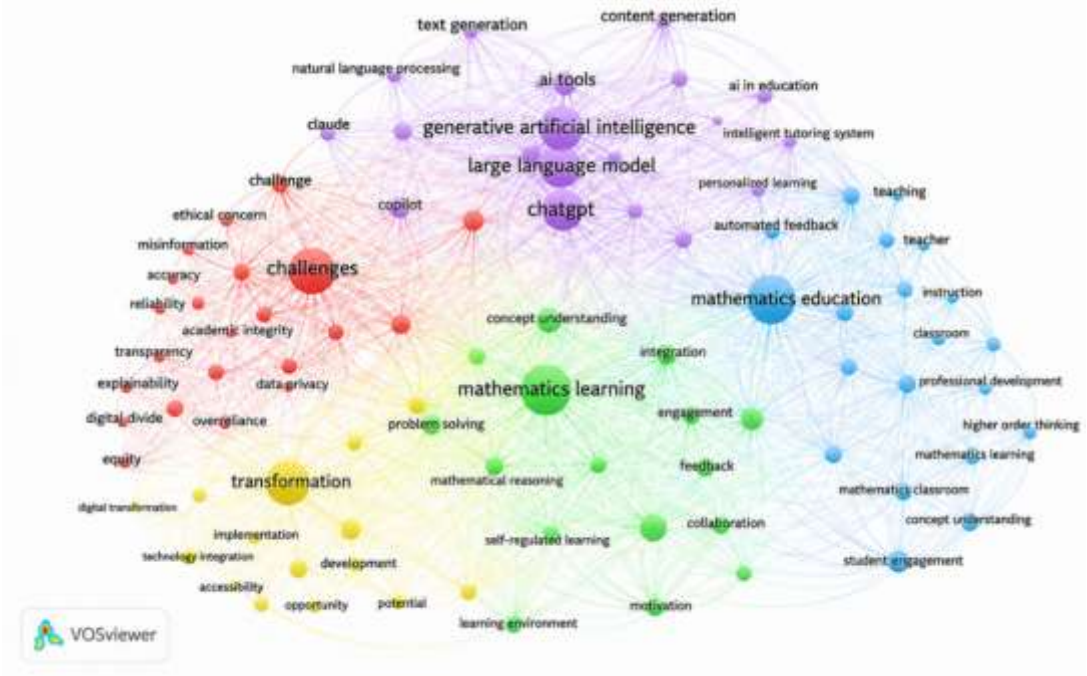


Figure 3. Visualization of the Research Keyword Network

Figure 3 shows a mapping of the keyword network, divided into several main clusters based on the relevance of research topics. The purple cluster represents research themes focused on the development of Generative Artificial Intelligence as the foundation for transforming mathematics education. This cluster is dominated by the keywords Generative Artificial Intelligence, Large Language Model, ChatGPT, AI tools, text generation, content generation, natural language processing, AI in education, intelligent tutoring system, personalized learning, and automated feedback. The dominance of these keywords indicates that research is still largely directed toward developing the

capabilities of Generative Artificial Intelligence in generating learning content, providing automated feedback, and supporting more adaptive and personalized learning.

The blue cluster illustrates the implementation of Generative Artificial Intelligence in mathematics education. Dominant keywords include mathematics education, teaching, teacher, instruction, classroom, professional development, student engagement, higher-order thinking, and concept understanding. This cluster indicates that research focuses on integrating Generative Artificial Intelligence into the learning process, enhancing teacher competencies, fostering student engagement, and developing higher-order thinking skills and an understanding of mathematical concepts.

The green cluster represents research focused on improving mathematics learning processes and outcomes. This cluster consists of the keywords "mathematics learning," "problem solving," "mathematical reasoning," "concept understanding," "feedback," "collaboration," "engagement," "motivation," "learning environment," and "self-regulated learning." The interconnections among these keywords indicate that Generative Artificial Intelligence is utilized to enhance students' problem-solving skills, mathematical reasoning, learning motivation, collaboration, and self-regulated learning.

