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Socio-Technical Perspective on Artificial Intelligence in Secondary Mathematics Education: A Systematic Review

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ABSTRACT

Artificial intelligence (AI) is increasingly integrated into mathematics education; however, research on its application in secondary mathematics education remains limited. This systematic review examines AI adoption in secondary mathematics from a socio-technical systems perspective, aiming to clarify opportunities and challenges and identify technologies that align with educational needs and practices. The review follows the PRISMA methodology and employs a hybrid deductive-inductive qualitative content analysis. The review included 32 studies predominantly from Asia. The findings indicate that approximately 47% of reviewed studies involved ChatGPT, with adaptive scaffolding and teacher mediation identified as primary mechanisms. AI provides personalized learning and additional benefits, although socio-technical challenges persist. This review offers insights into effective AI adoption in secondary mathematics education and delineates socio-technical implications for practice, policy, and future research.

KEYWORDS AI adoption constraints, Secondary mathematics education, Pedagogical mechanisms, Socio-technical systems, ChatGPT

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Introduction

Research has shown that artificial intelligence (AI) enables machines to perform tasks that require human intelligence, including reasoning, learning, problem-solving, and decision-making (Yanar & Ergene, 2025; Zawacki-Richter et al., 2019). AI encompasses methods such as machine learning, natural language processing, and neural networks. In contrast, digital technologies such as calculators, spreadsheets, geometry software, and whiteboards automate processes, provide content, or supply static resources but operate on pre-set rules and cannot learn or adapt (Zawacki-Richter et al., 2019). AI technologies, including intelligent tutoring systems (ITS), perform tasks that require human-like intelligence, such as learning from data, reasoning, prediction, and response customization (Zawacki-Richter et al., 2019).

Furthermore, the literature indicates that AI enhances mathematics teaching and learning by using technologies

that simulate human behaviors, including adaptive instruction, feedback provision, and personalized learning support (Yi et al., 2025). According to Yi et al. (2025), AI applications such as ITS, adaptive platforms, and generative tools improve achievement, motivation, and engagement in mathematics. AI also supports teachers in planning, resource development, and assessment, enabling greater focus on instruction and student support (Colen, 2025; Yanar & Ergene, 2025). Despite AI's potential to enhance mathematics teaching and learning, its adoption in secondary schools remains limited (Colen, 2025; Pardede et al., 2026). Findings suggest that this problem stems from insufficient professional development, inadequate institutional support, and infrastructure challenges (Lima et al., 2026; Marienko et al., 2026; Yu Tarasova & Doroshko, 2025). Yu Tarasova and Doroshko (2025) outline a four-part remedial foundation: (a) understanding essential AI concepts and skills, (b) implementing interactive and project-based teaching methods, (c) establishing guidelines for curriculum and resource development, and (d) providing recommendations for teacher professional development. The authors present structured, practical solutions and aim to make AI education in secondary schools more comprehensive, engaging, and effective.

Constraints to adopting AI in secondary schools extend beyond technical challenges. Accordingly, this review examines AI adoption in secondary mathematics education from a socio-technical systems (STS) perspective. The STS framework clarifies the relationship between technology and human or social factors, enabling a comprehensive assessment of AI's impact, adoption, and effectiveness in educational contexts (Li & Manzari, 2025; Zha et al., 2025). This review is guided by the following questions: (1) What types of AI technologies are used in secondary mathematics education, and through which pedagogical mechanisms are they implemented? (2) What socio-technical challenges hinder AI adoption in secondary mathematics education? Applying the STS perspective can help teachers and policymakers design, implement, and sustain AI adoption in secondary mathematics education by ensuring they consider both technical and social factors. This review is significant because it clarifies the opportunities and challenges of AI adoption in secondary schools and how to align AI technologies with educational needs and practices.

Socio-Technical Systems Perspective

STS emphasizes the interdependence of social and technical components within organizations (Ali et al., 2023; Imanghaliyeva et al., 2020). Effective AI integration requires considering environmental and institutional contexts alongside technological factors (Ali et al., 2024). STS advocates that stakeholders integrate these elements to achieve effective, ethical, and sustainable outcomes. UNESCO (United Nations Educational, Scientific and Cultural Organization, 2023) further provides guidelines for ethical AI use, prioritizing human agency, inclusion, equity, and protective safeguards. The framework focuses on ensuring that AI empowers both teachers and students, enables equitable access, particularly for marginalized groups, while upholding data privacy, transparency, and age-appropriate protections (Ali et al., 2024; UNESCO, 2023).

Methods or analytical approach

Research Design

This study followed the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Figure 1) (Page et al., 2021).

Search Strategy

This study searched Scopus, Web of Science, and ERIC in May 2026 to identify relevant studies on AI integration in secondary mathematics education. The search included keywords related to "artificial intelligence," "mathematics education," and "secondary school," including their alternative spellings and conceptually related terms combined with Boolean operators. Filters limited results to empirical, journal-source research articles published from 2022 to 2026, in the social sciences and arts and humanities, at the final publication stage, and written in English (Appendix).

Eligibility Criteria

The initial database search identified 75 articles (Scopus n=11, Web of Science n=25, ERIC n=39). The study excluded 14 records before screening: 10 were duplicates, and the other four were inaccessible (Figure 1). Thus, this study screened only 61 studies for eligibility. The author conducted the screening using the quality appraisal protocol (Table 1), and a senior researcher independently verified it. Disagreements were resolved by consensus. This study included studies that focused on AI technologies in secondary mathematics education and were published in peer-reviewed journals. Otherwise, they were excluded. The study excluded 29 studies. As a result, this study systematically reviewed 32 eligible studies.

