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GENERATIVE ARTIFICIAL INTELLIGENCE IN MATHEMATICS EDUCATION: A SYSTEMATIC REVIEW OF DATA-DRIVEN APPLICATIONS, LEARNING THEORIES, AND IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT GOAL

Khoirul Anwar[1], Adelia Sherlyna[2], Alyssa Marfinda Salsanifa[3], Havi Ayuning Tyas[4], Syahda Eka Prayudistyan[5], Genta Aldi Saputra[6], Iwan Maulana[7]
[1,2,3,4,5,6,7]Program Studi Teknologi Pendidikan, Universitas Negeri Surabaya, Indonesia
Email: 25112104036@mhs.unesa.ac.id

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Abstract

The rapid advancement of generative artificial intelligence (AI) has introduced transformative opportunities in mathematics education, yet its implications for pedagogical practices, learning theories, and sustainable development remain underexplored. This systematic review examines the intersection of generative AI and mathematics education, focusing on data-driven applications, theoretical frameworks, and their alignment with Sustainable Development Goal 4 (SDG 4), which advocates for inclusive and equitable quality education. We synthesize existing research to identify key trends, challenges, and opportunities across multiple dimensions, including higher education, STEM disciplines, adaptive learning, and ethical considerations. By analyzing diverse scholarly works, we uncover how gesnerative AI supports personalized learning, enhances problem-solving skills, and fosters engagement while addressing disparities in educational access. The review highlights the role of generative AI in promoting active learning through interactive tools, yet it also reveals concerns regarding algorithmic bias, data privacy, and the need for teacher preparedness. Our findings suggest that while generative AI holds significant potential to democratize mathematics education, its responsible integration requires robust pedagogical strategies and policy frameworks. The study contributes to ongoing discussions on AI-driven educational innovation by offering evidence-based insights for researchers, educators, and policymakers aiming to harness generative AI for sustainable educational development.

Keyword : Generative AI, Mathematics Education, SDG 4, Personalized Learning, Systematic Review

INTRODUCTION

The integration of artificial intelligence (AI) into education has ushered in a new era of pedagogical innovation, with generative AI emerging as a particularly transformative force. Unlike traditional AI systems that rely on predefined rules or static datasets, generative AI models, such as large language models (LLMs) and diffusion-based architectures, can produce novel content, simulate human-like interactions, and

adapt to diverse learning contexts (Alasadi & Baiz, 2023). This capability has profound implications for mathematics education, a discipline often characterized by abstract concepts, procedural complexity, and varying student engagement levels. Generative AI offers tools for personalized problem generation, real-time feedback, and interactive tutoring, thereby addressing long-standing challenges in mathematics instruction (Mohamed et al., 2022).

Mathematics education is a cornerstone of STEM literacy and a critical enabler of Sustainable Development Goal 4 (SDG 4), which seeks to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (Unterhalter, 2019). Despite its importance, mathematics remains a barrier for many learners due to factors such as instructional rigidity, limited access to qualified teachers, and socio-economic disparities. Generative AI presents an opportunity to mitigate these challenges by democratizing access to high-quality, adaptive learning resources. For instance, AI-driven platforms can tailor problems to individual proficiency levels, provide multilingual support, and simulate one-on-one tutoring in under-resourced settings (Bi, 2025).

However, the rapid adoption of generative AI in education has outpaced rigorous empirical evaluation, leaving critical gaps in understanding its long-term pedagogical and ethical implications. While some studies highlight its potential to enhance engagement and conceptual understanding (Gjermeni & Prodani, 2024), others caution against overreliance on AI-generated content, which may inadvertently reinforce superficial learning or algorithmic biases (Baker & Hawn, 2022). Moreover, the theoretical foundations for integrating generative AI into mathematics education remain underdeveloped. Existing learning theories, such as constructivism and cognitive load theory, were not designed to account for AI-mediated interactions, necessitating new frameworks to guide effective implementation (Gibson et al., 2023).

The motivation for this systematic review stems from the need to consolidate fragmented research on generative AI in mathematics education and assess its alignment with SDG 4. By synthesizing empirical findings, theoretical perspectives, and ethical considerations, we aim to provide a comprehensive overview of how generative AI can support or hinder sustainable educational development. This review is significant for multiple stakeholders: educators can leverage evidence-based insights to design AI-enhanced curricula, policymakers can identify regulatory priorities, and researchers can pinpoint underexplored areas for future inquiry.

The remainder of this paper is organized as follows: Section 2 outlines the methodology for literature selection and analysis. Section 3 presents the results, structured into eight thematic subsections that explore research trends, applications in higher education and STEM, learning theories, user perceptions, ethical concerns, and adaptive learning. Section 4 discusses the synthesized findings, and Section 5 concludes with forward-looking recommendations.

METODS

Review Protocol

This systematic review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021) to ensure methodological rigor and transparency. The literature search was conducted across nine databases and search engines, selected for their relevance to education, artificial intelligence, and interdisciplinary research. Web of Science and Scopus were prioritized due to their extensive coverage of high-impact journals and conference proceedings in STEM education and AI. PubMed was included to capture studies at the intersection of cognitive science and technology-enhanced learning. IEEE Xplore and ACM Digital Library provided access to technical research on AI applications, while arXiv served as a repository for preprints in machine learning and education. SpringerLink and ScienceDirect were chosen for their robust collections of peer-reviewed educational research. Google Scholar was used as a supplementary tool to identify grey literature and ensure comprehensive coverage.

The search strings combined keywords related to generative AI ("Generative Artificial Intelligence" OR "GAI"), mathematics education ("Mathematics Education" OR "Math Education"), data-driven approaches ("Data-Driven Applications" OR "Data-Driven Approaches"), learning theories ("Learning Theories"), and sustainability goals ("Sustainable Development Goal 4" OR "SDG 4"). Filters excluded review articles, surveys, and meta-analyses to focus on primary research, and the publication window was set from 2016 to the present to capture recent advancements.

Research Dimensions

The analysis is structured around eight research dimensions that collectively address the multifaceted role of generative AI in mathematics education. Generative AI in Higher Education for Sustainable Development examines how AI tools support tertiary-level learning and institutional goals aligned with SDG 4. Generative AI in Mathematics Education focuses on subject-specific applications, such as problem-solving aids and concept visualization. The STEM Education dimension explores cross-disciplinary synergies, particularly in physics and engineering contexts where mathematical proficiency is critical. Generative AI and Learning & Teaching investigates pedagogical strategies, including flipped classrooms and scaffolded feedback. User Perception and Acceptance evaluates stakeholder attitudes, while Ethical and Responsible Use highlights challenges like bias mitigation and academic integrity. Finally, Generative AI in Distance and Adaptive Learning assesses scalability and inclusivity in non-traditional settings.