The red cluster represents various challenges and ethical issues in the implementation of Generative Artificial Intelligence in mathematics education. Keywords such as "challenges," "ethical concerns," "misinformation," "accuracy," "reliability," "academic integrity," "data privacy," "transparency," "explainability," "digital divide," "overreliance," and "equity" indicate that research attention is focused not only on the benefits of the technology but also on risks related to information accuracy, data privacy, academic integrity, system transparency, and equitable access to technology.

The yellow cluster reflects the theme of transformation and the direction of development in mathematics education based on Generative Artificial Intelligence. This cluster is dominated by the keywords "transformation," "digital transformation," "technology integration," "implementation," "development," "accessibility," "opportunity," and "potential." This indicates that research is beginning to focus on strategies for integrating Generative Artificial Intelligence into the education system to create mathematics education that is more innovative, accessible, sustainable, and capable of supporting educational transformation in the digital age.

Based on the results of the keyword network mapping in Figure 3, several research groups with interrelated research focuses can be identified. To provide a more systematic overview of this research structure, a literature synthesis was conducted by grouping articles based on similarities in research fields, the authors contributing to each field, and the main variables that are the focus of the research. The results of this synthesis are presented in Table 1.

Table 1. Synthesis of Research Fields and Key Variables of Generative Artificial Intelligence in Mathematics Education

No.	Research Field / Focus	Authors	Insights / Research Variables
1	Utilization of Generative AI in Mathematics Learning	Walkington (2025); Hau et al. (2026); Nuraini et al. (2026); Liu et al. (2025); Trends & Themes (2025)	ChatGPT, *Large Language Models* (LLMs), problem solving, *step-by-step reasoning*, *Intelligent Tutoring Systems* (ITS), adaptive feedback, personalized learning, dialogue-based interaction

2	Pedagogical Implementation and Support for Teachers	Aravantinos et al. (2026); Su et al. (2026); Segal & Klemer (2025); Masriyah et al. (2026); Shi (2024); Tatiana et al. (2026)	Lesson planning, instructional design, teaching material development, task development, learning assessment, AI literacy, teacher professional competence, collaborative problem solving, student-centered learning
3	Impact of GenAI Implementation on Mathematics Learning Processes and Outcomes	Kamau & Shukla (2026); Borah (2024); Daher (2025); Hadzhikoleva et al. (2025); Megan et al. (2026); Maulida et al. (2024); Liu et al. (2026); Laeeq et al. (2025)	Learning outcomes, learning achievement, real-time feedback, interactive learning, personalized learning, automation, assessment, mathematical disposition, metacognition, collaboration, *creative transformation*, geometry learning
4	Challenges, Risks, and Ethical Issues in GenAI Implementation	Raman et al. (2026); Bani-Mattar (2025); García-López et al. (2025); Jonnala et al. (2025); Yang et al. (2024); Artemova (2025); Ololoh (2026); Alshammari et al. (2026)	Academic integrity, ethical AI, accuracy, algorithmic bias, data privacy, data protection, digital infrastructure, teacher competence, regulation, cognitive autonomy, critical thinking, mathematical reasoning, *Responsible AI*
5	Strategies for Integrating Generative AI into Mathematics Learning Transformation	Kumar & Archana (2024); Canonigo (2024); Tatiana et al. (2026); Bani-Mattar (2025); Liu et al. (2026)	Creative transformation, *Human Oversight*, collaborative learning, lesson planning, teacher competence, digital infrastructure, AI policies, instructional strategies, mathematics learning integration
6	Development Directions and Research Agenda for Generative AI	Hussein (2026); Su (2026); Hutson et al. (2024); Rivera et al. (2024); Guettala (2024); Mcgalliard & Otten (2025); Munenakoppa et al. (2026)	*Longitudinal studies*, mathematical proof, mathematical reasoning, curriculum development, assessment systems, AI literacy, teacher training, technological infrastructure, inclusive education, sustainable implementation