Data Analysis

This review employed a hybrid deductive–inductive qualitative content analysis to quantify and describe content from the included studies (Saldaña, 2018). The study used CIMO (Context, Intervention, Mechanism, and Outcome) to organize the data (Denyer et al., 2008). This study organized the data into the following sub-categories: study ID, year, study title, study location, methodology, participants, AI name, mechanisms, findings on educational benefits, and findings on AI adoption constraints.

This study coded the data manually using a descriptive process in Microsoft Word. To enhance the trustworthiness of the findings, this study conducted peer debriefing by engaging two independent researchers to review the coding and themes. The study developed inductive codes based on the terminology, descriptions, and functions reported in the included studies. The study further refined the categories into themes. The AI technology themes followed Hammad (2025). The framework categorizes AI in education into four groups: personalized and adaptive learning (PAL), intelligent tutoring systems (ITS), generative AI (GenAI), and multimodal learning analytics (MMLA).

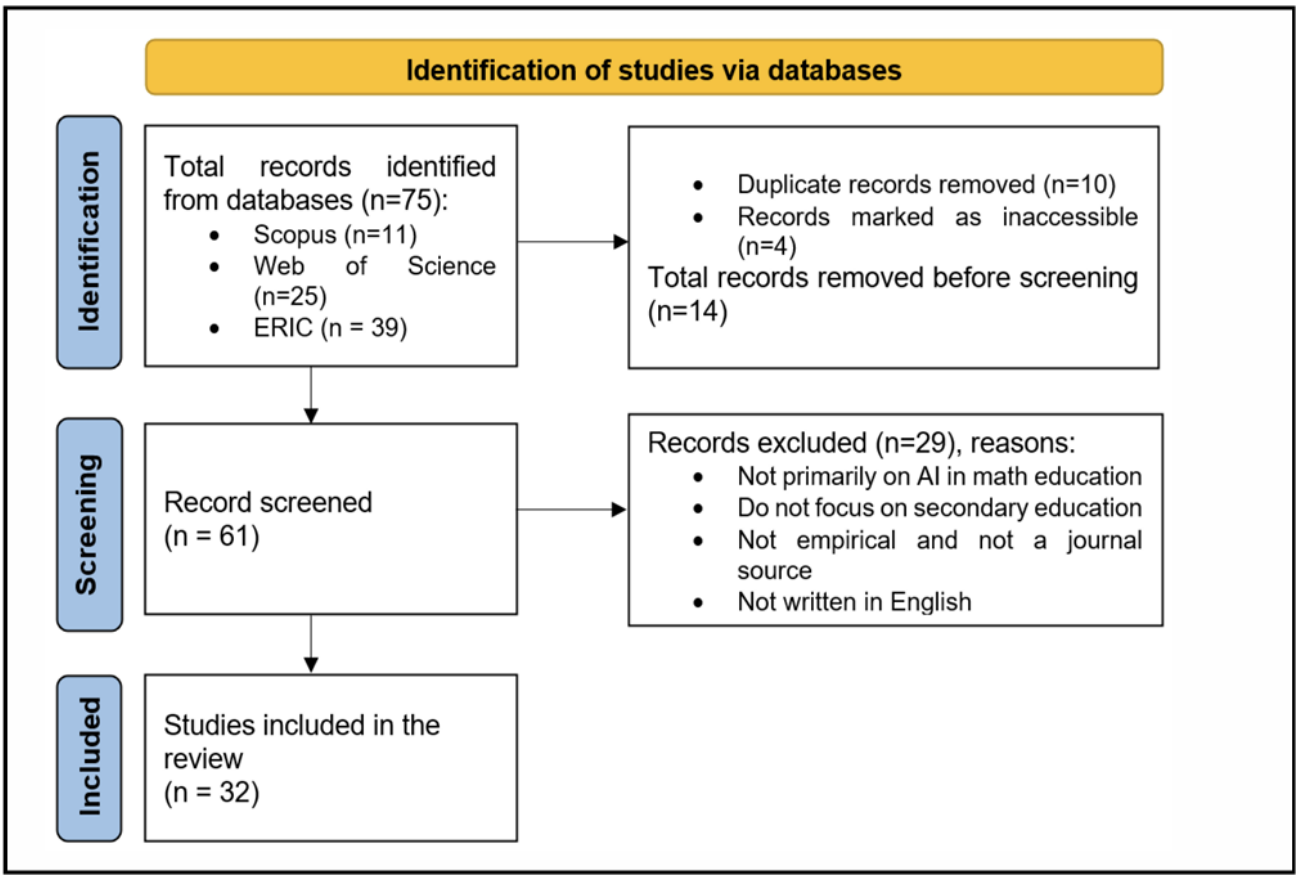


Fig. 1. PRISMA Diagram

Table 1. Quality Appraisal Protocol

Inclusion Criteria	Exclusion Criteria
Relevance to AI in mathematics education. Must address mathematics only.	Irrelevant to AI in mathematics education. Excluded even if they report the use of AI. Not relevant to math only if focused on STEM or STEAM, even if primarily about AI.
Relevance to secondary education and secondary education alongside other educational levels. Including Grades 5-8, Grades 9 12, Grades 6-9, Junior secondary, K-12, Lower secondary, Middle and High school mathematics, Middle school, Secondary school, Secondary mathematics teachers, and Senior Secondary School.	Irrelevant if the focus is not on secondary education; even if it focuses on teacher preparation or references secondary mathematics preservice.
Publication period: from January 2022 to July 2026	Irrelevant if outside of January 2022 and July 2026.
Subject areas: Social Sciences & Arts and Humanities	Other subject areas apart from Social Sciences & Arts and Humanities are irrelevant.
Source & Document type: Journal Article	Irrelevant if they are non -empirical or not a journal source.
Language: English	Irrelevant if written in any language other than English.