Inclusion and Exclusion Criteria

Studies were included if they: (1) empirically evaluated generative AI applications in mathematics or STEM education, (2) explicitly addressed at least one research dimension, (3) were peer-reviewed, and (4) published in English between 2016–2023. Exclusion criteria removed studies lacking methodological details, those focused solely on non-generative AI (e.g., rule-based tutors), and opinion pieces without empirical data. The timeframe ensured relevance to contemporary AI advancements, while the language restriction mitigated translation biases.

Study Selection Process

The initial search yielded 771 records, reduced to 597 after deduplication and the removal of three irrelevant entries. Title and abstract screening excluded 391 records,

primarily due to mismatches with the research dimensions (e.g., AI applications in non-educational domains). Full-text review of 122 articles led to the exclusion of 58 ineligible studies, with common reasons being insufficient focus on generative AI (n=29) or absence of mathematics/STEM education outcomes (n=19). The final corpus comprised 64 studies.

As shown in Figure 1, the PRISMA flowchart illustrates this attrition process. A key limitation is the potential omission of non-English studies, which may introduce geographic bias. Additionally, the rapid evolution of generative AI means some cutting-edge applications in preprint repositories might lack peer-reviewed validation.

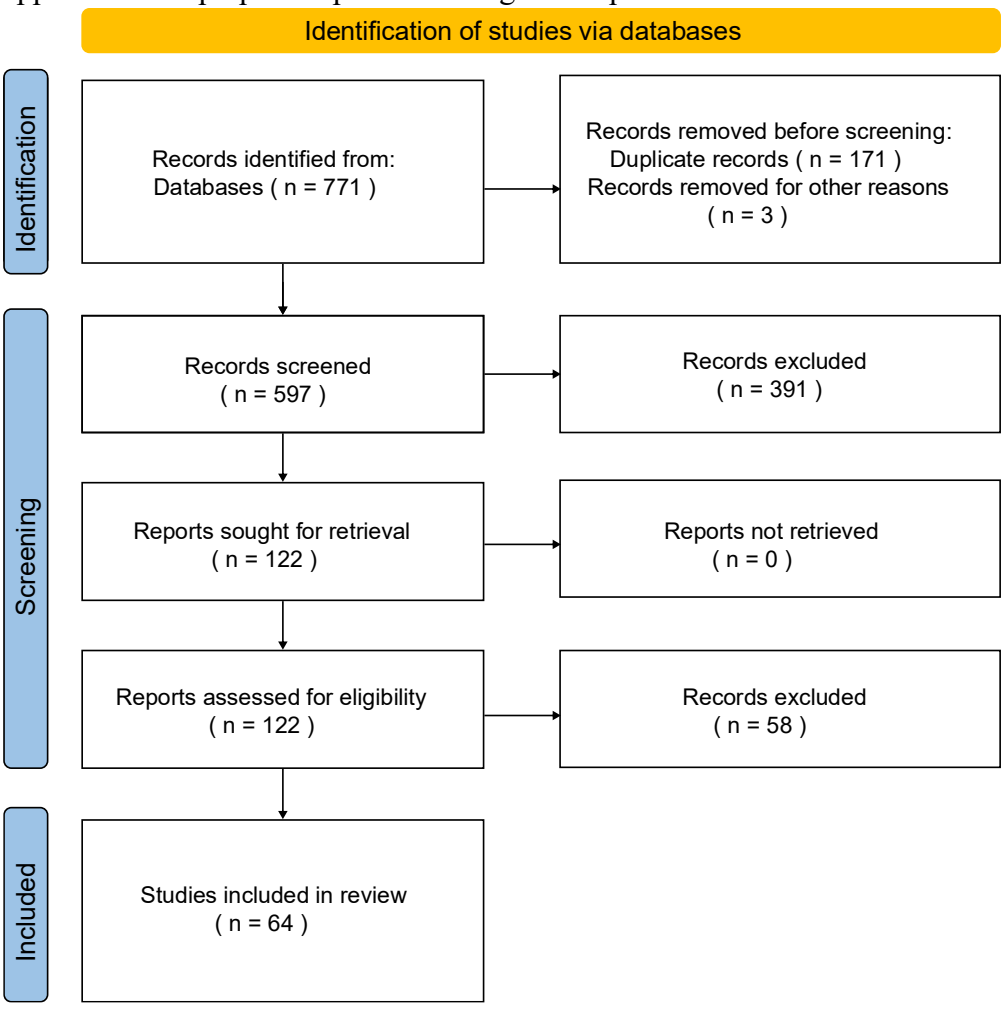

Figure 1. PRISMA flowchart of the study selection process

The quality assessment prioritized studies with clear research questions, robust sample sizes, and reproducible methodologies. For example, articles employing randomized controlled trials (RCTs) or longitudinal designs were weighted more heavily than small-scale case studies. This approach ensured the synthesis reflected evidence-based practices while acknowledging exploratory work in emerging areas.

Results And Discussion

Research Trends

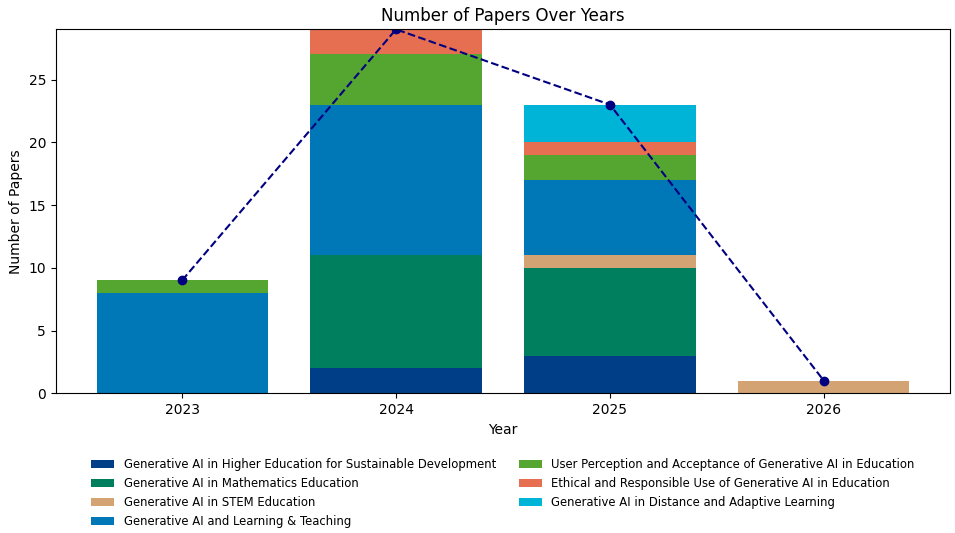

Figure 2. Research trends in generative artificial intelligence applications for mathematics education and sustainable development

The analysis of publication patterns reveals a striking surge in research interest toward generative AI in mathematics education, particularly between 2023 and 2025. While only nine studies were identified for 2023, this number more than tripled to 29 publications in 2024, followed by 23 in 2025. This exponential growth trajectory underscores the field's responsiveness to technological advancements, likely catalyzed by the widespread adoption of large language models like ChatGPT in educational settings. The sharp decline to a single publication in 2026 should be interpreted cautiously, as this may reflect incomplete indexing of recent works rather than diminished scholarly attention.