Based on Table 1, the results of the literature synthesis indicate that research on Generative Artificial Intelligence (GenAI) in mathematics education has a multidimensional scope. The studies identified not only focus on the development of Generative Artificial Intelligence technology but also cover pedagogical implementation, evaluation of the impact on learning processes and outcomes, ethical and technical challenges, integration strategies in mathematics education, and directions for future research. This categorization indicates that GenAI research has shifted from a technology-

oriented approach toward a more comprehensive integration with pedagogical aspects and the transformation of mathematics education. This synthesis serves as the foundation for the discussion in the following section, which outlines research trends, opportunities and challenges in implementation, and future directions for the development of Generative Artificial Intelligence in the transformation of mathematics education.

1. Research Trends in Generative Artificial Intelligence in Transforming Mathematics Learning

Main Research Themes of Generative Artificial Intelligence in the Transformation of Mathematics Education

The main themes of research on *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education have continued to evolve and have become increasingly diverse over the past decade. Walkington (2025), together with Hau et al. (2026), explains that one of the most dominant themes is the use of GenAI as a problem-solving support tool, particularly through *Large Language Models* (LLMs) such as ChatGPT, which are capable of generating step-by-step solutions and providing conceptual explanations for various mathematical problems. In addition, researchers have increasingly focused on the development of *Intelligent Tutoring Systems* (ITS) and adaptive feedback to support personalized learning by providing interactive guidance, adjusting learning materials, and adapting the level of difficulty to students' needs (Trends & Themes, 2025). Another widely studied theme concerns the use of GenAI to support teachers in lesson planning and instructional design, including the development of teaching materials, task design, and learning assessment (Aravantinos et al., 2026). Su et al. (2026) emphasize that the effectiveness of such implementation is strongly influenced by the quality of instructional design and educators' level of AI literacy. In addition, research has increasingly focused on ethical issues and academic integrity, including system output accuracy, algorithmic bias, data privacy, and unequal access to technology as important considerations in the implementation of GenAI in education (Raman et al., 2026). More recent developments have also introduced the theme of pedagogical evaluation and validation, focusing on the effectiveness of GenAI in influencing various aspects of learning, such as mathematical disposition, metacognition, and student collaboration (Laeeq et al., 2025). Overall, these themes indicate that research on GenAI in mathematics education has evolved from a focus on the technical capabilities of technology toward its use as a pedagogical innovation that supports the transformation of mathematics education in a more systematic, adaptive, and integrated manner.

Dynamics and Development of Generative Artificial Intelligence Research in the Transformation of Mathematics Education

The development of research on *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education demonstrates a gradual shift in research focus, from exploring technological capabilities toward more comprehensive integration into mathematics teaching and learning practices. In the early stages of research development, studies primarily focused on exploring the ability of GenAI models to solve mathematical problems, generate conceptual explanations, and provide automated feedback, as demonstrated by Nuraini et al. (2026) through various studies on the use of ChatGPT in mathematics education. As artificial intelligence technology has advanced, research has gradually shifted toward integrating GenAI into the learning process through the development of intelligent

tutoring systems, adaptive learning, and dialogue-based interactions that enable students to receive more personalized learning support (Liu et al., 2025). The next stage of development has been characterized by an expansion of research that involves not only students but also teachers as users of GenAI for lesson planning, teaching material development, and the use of various digital learning media integrated with artificial intelligence technologies. These findings are supported by Segal & Klemer (2025) and Masriyah et al. (2026), who indicate that GenAI is increasingly being used to support learning activities and the professional development of teachers. In recent years, the research focus has expanded toward more comprehensive investigations that integrate pedagogical and ethical dimensions with the transformation of mathematics education paradigms in the era of artificial intelligence, including changes in interaction patterns among students, teachers, and digital learning resources (Alberto et al., 2026; Hendry & Sumartiningsih, 2026). This dynamic indicates that research on GenAI in mathematics education continues to expand in scope, moving from studies focused on technological capabilities toward research that positions GenAI as an integral component of the mathematics education ecosystem as a whole (Baguinat & Anito, 2026).