PAL encompasses AI-driven systems that customize educational content, pacing, and feedback according to each student's needs, preferences, and progress (Akçay & Altıner, 2025; Cho & Kim, 2025; Hammad, 2025). This approach departs from traditional one-size-fits-all models to improve engagement and learning outcomes. ITS are AI-powered platforms that model student knowledge and behavior to provide individualized instruction, guidance, and assessment (Akçay & Altıner, 2025; Hammad, 2025; Manto et al., 2026). These systems adapt teaching strategies and content based on real-time student data. GenAI, including large language models, produces new content such as text, images, or code in response to prompts (Hammad, 2025). This technology supports both students and teachers in tasks such as idea generation, feedback provision, and resource creation. MMLA utilizes advanced AI analytics to integrate and analyze data

from multiple sources, such as learning management systems and sensors (Hammad, 2025; Manto et al., 2026). MMLA aims to understand learning processes, monitor progress, and inform interventions across diverse educational contexts.

Results and findings

Characteristics of the Included Studies

The 32 studies cover Asia (Indonesia, Turkey, Philippines, Singapore, Nepal, China, Taiwan), Europe (Germany, Greece, Serbia, Portugal, Ukraine), Africa (Nigeria), North America (USA, Mexico), and South America (Argentina, Peru). Study 9 involved ten Southeast Asian countries, and Study 23 combined Nigeria, Ghana, and South Africa. Quantitative methods were the most common methodology used in the studies (n=19), followed by mixed methods (n=9), while qualitative methods were the least common (n=4).

Of the 32 studies, 24 focused on students only, five on teachers only, two studies involved both students and teachers, and one study involved no humans. Sample sizes ranged from 2 to 53298; qualitative (Study 13) and quantitative (Study 23) studies, respectively, both involved only students.

Table 2. The Studies' Years and Locations

Study ID	Year	Country
1	2025	Turkey
2	2024	Greece
3	2026	Greece
4	2026	Indonesia
5	2023	Nigeria
6	2026	Turkey
7	2025	Turkey
8	2026	Ukraine
9	2025	10 Southeast Asia: Indonesia, Thailand, Malaysia, Singapore, Philippines, Vietnam, Cambodia, Laos, Myanmar, and Brunei Darussalam
10	2025	USA
11	2024	Germany
12	2025	Germany
13	2024	Greece
14	2025	Serbia
15	2024	Indonesia
16	2025	Germany
17	2024	Nigeria
18	2025	Germany
19	2022	Indonesia
20	2025	Indonesia
21	2025	Singapore
22	2026	Portugal
23	2025	Nigeria, Ghana, and South Africa
24	2022	Mexico
25	2025	Argentina
26	2023	Philippines
27	2026	Nepal
28	2024	Philippines
29	2026	USA
30	2025	China
31	2025	Taiwan
32	2026	Peru

AI technologies involved in Included Studies

Some included studies evaluated AI's capabilities, while others assessed different aspects of AI; these distinctions informed the categorization. For example, both Studies 15 and 22 involved ChatGPT and GeoGebra, but the purpose of ChatGPT use differed. Study 15 utilizes ChatGPT to simplify GeoGebra tasks for students, whereas Study 22 investigated how ChatGPT supports learning. Consequently, these studies were categorized as GenAI and 'others', respectively (Table 3).

The review found that AI platforms such as Fractions Lab, Smart Learning Environments (SLE), Magic School, and Alberta AI also provided teachers with resources such as lesson planning, assignments, and instructional materials, while supporting students with explanations and tailored feedback. Their functionality aligned with ITS, while they often integrated GenAI. Similarly, this review identified some enabler models, including Photomath, Optical Character Recognition (OCR), and RoBERTa, as AI-based methods. These methods often use ChatGPT (Study 8 and Study 21) to help OCR systems handle complex tasks such as recognizing characters in various fonts, languages, and handwritten notes.

Some studies did not fit into Hammad's (2005) categories and were therefore categorized as 'others'. These include studies examining AI perceptions and acceptance, measuring AI's impact on mathematics outcomes, or exploring psychological and behavioral implications (Table 3). 'Others' was the dominant category with 12 counts (37.5%). The categories used in this study are not mutually exclusive. As a result, this review selected the category that best reflects each study's primary purpose.

Pedagogical Mechanisms of AI Adoption

The reviewed studies indicate that AI's impact in mathematics education depends on the pedagogical mechanisms through which these tools influence learning, teaching, feedback, assessment, and engagement. For example, Study 3 utilized DreamBox Learning, Fractions Lab, ChatGPT, and Mathia within a theory-driven intervention focused on fraction learning. Study 20 incorporated AI-driven scaffolding into realistic mathematics education and gamification. In both cases, AI served as an integral component of a purposefully designed instructional system rather than as an isolated tool. Conversely, when AI primarily generated solutions, as in Study 1 (chatbot-generated responses for e-textbook problems) and Study 14 (o1 and o3-mini solutions for competition problems), results indicated that AI-generated answers might be beneficial but still required critical evaluation and expert oversight. Key pedagogical approaches identified in the included studies include adaptive scaffolding, teacher mediation, dialogic reasoning, output evaluation, and representation mediation (Table 4).