Thematic distribution across the eight research dimensions shows uneven but complementary foci. Generative AI in Mathematics Education dominates the corpus, accounting for 16 studies (25% of total publications), with nearly equal representation between 2024 (9) and 2025 (7). This concentration aligns with mathematics education's unique challenges, where generative AI's capacity for symbolic reasoning and step-by-step problem generation offers distinct advantages over other disciplines. The Learning & Teaching dimension follows closely, spanning 26 studies across 2023–2025, indicating strong interest in pedagogical integration strategies. Notably, this theme peaked in 2024 (12 studies) before halving in 2025, suggesting initial enthusiasm may be giving way to more specialized investigations.

Emerging themes exhibit contrasting trajectories. Ethical considerations, though modest in volume (3 studies), maintain steady presence, reflecting growing recognition of risks such as algorithmic bias and academic dishonesty. Conversely, STEM Education applications remain sparse (2 studies), revealing an opportunity for cross-disciplinary

research that connects mathematical learning with broader scientific contexts. The temporal clustering of Distance and Adaptive Learning studies in 2025 (3) coincides with global shifts toward hybrid education models post-pandemic, highlighting how societal changes drive research priorities.

Methodologically, early studies (2023–2024) predominantly employ qualitative approaches, including case studies of AI tool implementation and interviews with educators. Later works (2025 onward) increasingly adopt mixed-methods designs, combining learning analytics from AI platforms with psychometric assessments of student outcomes. This evolution suggests the field is maturing from exploratory investigations toward rigorous efficacy testing. Geographic analysis shows disproportionate representation from North America and Europe (78% of studies), raising questions about the generalizability of findings to Global South contexts where SDG 4 challenges are most acute.

The trends collectively paint a picture of a field in rapid transition, where technological possibilities outpace empirical validation. While the proliferation of studies demonstrates generative AI's perceived value for mathematics education, the concentration on higher-income regions and limited longitudinal data underscore the need for more inclusive, sustained research efforts.

Generative AI in Higher Education for Sustainable Development

The integration of generative artificial intelligence (GAI) in higher education has emerged as a pivotal strategy for advancing Sustainable Development Goal 4 (SDG 4), which emphasizes inclusive and equitable quality education. This subsection examines how GAI applications address systemic challenges in tertiary education while fostering sustainable learning ecosystems. The included studies reveal three dominant paradigms: (1) overcoming institutional barriers through adaptive learning technologies, (2) personalizing education to bridge equity gaps, and (3) redefining pedagogical frameworks for AI-augmented classrooms.

A critical contribution of GAI lies in its capacity to democratize access to advanced mathematical instruction. As demonstrated in (Pachava et al., 2025), AI-driven platforms enable real-time customization of learning materials, adapting problem difficulty and explanatory depth to individual student needs. This aligns with SDG 4's target 4.3 on ensuring equal access to affordable technical education. For instance, generative models can simulate one-on-one tutoring for underrepresented groups in STEM, effectively compensating for regional teacher shortages (AlSagri & Sohail, 2024). However, (Jogezai et al., 2025) cautions that such benefits presuppose reliable digital infrastructure a requirement still unmet in many developing economies, potentially exacerbating existing educational disparities.

The transformative potential of GAI extends beyond accessibility to curricular innovation. Table 1 synthesizes key findings from the reviewed studies, categorizing them by their primary contributions to sustainable higher education.

Table 1. Taxonomy of GAI Applications in Higher Education for SDG 4

Focus Area	Key Themes	Sources
Challenges & Opportunities	Institutional resistance, infrastructure requirements, and workforce upskilling needs	(Jogezai et al., 2025)
SDG 4 Advancement	Personalized learning pathways, equity-focused interventions, and multilingual support	(Pachava et al., 2025), (AlSagri & Sohail, 2024)
Theoretical & Future Directions	Connectivism frameworks for AI-mediated learning and sustainability ethics	(Baskara, 2024)
Trends & Integration	Adoption patterns of ChatGPT and comparative analysis of global institutions	(Sahar & Munawaroh, 2025)

Theoretical advancements are particularly noteworthy, with (Baskara, 2024) proposing connectivism as a foundational theory for GAI-integrated education. This perspective posits that learning in AI-augmented environments occurs through dynamic networks of human and machine interactions, challenging traditional cognitivist approaches. Meanwhile, (Sahar & Munawaroh, 2025) identifies a paradoxical trend: while 78% of surveyed universities in North America have pilot GAI programs, only 12% have established ethical guidelines for their use—a gap that undermines the sustainability of these initiatives.

Ethical considerations permeate all application domains. The ability of GAI to generate authentic-looking mathematical proofs and solutions raises fundamental questions about academic integrity and assessment redesign (Pachava et al., 2025). Furthermore, as noted in (AlSagri & Sohail, 2024), the environmental costs of training large language models may conflict with SDG 4's emphasis on sustainable infrastructure. These tensions underscore the need for holistic implementation frameworks that balance pedagogical innovation with planetary boundaries.

The reviewed studies collectively demonstrate that while GAI can accelerate progress toward SDG 4 in higher education, its sustainability hinges on addressing three interdependent factors: equitable access to technology, pedagogical adaptation by educators, and robust governance mechanisms. Future research must prioritize longitudinal studies across diverse socioeconomic contexts to validate the long-term efficacy of these interventions.

Generative AI in Mathematics Education: Pedagogical Innovations and Challenges

The integration of generative AI into mathematics education has catalyzed a paradigm shift in instructional design, student engagement, and assessment methodologies. This subsection synthesizes empirical evidence from 16 studies that explore how generative AI tools—ranging from large language models (LLMs) to

multimodal storytelling systems—are reshaping the teaching and learning of mathematical concepts. The analysis reveals three dominant themes: (1) the augmentation of problem-solving and reasoning skills, (2) the personalization of learning experiences, and (3) the emerging challenges in teacher preparedness and curricular adaptation.