Based on the synthesis of various studies, it can be interpreted that research trends concerning *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education have undergone a clear shift from a technology-oriented to a pedagogy-oriented approach. In the early stages, research primarily focused on the technical capabilities of GenAI to generate answers, solve mathematical problems, and provide conceptual explanations. However, as the technology has developed and the demands of twenty-first-century learning have increased, the research focus has shifted toward utilizing GenAI as an integral part of the learning process through personalized learning, the development of intelligent tutoring systems, adaptive feedback, teacher support, and the creation of more interactive and student-centered learning experiences. This shift indicates that research on GenAI is no longer focused solely on technological capabilities but increasingly positions GenAI as a pedagogical component that supports the transformation of mathematics education in a more comprehensive manner. The synthesis also indicates that most studies remain oriented toward the development and implementation of technology in the learning process, whereas studies evaluating the long-term effects on the quality of mathematics education, such as the development of students' mathematical reasoning, metacognition, and mathematical disposition, remain relatively limited. Therefore, current research trends indicate that the transformation of mathematics education through GenAI is increasingly directed toward the meaningful integration of technology with pedagogical approaches. Research is consequently moving beyond the technical capabilities of systems to also emphasize the quality of implementation in improving the processes and outcomes of mathematics education in an adaptive, systematic, and sustainable manner.

2. Opportunities and Challenges of Implementing Generative Artificial Intelligence in Transforming Mathematics Learning

Opportunities for Implementing Generative Artificial Intelligence to Improve the Quality of Mathematics Education

The implementation of *Generative Artificial Intelligence* (GenAI) offers various opportunities to improve the quality of mathematics education through more personalized, adaptive, and efficient learning. Kamau & Shukla (2026) reported that, based on a synthesis of 20 studies published between 2023 and 2025, approximately

70% of the studies indicated that the use of GenAI had a positive impact on improving student learning outcomes, while 85% reported positive perceptions among educators regarding the use of this technology in the learning process. These findings are supported by Borah (2024) and Daher (2025), who concluded that GenAI can support personalized learning by adapting learning materials to students' needs, providing real-time feedback, and creating a more interactive learning environment through mathematical problem-solving activities. In addition to providing benefits for students, GenAI creates opportunities for teachers to develop more diverse teaching materials, design adaptive tasks, and implement innovative instructional approaches, such as inquiry-based learning and collaborative problem solving, thereby making mathematics education more contextualized and student-centered (Shi, 2024; Tatiana et al., 2026). Furthermore, the use of GenAI can improve teachers' work efficiency by automating various activities, including question generation, feedback provision, learning assessment, and lesson planning, thereby allowing teachers to devote more attention to fostering students' mathematical thinking skills (Hadzhikoleva et al., 2025; Megan et al., 2026). Based on the synthesis of these studies, it can be concluded that the opportunities for implementing GenAI in mathematics education extend beyond improving student learning outcomes. They also include its capacity to support more personalized learning, enhance the effectiveness of the learning process, and strengthen teachers' capacity to design more innovative, adaptive, and student-centered mathematics instruction.

Challenges, Risks, and Ethical Issues in Implementing Generative Artificial Intelligence in Mathematics Education