Table 3. Categories of AI Technologies Adapted from Hammad (2025)

AI Category	Example	Study ID
ITS	ASSISTments, Smart Learning Environment (SLE), ALTER-Math, ADA C-GPT, Photomath, Multi-target classification model (LLaMA 3 + LoRA), and Cooperative conversation-based intelligent tutor system (CCITS)	2; 5; 10; 12; 24; 26; 29; 31 (n=8)
MMLA	ChatGPT on Google Sites & Google Forms, ChatGPT on MRIIA+ ecosystem & OCR, k nearest neighbors (KNN) & Random Forest & Support vector machine (SVM), Roberta powered by ChatGPT, and Chain of-thought (CoT) & GPT-4 on AMMORE Dataset	4; 8; 18; 21; 23 (n=5)
GenAI	ChatGPT, MathGPT, Gemini, OpenAI o1, and OpenAI o3-mini	1; 13; 14; 15 (n=4)
PAL	DreamBox Learning, Fractions Lab, ChatGPT, Mathia, Semantha® (AIEDN), and AI-based Gamification	3; 11; 20 (n=3)
Others	ChatGPT, AI in General, Machine-learning paradigm, ChatGPT-based Questionnaire (MTAPACQ), and Chatbots (ChatGPT, Gemini & Copilot)	6; 7; 9; 16; 17; 19; 22; 25; 27; 28; 30; 32 (n=12)

Table 4. Pedagogical Mechanisms Revealed in the Studies

Mechanism	Description
Adaptive scaffolding	Immediate feedback, hints, adaptive pathways, personalized worksheets, and scaffolding.
Teacher mediation	Select tools, design tasks, verify accuracy, customize resources, and address equity or infrastructure issues.
Dialogic reasoning	Encourage students to ask questions, explain their reasoning, justify their answers, or engage in mathematical dialogue.
Evaluation of outputs	Evaluate outputs, correct errors, refine prompts, debug, interpret feedback, or teach AI.
Representation mediation	Visual models, videos, GeoGebra, Photomath, decision trees, artifacts, and multimodal tools.

Adaptive scaffolding. Study 3 used DreamBox and Mathia to adjust the difficulty and feedback during fraction lessons, while ChatGPT provided questions and prompts that elicited explanations. Study 20 presented a clearer scaffolding model with tiered AI hints that guide students from action-level help to reasoning at the process and schema levels, without direct answers. Similarly, Study 31 employed a conversation-based ITS that offered hints, prompts, and cues during Pythagorean argumentation tasks, and Study 8 employed MRIIA+ with ChatGPT and OCR to analyze handwritten solutions, classify errors, and generate personalized feedback. These findings suggest that AI feedback is most effective when it focuses on students' reasoning processes rather than just confirming answers.

Teacher mediation. This was common across several studies. The mechanism showed that AI was more effective when teachers selected appropriate tools, designed tasks, monitored outputs, helped students interpret feedback, and aligned AI activities with curriculum goals. For example, Study 13 found that prompt quality influenced the usefulness of ChatGPT-created worksheets for students with special needs. Study 25 showed that teachers produced more specific, pedagogically sound fractal lesson plans than chatbots did. At the same time, Study 12 noted that the ADA chatbot still required teacher oversight because of potential hallucinations and confusing guidance. These findings demonstrate that successful AI integration depends heavily on teacher judgment.

Dialogic reasoning. This mechanism involves dialogic interaction. GenAI chatbots and teachable agents provided students with opportunities to ask questions, explain concepts, justify solutions, correct AI-generated errors, and engage in iterative reasoning. In Study 10, ALTER-Math positioned students as teachers of an AI-powered teachable agent, requiring them to explain mathematical concepts and correct the agent's errors. Study 29 adopted a similar learning-by-teaching approach, in which students identified errors in AI-generated solutions and justified their corrections. Study 22 demonstrated students using ChatGPT alongside GeoGebra to ask questions about quadratic functions and to compare textual explanations with graphical representations. These examples indicate that dialogue is most effective when students articulate and test their mathematical reasoning rather than simply requesting

answers. However, Study 15 found that students often struggled to get usable GeoGebra commands from ChatGPT because their prompts were vague. Study 12 showed that the ADA chatbot could facilitate Socratic questioning but also posed risks, such as confusing terminology, hallucinations, and increased cognitive load when used with paper-based materials. These findings suggest that AI dialogue does not replace mathematical expertise but instead shifts part of the learning challenge to questioning, interpreting, and validating machine-generated explanations.

Evaluation of outputs. Learning through critique emerged as a central mechanism across the reviewed studies. Multiple studies demonstrated that AI enhances pedagogical value when students actively inspect, challenge, revise, or improve AI-generated responses. For instance, Study 15 reported that students tested ChatGPT-generated GeoGebra commands, identified syntax or language errors, and refined prompts until the output was usable. Similarly, Study 4 described a culturally grounded geometry task in which students revised prompts when ChatGPT's representations of the Sanggah Cucuk did not align with the intended geometric structure. Studies 10 and 29 further developed this approach by using teachable agents that required students to teach, correct, and justify mathematical ideas to AI, shifting the focus from passively receiving solutions to exercising mathematical authority. These mechanisms are significant because they transform AI limitations, such as hallucinations, inconsistent terminology, incorrect

reasoning, or incomplete justifications, into learning opportunities when tasks are carefully designed. Study 14 recommended that advanced students critically analyze each step of AI-generated solutions, as not all were correct. Study 25 compares chatbot- and teacher-generated fractal solutions and finds that chatbots often omit intermediate reasoning steps or provide less detailed classroom proposals. Collectively, these findings indicate that the mechanism extends beyond AI providing explanations; students and teachers learn through questioning AI explanations, under conditions that promote verification and reflection.