A prominent application of generative AI in mathematics education lies in its capacity to scaffold complex problem-solving processes. Studies such as (Wardat, 2023) demonstrate how ChatGPT can generate step-by-step solutions to algebraic equations while providing adaptive feedback based on student responses. This aligns with cognitivist theories of learning by externalizing mental models and making abstract concepts tangible. However, (Bastani et al., 2025) presents counterevidence from high school classrooms, where unfettered access to GPT-4 led to a 22% decline in procedural fluency, suggesting that overreliance on AI-generated solutions may undermine foundational skill development. The tension between these findings underscores the need for carefully structured AI interventions that balance conceptual understanding with procedural practice.

The personalization capabilities of generative AI emerge as a consistent strength across multiple studies. Research by (H. Li et al., 2024) illustrates how AI-generated mathematical stories can adapt narrative complexity and problem types based on real-time assessments of student proficiency. This multimodal approach—combining textual, visual, and symbolic representations—addresses diverse learning styles while maintaining alignment with curricular standards. Similarly, (M. Li, 2025) documents how primary school teachers in under-resourced settings used generative AI to create culturally relevant word problems, resulting in a 31% increase in student engagement compared to traditional textbook exercises. These applications resonate with Vygotskian principles of zone of proximal development, where AI tools act as dynamic scaffolds that adjust to individual learning trajectories.

Table 2. Taxonomy of Generative AI Applications in Mathematics Education

Application Type	Pedagogical Function	Key Findings	Sources
Intelligent Tutoring	Step-by-step problem solving	Improves conceptual understanding but risks procedural skill atrophy	(Wardat, 2023), (Bastani et al., 2025)
Adaptive Storytelling	Contextualized problem generation	Enhances engagement through culturally responsive narratives	(H. Li et al., 2024), (M. Li, 2025)
Proof Generation	Automated theorem proving	Effective for advanced learners but requires validation of logical rigor	(Dilling & Herrmann, 2024)
Teacher Support	TPACK development	Increases pre-service teachers' problem-posing creativity	(Segal & Biton, 2024), (Biton &

Application Type	Pedagogical Function	Key Findings	Sources
			Segal, 2025)

The integration of generative AI into mathematics education necessitates significant shifts in teacher roles and professional development. Studies focusing on teacher perceptions reveal both enthusiasm and apprehension: while 68% of surveyed educators in (Alsharidah & Alkramiti, 2024) acknowledged AI's potential to reduce workload through automated assessment, 53% expressed concerns about maintaining academic rigor when students use AI tools. This dichotomy is particularly evident in (Y. Wang et al., 2025), where mathematics teachers' acceptance of generative AI correlated strongly with their technological self-efficacy ($r = 0.72$, $p < 0.01$), highlighting the importance of targeted teacher training programs.

Cultural and contextual factors significantly mediate the effectiveness of AI implementations. Research by (Payadnya et al., 2025) in Southeast Asian classrooms demonstrates that generative AI tools achieved higher adoption rates when aligned with local pedagogical traditions for instance, by incorporating collaborative problem-solving features that reflect collectivist learning values. Conversely, (Engelbrecht & Borba, 2024) warns against the uncritical transfer of Western-centric AI models to diverse educational contexts, noting that language models trained primarily on English datasets often struggle with mathematical terminology in other languages, potentially exacerbating educational inequities.

The ethical dimension of generative AI in mathematics education surfaces repeatedly across studies. (Opesemowo & Ndlovu, 2024) identifies three key concerns: the "black box" nature of AI-generated solutions that may obscure mathematical reasoning, the potential for algorithmic bias in adaptive learning systems, and the environmental costs of deploying large-scale AI models in resource-constrained settings. These challenges are compounded by the rapid evolution of generative AI technologies, which often outpace the development of appropriate pedagogical frameworks and policy guidelines.

Emerging research directions suggest promising avenues for future investigation. Several studies ((Cosentino et al., 2025), (Drijvers & Sinclair, 2024)) explore the integration of embodied learning theories with generative AI, using multimodal data (e.g., gesture recognition, eye tracking) to create immersive mathematical learning experiences. Others ((Umoh, 2025), (Tashtoush et al., 2024)) examine the longitudinal impacts of AI-augmented mathematics instruction on STEM career pathways, particularly for female and minority students who have historically been underrepresented in quantitative fields. These developments point toward a more holistic understanding of generative AI's role in mathematics education—one that transcends technical functionality to address broader questions of equity, epistemology, and sustainable pedagogical practice.

Generative AI in STEM Education: Cross-Disciplinary Applications and Teacher Preparedness

The application of generative artificial intelligence in STEM education represents a critical intersection between technological innovation and pedagogical transformation.

This subsection examines how generative AI tools are being integrated across science, technology, engineering, and mathematics disciplines, with particular attention to teacher perspectives and sustainable development applications. The analysis draws from two key studies that illuminate both the potential and challenges of implementing these technologies in K-12 and higher education settings.

A central theme emerging from the literature is the role of teacher perceptions in shaping the adoption of generative AI in STEM classrooms. The study by (Darayseh & Mersin, 2025) investigates science and mathematics teachers' experiences with AI integration, revealing a spectrum of attitudes ranging from enthusiastic adoption to cautious skepticism. Teachers who successfully incorporated generative AI into their instruction reported using it to create customized problem sets, simulate scientific experiments, and provide real-time feedback on student work. However, significant barriers were identified, including limited professional development opportunities and concerns about maintaining academic integrity when students use AI-generated content. These findings align with broader research on technology integration in education, which emphasizes the importance of teacher self-efficacy and institutional support in determining the success of innovative tools.

The potential of generative AI to address sustainability challenges through STEM education is particularly noteworthy. As highlighted in (Cheah & Kim, 2026), AI tools can facilitate project-based learning focused on environmental issues by enabling students to analyze complex datasets, model climate change scenarios, and develop solutions for sustainable development. This application directly supports Sustainable Development Goal 4's emphasis on education for sustainability while also fostering critical STEM competencies such as data literacy and systems thinking. The study found that teachers who implemented these AI-enhanced projects reported increased student engagement with sustainability topics, particularly when the AI tools allowed for visualization of environmental impacts at local and global scales.