The implementation of *Generative Artificial Intelligence* (GenAI) in mathematics education continues to face various challenges, risks, and ethical issues that require careful attention to ensure that its use is effective and responsible. Bani-Mattar (2025) reported that, based on a synthesis of 20 studies conducted between 2023 and 2025, approximately 75% of the studies emphasized the importance of ethical use of GenAI in education, 80% identified infrastructure limitations and data privacy protection as major challenges, and 75% indicated that limited teacher competence and training were significant barriers to implementing GenAI in educational settings. These findings are consistent with the analysis by García-lópez et al. (2025) of 53 scholarly articles, which revealed risks related to the misuse of student data, reduced cognitive autonomy, and inadequate regulations governing the use of artificial intelligence in educational institutions. In the context of mathematics education, other challenges frequently discussed include the accuracy of solutions generated by GenAI, the potential for bias in training data, and the importance of maintaining a balance between the use of technology and the role of teachers in guiding students' mathematical thinking (Jonnala et al., 2025; Yang et al., 2024). In addition, several studies indicate that excessive use of GenAI may reduce students' engagement in reasoning processes, create an illusion of conceptual understanding, and weaken critical thinking skills when the use of GenAI is not accompanied by reflection and verification of system-generated answers (Artemova, 2025; Ololoh, 2026). Based on the synthesis of these studies, it can be concluded that the challenges of implementing GenAI in mathematics education are not limited to technical aspects but also encompass pedagogical, ethical, data security, regulatory, and human resource readiness dimensions (Alshammari et al., 2026). Therefore, these challenges need to be carefully considered during implementation to ensure that the use of GenAI

continues to support the quality of mathematics education in a responsible and sustainable manner.

Based on the synthesis of various studies, it can be interpreted that the implementation of *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education is at a developmental stage characterized by increasingly significant opportunities for technological utilization, accompanied by increasingly complex implementation challenges. Various studies indicate that GenAI can support personalized learning, provide real-time feedback, improve teacher efficiency, and create more interactive and adaptive mathematics learning processes. These conditions indicate that the transformation of mathematics education is no longer influenced solely by technological innovation but also by the capacity of GenAI to support more student-centered pedagogical processes. On the other hand, challenges related to teacher readiness, digital infrastructure, data privacy, system output accuracy, algorithmic bias, and the potential decline in mathematical thinking skills indicate that successful GenAI implementation depends on the readiness of the entire educational ecosystem rather than solely on the sophistication of the technology being used. Thus, the opportunities and challenges of implementing GenAI are interconnected aspects of the transformation of mathematics education. As the use of GenAI in learning expands, so does the need to ensure that the technology is implemented ethically, pedagogically, and responsibly so that it can provide optimal benefits without compromising the quality of mathematics education processes or learning outcomes.

3. Direction of Generative Artificial Intelligence Development in the Transformation of Mathematics Learning

Strategies for Integrating Generative Artificial Intelligence to Support the Transformation of Mathematics Education

Strategies for integrating *Generative Artificial Intelligence* (GenAI) into the transformation of mathematics education need to be systematically designed so that the technology can be effectively incorporated into the learning process and improve both the quality of instruction and mathematics learning outcomes. Liu et al. (2026), through a meta-analysis of 22 empirical studies involving 46 independent samples (N = 5,232), reported that the implementation of GenAI had a moderate positive effect on mathematics learning outcomes (g = 0.534), with the highest effectiveness found in creative transformation-based integration models and geometry learning. These findings indicate that the effectiveness of GenAI integration is determined more by the quality of the implementation strategy than by the mere presence of the technology. Therefore, instructional designs that promote creativity, conceptual exploration, and active student engagement are key factors in successful implementation (Kumar & Archana, 2024). Similarly, Bani-Mattar (2025) emphasizes that successful GenAI implementation requires an adequate educational ecosystem, particularly through strengthening teacher competencies, providing digital infrastructure, and establishing policies that ensure the security and ethical use of technology in learning. Additional empirical evidence is provided by the quasi-experimental study of Maulida et al. (2024), which found that GenAI-assisted mathematics instruction produced significantly better learning outcomes than conventional instruction. Therefore, various studies recommend that GenAI integration strategies be implemented through structured lesson planning, active teacher supervision (*human oversight*), the use of targeted feedback, and collaborative learning approaches. In this way, GenAI can function as a facilitator that strengthens students' mathematical thinking

processes without replacing the teacher's role as a facilitator or reducing students' active involvement in constructing mathematical knowledge (Tatiana et al., 2026; Canonigo, 2024).