Representation mediation. AI has influenced learning by expanding students' access to diverse mathematical representations. For example, Study 3 used Fractions Lab to enable visual manipulation of fraction models, helping students connect equivalence and operations to concrete visuals. Study 16 implemented CODAP with the Arbor plug-in to demonstrate decision-tree construction and misclassification rates, thereby making aspects of machine learning observable. Studies 15 and 22 integrated ChatGPT with GeoGebra, enabling students to combine textual explanations with dynamic geometric or graphical representations. Study 26 showed that Photomath supported pre-calculus learning through step-by-step solutions, while Study 11 linked students' questions to relevant videos using a semantic AI assistant. Collectively, these examples demonstrate that representational mediation can help students connect symbolic procedures with visual, procedural, or contextual understanding.

Nevertheless, several studies indicated that support based on representations was inconsistent. Study 7 reported that ChatGPT could generate numerous mathematics problems but struggled with visual or geometric representations, which could lead to misclassification or gaps in understanding. Similarly, Study 22 found that ChatGPT-3.5 could not produce graphs, so researchers used GeoGebra to represent quadratic functions visually. Study 1 omitted geometry and figure-based problems because certain AI models could not process images. These findings indicate that the most effective approach combines AI with representational tools and teacher expertise.

Several studies also found that GenAI chatbots and teachable agents enable students to explain concepts, justify solutions, correct AI-made mistakes, and reason iteratively. In Study 10, ALTER-Math had students teach an AI agent. Study 29 used a similar approach: students identified errors in AI solutions and justified their corrections. Similarly, Study 22 showed students using ChatGPT and GeoGebra to ask questions about quadratic functions and to compare textual explanations with graphical representations. The students actively inspected, challenged, revised, or improved AI-generated responses.

Reported Outcomes of AI Integration

The following sub-sections present the study's outcomes regarding AI educational benefits and challenges related to AI integration.

Educational benefits of AI adoption

The review categorized AI benefits in secondary mathematics, as reported in the included studies, into six categories (Table 5): Student agency and social learning, which include independent learning, autonomy, self-reliance, collaboration, and learning by teaching (Studies 1, 2, 3, 4, 6, 10, 13, 20, 21, 22, 26, 31); Personalized support and feedback, which include explanations, accessibility, personalization, scaffolding, feedback, error correction, and learning support (Studies 1, 2, 5, 6, 8, 10, 14, 17, 18, 22, 31); Motivational and affective outcomes, which include engagement, interest, motivation, and attitudes (Studies 3, 4, 5, 10, 12, 13, 20, 21, 26, 27); Higher-order mathematical skills, which include critical thinking, reasoning, problem solving, debugging, and argumentation (Studies 4, 15, 16, 20, 21, 22, 31); Cognitive learning outcomes, which include conceptual understanding, procedural fluency, achievement, knowledge transfer, and retention (Studies 3, 4, 10, 11, 13, 24, 26); and Teaching and assessment benefits, which include teaching efficiency, instructional support, and grading (Studies 1, 17, 23).

These results indicated that AI enhanced mathematical thinking and achievement, primarily in studies that embedded AI within structured instruction. A quasi-experimental study showed that students who received AI-supported mathematics instruction using DreamBox Learning, Fractions Lab, ChatGPT, and Mathia for fraction lessons had higher understanding, improved procedural skills, and greater engagement than those using traditional methods (Study 3). Study 20 found similar increases in understanding with the AI-RME-gamification model, which may contribute to the

positive overall learning outcomes observed. Some of the included studies also suggested that AI-driven learning is most effective when aligned with curriculum goals, scaffolding, and active reasoning. Several studies reported improvements in reasoning, problem-solving, critical and computational thinking, and argumentation. One example is Study 20, which showed that AI-supported RME enhanced problem-solving gamification, and tiered hints helped students persist without direct answers. Similarly, Study 31 found that students using an ITS (CCITS) outperformed their peers during the argumentation stages of the Pythagorean theorem. A qualitative study, Study 15, added interpretive depth, noting that ChatGPT and Gemini could handle demanding tasks and improve computational thinking through debugging AI commands.

Regarding AI-supported assessment, Study 8 showed that AI-assisted assessment using MRIIA+ and ChatGPT facilitated error correction, while also noting that traditional feedback was clearer and more engaging. GPT-4-based automated grading, particularly with chain-of-thought prompting, aligned more closely with human scoring than rule-based string-matching and text-processing methods (Study 23). In addition, some studies suggested that AI also boosted affective, engagement, and motivational outcomes (Studies 2, 3, 12, and 26). Notably, Study 2 reported that 94% of students (high) were interested in using ASSISTments; however, more than half of the students also reported that the platform caused them anxiety. This was like Study 27, which linked more time spent on digital resources to enjoyment but also to negative effects on achievement. Students with higher mathematics anxiety relied more on AI, but AI did not reduce anxiety (Study 30).