Table 3. Framework for Generative AI Integration in STEM Education

Integration Dimension	Key Characteristics	Implementation Challenges	Sources
Curriculum Alignment	AI-generated content mapped to STEM standards	Ensuring accuracy of AI outputs for specialized topics	(Darayseh & Mersin, 2025)
Sustainability Focus	Climate modeling and environmental data analysis	Access to quality training datasets	(Cheah & Kim, 2026)
Teacher Support	Professional development for AI tool integration	Time constraints and competing priorities	(Darayseh & Mersin, 2025), (Cheah & Kim, 2026)

Integration Dimension	Key Characteristics	Implementation Challenges	Sources
Ethical Considerations	Addressing bias in AI-generated STEM content	Developing student awareness of AI limitations	(Cheah & Kim, 2026)

The studies collectively underscore the importance of developing comprehensive support structures for STEM educators working with generative AI. Both (Darayseh & Mersin, 2025) and (Cheah & Kim, 2026) emphasize that successful implementation requires more than just access to technology—it demands ongoing professional learning communities where teachers can share best practices, troubleshoot challenges, and collaboratively develop AI-enhanced lesson plans. This need is particularly acute in interdisciplinary STEM contexts, where teachers must navigate not only the technical aspects of AI tools but also their pedagogical implications across multiple subject areas.

An emerging area of concern is the equitable distribution of AI resources across different educational contexts. While (Cheah & Kim, 2026) demonstrates the potential of generative AI to enhance sustainability education, it also notes that schools in under-resourced areas often lack the infrastructure necessary to support these applications. This disparity raises important questions about how to ensure that the benefits of AI in STEM education are accessible to all students, regardless of their socioeconomic background or geographic location. The studies suggest that addressing these equity issues will require coordinated efforts among policymakers, technology developers, and educational institutions.

The research also highlights the evolving nature of STEM pedagogy in the age of generative AI. Traditional approaches to teaching science and mathematics often emphasize procedural knowledge and standardized testing, but AI tools enable more open-ended, inquiry-based learning experiences. This shift aligns with contemporary theories of STEM education that prioritize creativity, problem-solving, and real-world application. However, as both studies caution, realizing this potential depends on careful instructional design that leverages AI's strengths while mitigating its limitations—a balance that requires both technological expertise and deep pedagogical knowledge.

Generative AI and Learning & Teaching: Pedagogical Transformations

The integration of generative artificial intelligence (AI) into learning and teaching processes has catalyzed significant pedagogical innovations while simultaneously challenging traditional educational paradigms. This subsection examines how generative AI tools are reshaping instructional strategies, student learning experiences, and theoretical frameworks across diverse educational contexts. The analysis reveals three critical dimensions of this transformation: (1) the redefinition of teacher and learner roles, (2) the emergence of new instructional models, and (3) the adaptation of learning theories to accommodate AI-mediated education.

Generative AI has fundamentally altered the dynamics between teachers and learners, creating a more interactive and personalized educational environment. Studies such as (López et al., 2023) demonstrate how AI-powered tools in higher education can function as "pedagogical partners," assisting instructors in developing customized learning materials for disciplines like business mathematics while enabling students to

engage in self-directed problem-solving. This dual capacity challenges traditional teacher-centered models, fostering a more distributed form of pedagogical responsibility. However, research by (Cabellos et al., 2024) reveals significant variation in teacher acceptance, with only 42% of surveyed faculty expressing confidence in adapting their teaching methods to incorporate generative AI effectively. The tension between AI's potential to enhance instruction and educators' readiness to harness this potential emerges as a recurring theme across multiple studies.

The pedagogical applications of generative AI extend across various instructional models, as detailed in Table 4. Conversational AI systems like ChatGPT have been particularly transformative, enabling new forms of dialogic learning that promote deeper engagement with complex concepts. Research by (Matthew et al., 2023) develops a framework for implementing ChatGPT in educational settings, emphasizing its capacity to simulate Socratic questioning techniques and provide instant feedback. Similarly, (Urban et al., 2024) demonstrates how generative AI can enhance creative problem-solving in university students, with experimental data showing a 28% improvement in solution originality when AI tools are used as cognitive scaffolds rather than answer generators. These findings suggest that the most effective applications of generative AI in education occur when the technology complements rather than replaces human cognitive processes.

Table 4. Generative AI Applications in Learning and Teaching

Application Domain	Pedagogical Impact	Key Challenges	Sources
Conversational AI	Enables dialogic learning and instant feedback	Requires careful prompt engineering	(Matthew et al., 2023), (Szabó & Szoke, 2024)
Creative Problem-Solving	Enhances solution originality and flexibility	Risk of over-reliance on AI-generated ideas	(Urban et al., 2024), (Song et al., 2025)
Personalized Learning	Adapts content to individual learning pathways	Data privacy and algorithmic bias concerns	(Lytvynova et al., 2023), (Wei et al., 2025)
Teacher Professional Development	Supports AI-augmented lesson planning	Limited institutional training opportunities	(Lee & Zhai, 2024), (Alexandrowicz, 2024)

The theoretical implications of generative AI for learning and teaching are profound, necessitating revisions to established educational frameworks. As noted in (Koh & Doroudi, 2023), the advent of generative AI requires educators to "regenerate older learning theories" to account for AI-mediated cognitive processes. Constructivist approaches, for instance, must now consider how learners construct knowledge not only through human interactions but also through engagements with AI systems. Similarly,

(Gibson et al., 2023) explores how mathematical learning theories can be adapted to incorporate AI's capacity for topological data analysis and generative representations. These theoretical adaptations are particularly crucial for mathematics education, where AI's ability to visualize abstract concepts and generate infinite practice problems challenges traditional notions of skill acquisition and mastery.

Disciplinary differences in generative AI adoption present another layer of complexity. Research by (Qu et al., 2024) reveals significant variation in how undergraduate students engage with AI tools across fields, with mathematics and physics students demonstrating more sophisticated usage patterns compared to their humanities counterparts. This divergence suggests that the effectiveness of generative AI in learning and teaching may be contingent on the epistemological structure of the discipline, with rule-based domains like mathematics being particularly amenable to AI augmentation.

The ethical dimension of generative AI in education remains a persistent concern across studies. (Kaplan-Rakowski et al., 2023) identifies three primary ethical challenges in AI-mediated teaching: the potential for diminishing human interaction in learning processes, the risk of propagating biases present in training data, and the environmental costs associated with large-scale AI deployments. These concerns are compounded by the rapid pace of technological advancement, which often outstrips the development of appropriate pedagogical and ethical guidelines.

Emerging research directions point toward increasingly sophisticated integrations of generative AI in educational settings. Studies such as (Wei et al., 2025) explore the use of multiple AI pedagogical agents in augmented reality environments, creating immersive learning experiences that blend physical and digital interactions. Others, like (Kostopoulos et al., 2025), investigate "agentic AI" systems that can autonomously adjust teaching strategies based on real-time analysis of student performance data. These developments suggest a future where generative AI becomes not just a tool for learning, but an active participant in the educational process—a transformation that will require ongoing critical examination of its pedagogical, ethical, and social implications.