Research and Implementation Recommendations for Generative Artificial Intelligence to Support the Transformation of Mathematics Education

The development of research and implementation of *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education should be directed toward strengthening the quality of technological implementation while expanding the scope of scientific inquiry. Hussein (2026) argues that research on GenAI remains dominated by exploratory studies focusing on short-term benefits, whereas studies examining its effects on conceptual understanding, mathematical proof, reasoning, curriculum design, assessment systems, equitable access, and ethical considerations remain relatively limited. Therefore, future research should employ longitudinal designs and involve larger samples to generate empirical evidence regarding the long-term effectiveness of GenAI in developing students' mathematical abilities (Su, 2026; Hutson et al., 2024). From an implementation perspective, various studies recommend that GenAI use be supported through the development of teachers' AI literacy, the application of human oversight, and the structured use of GenAI as a support tool for the learning process rather than as a replacement for educators (Rvera et al., 2024; Tatiana et al., 2026). In addition, Guettala (2024) emphasizes the importance of developing more flexible curricula, providing continuous teacher training, and ensuring adequate technological infrastructure so that GenAI implementation can take place optimally across different educational levels. Thus, recommendations for the development of GenAI in mathematics education should not focus solely on technological improvement but also on strengthening teacher capacity, developing curricula, and building an educational ecosystem capable of supporting effective, inclusive, and sustainable GenAI implementation (Mcgalliard & Otten, 2025; Munenakoppa et al., 2026).

Based on the synthesis of various studies, it can be interpreted that the direction of *Generative Artificial Intelligence* (GenAI) development in the transformation of mathematics education is increasingly focused on strengthening the integration of technology with pedagogical aspects rather than merely improving technological capabilities. Various studies indicate that successful GenAI implementation is strongly influenced by systematically designed integration strategies, teachers' competence in using the technology, and adequate educational policies and infrastructure. In addition, future research directions indicate the need to expand investigations into the long-term effects of GenAI on students' mathematical abilities, curriculum development, assessment systems, and the development of ethical frameworks that ensure the safe, inclusive, and responsible use of technology. Therefore, the development of GenAI in the transformation of mathematics education should not be oriented solely toward technological innovation but also toward strengthening the quality of education through systematic, sustainable, and student-centered integration that recognizes and preserves the professional role of teachers.

Based on the synthesis of the main research themes, research development dynamics, opportunities and challenges of implementation, and future directions for the development of *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education, a conceptual mapping can be developed to illustrate the evolution of research focuses over time. The mapping illustrates changes in research orientations, the development of the variables examined, and strategic issues that

have received attention at each stage of development. A visualization of the evolution of research focuses is presented in Figure 4.