Some included studies also found that AI promotes equitable and inclusive education, especially through personalized learning (Studies 4, 9, and 13). For example, Study 13 found that personalized worksheets helped students with special needs gain concept mastery and engagement. Similarly, Study 4 used culturally grounded tasks to help students connect geometry to Balinese traditions. Culturally adapted AI technologies, local languages, and familiar examples are key to engagement and relevance (Study 9). In addition, the five teacher-only studies explored teachers' perceptions or knowledge of AI (Studies 9, 17, 25, 28 and 32). Teachers' responses indicated that AI supported teachers and teaching.

Challenges of integrating AI

Six themes emerged as constraints to AI adoption in secondary mathematics education (Table 6). The dominant constraint was AI's technical, output, and accuracy limitations. These include AI-generated reasoning errors, symbolic or notation errors, difficulty with visual representations, hallucinations, technical glitches, lag or system errors, and OCR problems. 15 studies across Asia, Europe, Africa, and America reported AI's technical, output, and accuracy limitations (Table 6).

Table 5. AI Benefits in Secondary Mathematics Education

Benefit	Main contributive AI	Total count
Student agency and social learning	ITS (Studies 2; 10; 26; 31)	12
Personalized support and feedback	ITS (Studies 2; 5; 10; 31)	11
Motivational and affective outcomes	ITS (Studies 5; 10; 12; 26)	10
Higher-order mathematical skills	MMLA (Studies 4; 21)	7
Cognitive learning ITS outcomes	(Studies 10; 24; 26)	7
Teaching and assessment benefits	GenAI & MMLA (Study 1 and Study 23 respectively)	3

Table 6. Constraints of AI Adoption in Secondary Mathematics Education

Constraints	Studies involved
Technical, output & accuracy limitations	1, 3, 4, 6, 7, 8, 10, 11, 14, 15, 17, 21, 22, 23, 25 (n=15)
Human oversight, competency & training	1, 3, 5, 6, 7, 9, 10, 15, 17, 19, 20, 27, 28, 32 (n=14)
Infrastructure, equity & access	1, 5, 11, 15, 17, 20, 22, 23, 27, 28, 31, 32 (n=12)
Student learning & psychological impacts	1, 2, 3, 6, 8, 10, 12, 17, 27, 28, 30 (n=11)
Diversity, culture & ethics	1, 2, 6, 8, 9, 11, 17, 19, 21, 22, 28 (n=11)
Pedagogy, instruction & integration barriers	1, 3, 8, 10, 11, 15, 17, 20, 28 (n=9)

Studies from Indonesia, Southeast Asia, Nigeria, Nepal, Peru, China, and the Philippines indicated that AI adoption needs language support, cultural relevance, infrastructure, teacher preparation, and students' digital literacy. Study 9 highlighted that culturally responsive AI technologies require local examples, multilingual options, and respect for regional norms. Study 4 cautioned that while cultural artifacts can improve mathematical understanding, AI without guidance might distort them. Study 5 and Study 17 noted that limited access to computers hindered AI use in Nigerian public secondary schools, and only 17% of Nigerian teachers were familiar with ChatGPT (Study 17). Similarly, Study 28 found that half of Metro Manila mathematics teachers were

unfamiliar with ChatGPT, and 82.7% cited technical training as a key need.

In addition, the findings indicated that GenAI is less reliable due to hallucinations. In Study 1, GPT-4o and GPT-4 performance accuracy declined as tasks became more complex. Study 14 confirmed this pattern, with OpenAI models excelling in Serbian mathematics contests but struggling with complex questions. Studies 7, 23, and 25 reported that ChatGPT reasoning is unstable: they sometimes accept correct corrections, defends false claims, or produces flawed proofs. Furthermore, AI representational mediation is limited for mathematical visuals, spatial, or handwritten artifacts. Study 1 excluded geometry problems with figures; Studies 7, 8, and 22 noted ChatGPT struggles with visual and geometric representations, especially with triangles. Study 8 indicated that ChatGPT assessments in MRIIA+ depend on OCR accuracy, scan quality, and recognition of mathematical notations and diagrams. Study 22 showed that ChatGPT-3.5 needs GeoGebra to generate dynamic graphs, as it cannot do so independently.

The review further revealed that the quality of AI output depends on users' AI knowledge. Students often failed because ChatGPT provided commands in an incorrect programming language or with syntax errors that GeoGebra could not interpret. In worksheet-generation and narrative-task studies, teachers had to modify ChatGPT outputs to suit students, curriculum levels, and classroom contexts. Meanwhile, some studies revealed that AI limitations often begin before output is generated. For example, Study 8 relied on OCR quality and the structured digitization of handwritten solutions. Study 21 showed that RoBERTa's dialogue-act classification required annotated tutoring data and synthetic examples from ChatGPT to handle rare codes.

ASSISTments, DreamBox, and adaptive scaffolding platforms often faced challenges including limited adaptability, limited emotional responsiveness, fixed interaction formats, and partial modeling of student thinking. Study 10 found that while ALTER-Math enhanced learning, it had uncleared prompts, limited math problem diversity, poor frustration management, and an occasional risk of hallucinations. Study 20 showed that the AI scaffolding tutor intentionally withholds direct answers to promote productive struggle, which can frustrate students who get stuck. Study 31 demonstrated that a cooperative conversation-based intelligent tutor system (CCITS) improved argumentation skills but limited students to responding rather than asking questions. Nevertheless, Studies 6, 17, 26, 27, 28, and 30 identify issues of overdependence, academic dishonesty, diminished independent reasoning, and less social interaction. These issues mostly involved students and related to how technologies like ChatGPT and Photomath provide instant answers and step-by-step solutions. Studies have found that AI hinders learning when students rely on it to do all the thinking. Study 30 showed that students with mathematics anxiety may turn to AI as a coping mechanism, yet frequent AI use does not necessarily lower anxiety.