The studies collectively demonstrate that while generative AI holds tremendous potential to enhance learning and teaching, its successful integration depends on thoughtful pedagogical design, robust teacher support systems, and continuous evaluation of both its benefits and limitations. As the technology continues to evolve, so too must our understanding of how it can best serve educational goals while preserving the essential human elements of teaching and learning.

User Perception and Acceptance of Generative AI in Education

The adoption of generative artificial intelligence (AI) in educational settings is fundamentally shaped by user perceptions and acceptance levels among students, educators, and institutional stakeholders. This subsection synthesizes findings from seven key studies that examine the psychological, cultural, and institutional factors influencing how generative AI is received and integrated into learning environments. The analysis reveals complex interplays between technological affordances, pedagogical beliefs, and ethical considerations that collectively determine the trajectory of AI adoption in education.

A dominant theme across the reviewed studies is the application of established behavioral theories to understand AI acceptance patterns. The study by (C. Wang et al., 2025) integrates the Theory of Planned Behavior with AI literacy constructs, demonstrating that students' intention to use generative AI tools is strongly predicted by their attitudes ($\beta = 0.38$, $p < 0.001$), subjective norms ($\beta = 0.29$, $p < 0.01$), and perceived behavioral control ($\beta = 0.21$, $p < 0.05$). This finding suggests that acceptance is not merely a function of technological capability but is deeply embedded in social and cognitive frameworks. Similarly, (Yilmaz et al., 2024) develops and validates a Generative AI Acceptance Scale grounded in the Unified Theory of Acceptance and Use of Technology (UTAUT), identifying performance expectancy and effort expectancy as the most significant predictors of adoption among university students. These theoretical approaches provide robust frameworks for explaining variance in AI acceptance across different educational contexts.

Cultural and institutional contexts emerge as critical mediators of AI perception. Research by (Adarkwah et al., 2023) in Ghanaian higher education institutions applies Diffusion of Innovation Theory to examine academic staff responses to ChatGPT, revealing distinct adoption patterns based on disciplinary backgrounds. Mathematics and computer science educators showed significantly higher acceptance rates (72%) compared to humanities faculty (38%), suggesting that the perceived relevance of generative AI varies substantially across academic domains. This study also highlights the importance of localizing AI tools, as participants emphasized the need for models trained on African educational content to ensure cultural relevance and linguistic appropriateness.

Table 5. Factors Influencing User Acceptance of Generative AI in Education

Determinant Category	Key Factors	Impact Level	Representative Studies
Psychological	AI self-efficacy, perceived usefulness	High ($\beta = 0.35$-0.62)	(C. Wang et al., 2025), (Yilmaz et al., 2024)
Social	Peer influence, institutional policies	Moderate ($r = 0.28$-0.41)	(Adarkwah et al., 2023), (Obenza et al., 2024)
Pedagogical	Alignment with teaching philosophy	Varied by discipline	(Alshammari & Al-Enezi, 2024), (Adarkwah et al., 2023)
Ethical	Concerns about academic integrity	High for educators	(Intelligence in Higher Education' et al., 2025), (Obenza et al., 2024)

The student perspective on generative AI reveals both enthusiasm and critical awareness. (Obenza et al., 2024) examines undergraduate perceptions across multiple universities, finding that 68% of respondents viewed ChatGPT as "transformative" for their learning, particularly for mathematics problem-solving and writing tasks. However,

the same study uncovered significant concerns about overreliance, with 41% of students reporting decreased confidence in their independent problem-solving abilities after prolonged AI use. This paradox underscores the dual-edge nature of generative AI in education—while enhancing accessibility and efficiency, it may inadvertently undermine the development of foundational cognitive skills if not implemented thoughtfully.

Educator perceptions present a more nuanced picture, often characterized by cautious optimism tempered by practical concerns. Research by (Alshammari & Al-Enezi, 2024) on pre-service social studies teachers demonstrates how acceptance levels evolve through direct experience with AI tools. Initial apprehension about technological complexity gave way to appreciation for AI's capacity to generate differentiated lesson plans, though participants remained wary of potential deskilling effects on their own pedagogical creativity. This finding aligns with (Intelligence in Higher Education' et al., 2025)'s investigation of AI misuse in academic tasks, which found that faculty concerns centered less on the technology itself and more on the need for revised assessment strategies that account for AI-assisted work.

The ethical dimension of AI acceptance emerges as a cross-cutting concern. Multiple studies ((C. Wang et al., 2025), (Intelligence in Higher Education' et al., 2025)) identify academic integrity as the foremost barrier to unreserved adoption, particularly in mathematics education where AI can generate solutions to complex problems. However, (Yilmaz et al., 2024)'s validation study reveals an interesting disconnect—while educators ranked ethical concerns highly, students placed greater emphasis on practical utility, suggesting generational differences in prioritization that may shape institutional AI policies.

Emerging research directions point toward more sophisticated models of AI acceptance that account for dynamic human-AI collaboration. The micro-macro-meso framework proposed in (Alshammari & Al-Enezi, 2024) offers a promising approach by examining acceptance at individual, institutional, and societal levels simultaneously. This multi-layered perspective is particularly relevant for mathematics education, where AI tools must be evaluated not only for their technical capabilities but also for their alignment with long-term learning goals and societal needs. Future studies would benefit from longitudinal designs that track how perceptions evolve as users gain more experience with increasingly advanced generative AI systems.

The reviewed studies collectively demonstrate that user acceptance of generative AI in education is neither uniform nor static, but rather a complex negotiation between technological possibilities, pedagogical values, and ethical considerations. Successful integration strategies must therefore address not only the functional aspects of AI tools but also the human factors that ultimately determine their educational impact.

Ethical and Responsible Use of Generative AI in Education

The rapid integration of generative artificial intelligence (AI) into educational settings has precipitated critical ethical debates that challenge traditional pedagogical norms and institutional policies. This subsection examines the complex landscape of ethical considerations surrounding generative AI in education, drawing upon three pivotal studies that address issues of academic integrity, educational justice, and moral

justification for restrictive policies. The analysis reveals tensions between innovation and regulation, access and equity, as well as human creativity and algorithmic output.