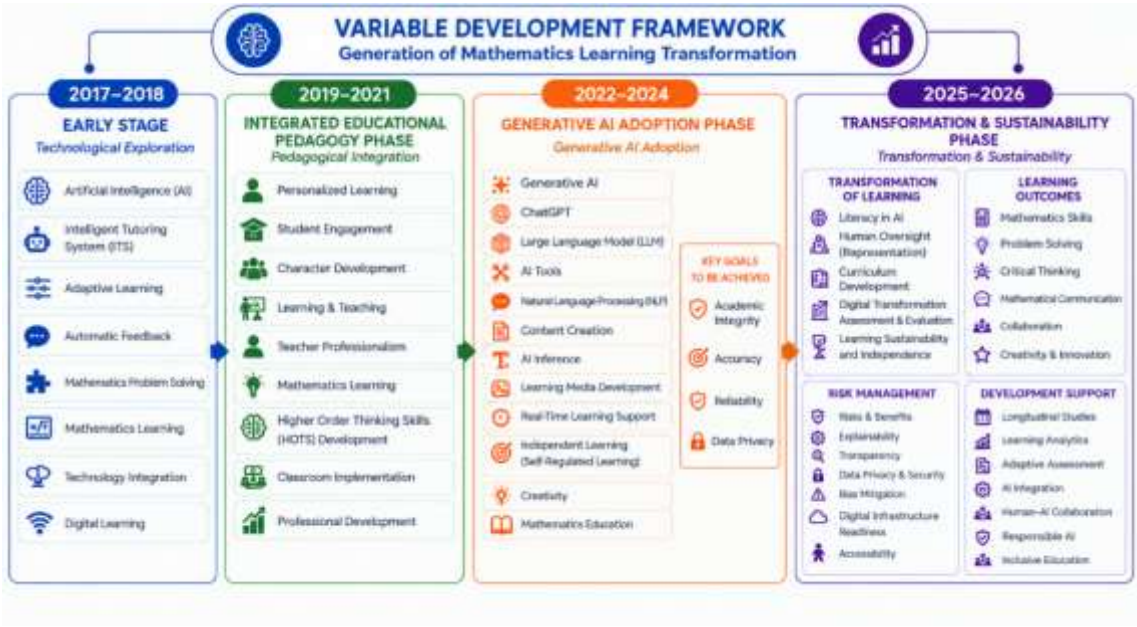


Figure 4. Development of *Generative Artificial Intelligence* Research Variables in the Transformation of Mathematics Education, 2017–2026

Figure 4 illustrates the development of research variables related to *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education during the 2017–2026 period, which occurred across four phases. In the initial phase (2017–2018), research focused on exploring the application of AI technologies in mathematics education. The pedagogical integration phase (2019–2021) was characterized by the use of AI to support personalized learning, student engagement, teacher competency development, and the enhancement of mathematical thinking skills. Subsequently, the Generative AI adoption phase (2022–2024) demonstrated the increasingly widespread use of technologies such as ChatGPT and *Large Language Models* (LLMs) in education, accompanied by emerging concerns regarding academic integrity, accuracy, reliability, data privacy, and ethics. Entering the transformation and sustainability phase (2025–2026), research expanded toward the integration of GenAI into the transformation of learning, improvement of mathematics learning outcomes, management of implementation challenges and risks, and the development of Responsible AI, learning analytics, adaptive assessment, human–AI collaboration, and inclusive education. Overall, the figure demonstrates that research on GenAI in mathematics education has shifted from exploring technological capabilities toward more pedagogical, ethical, and sustainable integration to support the transformation of mathematics education.

D. CONCLUSION AND SUGGESTIONS

Based on the results of thematic analysis and literature synthesis using a *Systematic Literature Review* (SLR) approach of scientific publications from 2017 to 2026, this study successfully identified research trends, opportunities, challenges, and future directions for the development of *Generative Artificial Intelligence* (GenAI) in the transformation of mathematics education. The findings indicate that research on GenAI has shown a continuous upward trend and has shifted from a technology-oriented focus toward a more pedagogical orientation. This study identified six major areas of research: the use of

GenAI in mathematics education, pedagogical implementation and teacher support, the impact of implementation on learning processes and outcomes, challenges and ethical issues, strategies for integrating GenAI, and future research directions. The synthesis also demonstrates that GenAI offers substantial opportunities to improve the quality of mathematics education through personalized learning, adaptive feedback, intelligent tutoring systems, and increased teacher efficiency. However, its implementation continues to face challenges related to system output accuracy, algorithmic bias, data privacy, academic integrity, teacher readiness, and limitations in digital infrastructure. Therefore, the transformation of mathematics education through GenAI requires systematic integration strategies supported by teacher competencies, educational policies, and a learning ecosystem that ensures the ethical, effective, inclusive, and sustainable use of technology. Future research should focus on longitudinal studies and experimental research involving larger and more diverse samples to evaluate the long-term effects of GenAI implementation on students' mathematical abilities, particularly mathematical reasoning, mathematical proof, metacognition, and mathematical disposition. In addition, future studies should develop GenAI integration models that combine pedagogical aspects, AI literacy, curriculum development, assessment systems, human oversight, and AI governance to establish effective, inclusive, and sustainable implementation frameworks for the transformation of mathematics education.

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