Discussion

This study found that AI effectiveness in secondary mathematics education depends on socio-technical alignment.

ChatGPT: The Most Common AI Technology

Reviewed studies reported that ITS, GenAI, and PAL are some of the AI technologies adopted in secondary mathematics education. Some studies involved multiple AI technologies. The findings show that conversational AI, especially ChatGPT and similar large language models (LLMs), was widely used in secondary mathematics education. The literature supports this finding that ChatGPT is popular in secondary school mathematics for lesson planning, problem-solving, and activities (Yanar & Ergene, 2025). This may be because it can generate explanations, support reasoning, provide feedback, and create materials. Although ChatGPT was common among the included studies – 15 out of the 32 included studies involved ChatGPT – it did not drive the popularity of GenAI (Table 3). This shows ChatGPT's influence and contributions in other categories. For instance, RoBERTa serves as an enabler model in natural language processing (Moussa et al., 2022). OCR systems often use AI to improve text recognition accuracy and efficiency (Zhang et al., 2023). Among the included studies, RoBERTa and OCR were powered by ChatGPT, and their use aligned more with the MMLA. Other frequently used AI technologies in the included studies include DreamBox; AI-powered teaching agents such as ALTER-Math; automated assessment systems such as MRIIA+; and specialized apps such as Photomath and GeoGebra.

Interconnection Effects of AI's Capacity, Pedagogical Mechanisms, and Educational Benefits

Another key finding is that the educational benefits of AI technologies, AI's technical characteristics, and their pedagogical mechanisms were interconnected. Adaptive scaffolding was the dominant mechanism, implying PAL addresses challenges such as feedback timeliness and individualization for many students. Some included studies suggest that AI breaks tasks into steps, provides hints, and supports struggle without giving answers, aligning technology with teaching goals. However, this mechanism depends on technology quality, student engagement, and teacher integration. Song et al. (2025) confirm that dialogue and scaffolding play a vital role, especially in GenAI, which encourages inquiry-based learning and critical thinking. Existing studies highlight personalized feedback as the most effective mechanism for providing real-time, tailored feedback, thereby increasing student engagement and improving learning outcomes (Mohamed et al., 2022; Yi et al., 2025). This suggests AI is most effective when it acts as a pedagogical mediator, supporting active knowledge construction through questioning.

Challenges of AI Adoption

AI in secondary mathematics education faces technical, pedagogical, and contextual challenges. These issues reflect system-social tensions, and effective outcomes require improvements in the system's social and technical factors (Ali et al., 2024). This review found that five out of the six

categories of AI constraints were socio-environmentally related (Table 6).

Challenges related to the AI adoption environment

Teacher-related challenges were prominent, including inadequate training, limited AI literacy, increased workload, and uncertainty about effective pedagogical integration. The literature confirms that in-service and pre-service teachers often lack structured opportunities to develop AI literacy and pedagogical strategies for effective integration (Açıkyıldız & Şahin, 2025; Ruiz & Yambao, 2026; Shrestha & Yi, 2026). Professional development seems insufficient, as teachers often call for targeted training to improve their skills and confidence in using AI (Atuahene & Boateng, 2026). Teachers also reported that heavy workloads, large class sizes, and administrative duties limited their time to explore new AI tools (Atuahene & Boateng, 2026). This underscores the need for professional development that covers pedagogical, ethical, and curricular aspects of AI use.

Teachers also worry that students' overreliance on AI reduces critical thinking and that AI's incorrect outputs often cause misconceptions and shallow learning. Existing studies confirm these challenges (Pardede et al., 2026; Shrestha & Yi, 2026). Pavlova (2024) adds that overreliance on AI can lead students to submit work that does not reflect their own reasoning, sometimes resulting in incorrect answers and hindering genuine learning. Moreover, easy access to AI-generated solutions can discourage students from developing their own problem-solving and critical thinking skills (Shrestha & Yi, 2026). To use AI effectively, students and teachers alike need digital literacy, which many lack, particularly those with special needs or from under-resourced areas (Atuahene & Boateng, 2026). This aligns with the STS theory that human capabilities shape effectiveness.

The findings also identified infrastructure, internet, device shortages, language issues, and mismatched AI systems as factors influencing AI success. Studies emphasize that unreliable electricity, poor internet connectivity, and limited access to digital devices remain significant barriers, particularly in low-resource or rural areas (Atuahene & Boateng, 2026; Fakoyede et al., 2026; Lessing & Ogbonnaya, 2025). In Ghana, mathematics teachers reported that poor internet connectivity and limited access to devices significantly hindered classroom use of ChatGPT (Atuahene & Boateng, 2026). Similarly, for students with special educational needs (SEN), unequal access to technology and high costs of AI-powered systems were identified as critical barriers (Lessing & Ogbonnaya, 2025). The literature further suggests that AI systems and their training data may embed cultural biases or depict scenarios that do not align with local students' experiences, leading to disengagement (Niño et al., 2026; Walkington, 2025). AI technologies may not support all local languages, limiting access for students unfamiliar with the tool's primary language (Sofroniou et al., 2025). STS places these systems within policies, resources, and support structures.