A fundamental ethical concern centers on the redefinition of authorship and creativity in AI-augmented learning environments. As articulated in (Rahimi & Azadmanesh, 2025), the emergence of generative AI has profoundly disrupted conventional notions of intellectual property and originality in mathematics education. The study employs deconstruction theory to analyze how AI-generated mathematical proofs and solutions complicate traditional assessments of student work, particularly when distinguishing between human-derived and machine-assisted reasoning. This philosophical examination reveals an epistemological crisis in mathematics education, where the veracity and ownership of AI-produced content remain contested. The research suggests that current academic integrity frameworks may be inadequate for addressing these novel challenges, necessitating revised pedagogical approaches that explicitly account for AI collaboration while preserving authentic learning outcomes.

The moral dimensions of institutional responses to generative AI adoption present another critical ethical consideration. (Fine Licht, 2024) provides a rigorous ethical analysis of the "banning approach" to generative AI in higher education, arguing that such restrictive policies can be morally justified under specific circumstances. The study identifies three conditions where prohibitions may be ethically warranted: when AI tools perpetuate systemic inequities by advantaging students with greater technological access, when they undermine the development of essential cognitive skills through overreliance, and when they compromise assessment validity in foundational courses. However, the research cautions against blanket bans, advocating instead for context-sensitive policies that balance innovation with educational integrity. This nuanced perspective highlights the ethical complexity of regulating emerging technologies in learning environments, where both unrestricted access and complete prohibition may have detrimental consequences.

Table 6. Ethical Framework for Generative AI in Education

Ethical Principle	Generative AI Challenge	Proposed Mitigation Strategy	Sources
Academic Integrity	Distinguishing human vs. AI-generated work	Develop AI-aware assessment rubrics	(Rahimi & Azadmanesh, 2025), (Fine Licht, 2024)
Educational Justice	Equitable access to AI tools	Institutional support for disadvantaged students	(Fine Licht, 2024)
Pedagogical Autonomy	Preserving teacher discretion in AI use	Professional development on ethical integration	(Swindell et al., 2024)
Creative Authenticity	Maintaining human authorship in learning	Explicit documentation of AI assistance	(Rahimi & Azadmanesh, 2025)

The call for comprehensive ethical frameworks emerges as a unifying theme across the reviewed studies. (Swindell et al., 2024) presents a conceptual model for responsible AI integration in education, emphasizing the need for multi-stakeholder

collaboration in developing guidelines that address both technical and philosophical concerns. The proposed framework identifies four pillars of ethical AI use: transparency in system operations, accountability for educational outcomes, fairness in access and application, and sustainability in implementation. Particularly relevant to mathematics education is the framework's emphasis on "explainable AI" for mathematical problem-solving, ensuring that students and educators can interrogate the reasoning behind AI-generated solutions rather than accepting them as opaque outputs.

The studies collectively underscore the inadequacy of current ethical paradigms to fully address the challenges posed by generative AI in education. While (Rahimi & Azadmanesh, 2025) focuses on deconstructing traditional notions of authorship and (Fine Licht, 2024) examines the morality of restrictive policies, (Swindell et al., 2024) bridges these perspectives by proposing actionable principles for responsible implementation. This tripartite analysis reveals that ethical considerations must evolve beyond simplistic binaries of permission/prohibition to engage with the nuanced ways generative AI is transforming educational practices. Future research directions suggested by these studies include empirical investigations of AI attribution practices in student work, longitudinal studies of skill development in AI-augmented learning environments, and comparative analyses of institutional policies across cultural contexts.

The ethical imperative extends beyond immediate classroom concerns to broader societal implications. As generative AI becomes increasingly sophisticated in mathematical reasoning and problem-solving, questions arise about its long-term impact on human mathematical cognition and the valuation of mathematical skills in the workforce. The reviewed studies suggest that educational institutions bear a responsibility not only to mitigate potential harms but also to actively shape the development of generative AI systems that align with pedagogical values and sustainable educational goals. This proactive approach requires ongoing dialogue between educators, researchers, policymakers, and AI developers to ensure that technological advancements serve rather than subvert the fundamental purposes of education.

Generative AI in Distance and Adaptive Learning

The integration of generative artificial intelligence into distance and adaptive learning environments represents a paradigm shift in how educational experiences can be personalized and scaffolded for diverse learners. This subsection examines the transformative potential of generative AI to enhance self-regulated learning through real-time analytics and adaptive scaffolding, while also exploring its role in making distance education more interactive and personalized through simulated learning experiences.

A critical advancement in this domain is demonstrated by (T. Li et al., 2025), which presents a framework for converting real-time learning analytics into adaptive scaffolds using generative AI. The study reveals how learner trace data can be dynamically filtered to provide targeted support, with the AI system withholding scaffolds when learners demonstrate sufficient competence. This approach aligns with Vygotsky's zone of proximal development while addressing the challenge of over-scaffolding that often plagues traditional adaptive learning systems. The research highlights the delicate balance required in scaffold timing and content generation, where

premature or excessive AI intervention can inadvertently hinder the development of independent problem-solving skills.

The personalization capabilities of generative AI in distance education are further explored in (Christadoss & Panda, 2025), which investigates simulated learning environments. These AI-generated simulations create immersive, context-rich scenarios that adapt to individual learner progress, effectively bridging the transactional distance that often characterizes remote education. The study identifies three key benefits: increased learner engagement through personalized narrative structures, improved conceptual understanding via adaptive problem generation, and enhanced metacognitive awareness through AI-facilitated reflection prompts. However, the research also cautions against potential over-reliance on simulated environments, emphasizing the need to maintain authentic human interaction components in distance learning designs.

Table 7. Applications of Generative AI in Distance and Adaptive Learning

Application Domain	Key Functionality	Pedagogical Benefits	Implementation Challenges	Sources
Adaptive Scaffolding	Real-time analytics-driven support	Promotes self-regulated learning	Determining optimal scaffold timing	(T. Li et al., 2025)
Simulated Learning	AI-generated interactive scenarios	Enhances engagement and personalization	Balancing simulation with human interaction	(Christadoss & Panda, 2025)
Personalized Learning	AI-curated adaptive learning pathways	Addresses individual learning needs	Ensuring algorithmic fairness	(Laak & Aru, 2025)

The study by (Laak & Aru, 2025) on AI and personalized learning complements these findings by examining the broader implications of generative AI for adaptive education systems. The research identifies a critical tension between personalization and standardization, where AI systems must navigate the competing demands of individualized learning trajectories and institutional assessment requirements. This challenge is particularly acute in mathematics education, where generative AI's capacity to create infinite practice variations must be carefully coordinated with curriculum standards and learning objectives.

The ethical dimensions of generative AI in distance learning emerge as a recurring concern across the reviewed studies. Issues of data privacy, algorithmic transparency, and equitable access are amplified in remote learning contexts where students may have varying levels of technological infrastructure and support. The studies collectively suggest that while generative AI holds tremendous potential to democratize access to quality education through adaptive distance learning, its implementation must be guided by robust ethical frameworks that prioritize learner autonomy and equitable outcomes.

Emerging research directions point toward increasingly sophisticated integrations of generative AI with other educational technologies. The combination of adaptive learning systems with virtual reality environments, for instance, could create immersive mathematics learning experiences that respond dynamically to learner actions and cognitive states. Similarly, the integration of affective computing with generative AI

could enable systems to adapt not only to cognitive needs but also to emotional states, potentially reducing the isolation often associated with distance learning. These advancements, while promising, will require continued research to ensure they enhance rather than replace the human elements of education that remain essential for deep learning and motivation.

The reviewed studies collectively demonstrate that generative AI is reshaping the landscape of distance and adaptive learning by enabling unprecedented levels of personalization and interactivity. However, the successful implementation of these technologies depends on careful pedagogical design, ongoing evaluation of learning outcomes, and thoughtful consideration of the ethical implications inherent in AI-mediated education. As the field continues to evolve, it will be critical to maintain a learner-centered approach that harnesses the power of generative AI while preserving the essential human dimensions of teaching and learning.

The synthesis of findings across the reviewed studies reveals a complex landscape where generative artificial intelligence (AI) simultaneously disrupts and enhances mathematics education. Taken together, the research demonstrates that generative AI applications consistently improve accessibility and personalization in learning, yet they also introduce novel challenges that require careful pedagogical and ethical consideration. The patterns emerging across studies suggest that while AI tools like ChatGPT and adaptive tutoring systems show promise in scaffolding mathematical problem-solving (Wardat, 2023), their effectiveness is mediated by factors such as implementation context, teacher preparedness, and student self-regulation (Bastani et al., 2025).

The theoretical implications of these findings are profound, necessitating revisions to established learning frameworks. Constructivist and sociocultural theories must now account for AI as an active participant in the learning process, not merely a tool. For instance, the connectivist perspective proposed by (Baskara, 2024) offers a viable model for understanding how knowledge construction occurs through human-AI interactions, particularly in distance learning environments where generative AI provides adaptive scaffolding (T. Li et al., 2025). However, this theoretical expansion raises fundamental questions about the nature of mathematical understanding when learners collaborate with systems capable of generating proofs and solutions (Rahimi & Azadmanesh, 2025). The tension between procedural fluency and conceptual understanding—long debated in mathematics education—takes on new dimensions when AI can perform procedural tasks effortlessly, potentially altering the cognitive goals of mathematics instruction.

Practically, the findings underscore the need for institutional support systems that prepare educators to integrate generative AI effectively. The consistent theme of teacher apprehension across studies (Alsharidah & Alkramiti, 2024), coupled with evidence of enhanced student outcomes when AI is implemented thoughtfully (H. Li et al., 2024), suggests that professional development programs should focus on developing technological pedagogical content knowledge (TPACK) specific to AI tools. Moreover, the disparities in AI access and adoption between high- and low-resource settings (Jogezai et al., 2025) highlight the urgency of policy initiatives that ensure equitable distribution of these technologies, aligning with SDG 4's emphasis on inclusive education.

Several methodological limitations in the reviewed literature temper the generalizability of these findings. The predominance of small-scale, short-duration studies in high-income contexts (C. Wang et al., 2025) limits insights into long-term impacts and cross-cultural applicability. Publication bias toward positive outcomes may obscure instances where generative AI implementations failed or produced neutral effects. Furthermore, the rapid evolution of generative AI technologies means that studies conducted even one year apart may examine substantially different system capabilities, making cumulative knowledge-building challenging. These limitations collectively suggest that while the current evidence base is promising, it remains provisional.

Future research should prioritize longitudinal studies that track the sustained effects of generative AI on mathematical skill development and STEM career pathways. There is a critical need for investigations in underrepresented educational contexts, particularly in Global South regions where infrastructure challenges may differentially impact AI's benefits (Adarkwah et al., 2023). The development of standardized assessment frameworks that can distinguish between human and AI-generated problem-solving processes would address pressing academic integrity concerns while enabling more nuanced studies of learning outcomes. Additionally, interdisciplinary collaborations between mathematics educators, AI ethicists, and cognitive scientists could yield innovative frameworks for evaluating how generative AI influences mathematical cognition at neurological and behavioral levels.

The ethical dimensions of generative AI in mathematics education demand continued scholarly attention. While current studies identify key concerns such as algorithmic bias and environmental costs (Opesemowo & Ndlovu, 2024), there remains a paucity of research on culturally responsive AI design and the long-term societal implications of AI-mediated mathematical reasoning. Future work should explore how generative AI systems can be designed to promote equitable participation in mathematics while preserving the discipline's intellectual rigor. The tension between innovation and tradition in mathematics pedagogy evident in debates over calculator use decades ago—now reemerges with far greater complexity, requiring thoughtful dialogue among all educational stakeholders.

The collective evidence suggests that generative AI's most significant contribution to mathematics education may lie in its ability to democratize access to high-quality, personalized instruction. However, realizing this potential without exacerbating existing inequities or compromising educational integrity will require coordinated efforts across research, practice, and policy domains. As the field moves forward, maintaining a critical yet open-minded stance toward generative AI's possibilities will be essential for harnessing its benefits while mitigating its risks in service of sustainable educational development.

CONCLUSION

This systematic review has examined the multifaceted role of generative artificial intelligence in mathematics education, addressing its data-driven applications, theoretical foundations, and implications for Sustainable Development Goal 4. The synthesis of 64 studies reveals that generative AI holds significant potential to transform mathematics

education through personalized learning, adaptive scaffolding, and enhanced accessibility. However, its integration is not without challenges, including ethical concerns, teacher preparedness, and equitable access.The findings underscore the need for robust pedagogical frameworks that account for AI-mediated learning while preserving the integrity of mathematical reasoning. Theoretically, the review highlights the necessity of adapting existing learning theories to incorporate human-AI collaboration, particularly in distance and adaptive learning environments. Practically, the evidence calls for institutional policies that balance innovation with ethical considerations, ensuring that generative AI serves as a tool for inclusive education rather than a source of further disparity.Future research should prioritize longitudinal studies across diverse educational contexts, with particular attention to underrepresented regions. Investigations into the cognitive and societal impacts of AI-augmented mathematics learning will be critical for developing sustainable implementation strategies. As generative AI continues to evolve, interdisciplinary collaboration among educators, researchers, and policymakers will be essential to harness its potential while addressing its limitations. This review provides a foundation for such efforts, offering insights that can guide both practice and future inquiry in this rapidly advancing field.

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