Challenges caused by the features of the AI system

A key challenge of AI systems is accuracy and reliability issues: included studies reported hallucinations, errors, and inconsistent feedback, especially with complex problems or advanced reasoning. The literature consistently reports that while models like GPT-4 demonstrate high accuracy on many mathematics problems, significant limitations persist, especially with complex, open-ended, or context-dependent tasks (Weinhandl et al., 2026). Teachers and students alike have raised concerns about the dependability of AI solutions. In a study of Ghanaian mathematics teachers, many reported skepticism about ChatGPT, citing misleading or incorrect outputs (Atuahene & Boateng, 2026). Nevertheless, some studies have shown that AI tutoring and assessment tools provide reliable feedback for structured tasks, suggesting that reliability varies with task complexity, context, and human mediation.

Research emphasizes the need for transparent data governance and well-defined privacy protection. Additionally, cultural challenges such as algorithmic bias, lack of transparency, and the potential to deepen educational inequalities arise when AI systems are not thoughtfully developed and supervised (Niño et al., 2026; Walkington, 2025). AI adoption requires supportive leadership, coherent policies, professional development, and resources, yet these are often inadequate. Schools often lack AI guidance, causing inconsistency and uncertainty. STS opines that AI integration depends on organizational support, teacher expertise, student AI literacy, ethical governance, and infrastructure.

This review's findings indicate that although AI increases engagement, provides personalized feedback, supports both students and teachers, promotes reasoning, and improves access, it is also associated with anxiety, inaccurate feedback, the need for substantial teacher mediation, overreliance, and inequity. These contrasting outcomes suggest that AI's benefits in secondary mathematics are conditional rather than inherent. These complexities highlight the need for a socio-technical systems approach, where effective AI integration relies on aligning reliable technology, teacher guidance, equitable infrastructure, ethical safeguards, and purposeful mathematics instruction.

Implications

The findings indicate that teachers should regard AI as a pedagogical partner rather than a replacement, especially when integrated into activities that foster reasoning and reflection. Teachers play a critical role in mediating AI use by teaching students to verify AI outputs and understand these technologies' limitations, thereby incorporating AI literacy into mathematics education. The effectiveness of AI adoption depends on the readiness of both teachers and students, requiring activities to align with their existing knowledge and skills. Further evidence suggests that schools and administrators should approach AI as a socio-technical transformation that requires adequate infrastructure, training, pedagogical support, and preparedness. Ongoing professional development is essential because of limited familiarity with AI and concerns about reliability. Schools should provide continuous training in technical skills, pedagogy, AI literacy, ethics, curriculum, and assessment. A

supportive environment with reliable internet access, devices, and technical assistance is crucial to prevent disparities. Administrators should promote responsible AI use through clear guidelines on integrity, privacy, ethics, and oversight. AI integration in secondary mathematics education should be approached as a socio-technical reform, encompassing policies on teacher training, curriculum development, infrastructure, and equity.

Limitations

A key limitation of this review is the potential for selection bias arising from the search strategy. The databases were restricted to the social sciences and the arts and humanities, and the review did not include backward and forward citation tracking or grey literature searches. These factors may have resulted in the omission of relevant studies. In addition, the evidence is skewed toward Asian and European countries. Educational systems and cultural attitudes toward AI vary widely across nations; results from one context may not apply directly to others. Many included studies also examined specific versions of ChatGPT, Gemini, Photomath, or other AI technologies that are continually updated. As AI capabilities evolve rapidly, some reported features, limitations, and performance results may become outdated. Future research should explore topic-specific uses of AI in secondary mathematics education, as the reviewed studies address topics such as fractions, geometry, calculus, quadratic functions, and problem-solving. It remains unclear whether AI's pedagogical benefits and challenges differ by topic.

Conclusion

This systematic review demonstrates that AI provides substantial benefits for secondary mathematics education, particularly through adaptive scaffolding. However, effective AI adoption requires recognizing AI technologies as specialized pedagogical mediators whose success depends on aligning STS. The reviewed studies indicate that evaluating AI limitations should focus on the degree of alignment between AI mechanisms, mathematical tasks, instructional design, and sociocultural context, rather than simply determining whether AI "works" or "does not work." When this alignment is strong, AI can enhance feedback, student engagement, problem posing, assessment, and personalized practice. In contrast, poor alignment may lead to hallucinations, superficial reasoning, generic outputs, overreliance, inequity, or pedagogical mismatches.

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Appendix

Databases used for the study and their respective query codes.

Database	String/Link	Filters
Scopus	TITLE-ABS-KEY ((artificial intelligence OR AI OR ChatGPT OR generative AI) AND (mathematics education OR mathematics teaching OR mathematics learning) AND (secondary school OR high school)) AND PUBYEAR > 2021 AND PUBYEAR < 2027 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "ARTS")) AND (LIMIT-TO (LANGUAGE , "English"))	AI, math education, secondary school, 2022-2026, article, social sciences & humanities, English
Web of Science	https://www.webofscience. com/wos/woscc/summary/ b44924de-2382-4f8d-a15a-a987f4f11f94-01b6454469/relevance/1	AI, math education, secondary school, 2022-2026, article, social sciences & humanities, English
ERIC	https://eric.ed.gov/?q=(%2 2artificial+intelligence%22 +OR+AI+OR+ChatGPT+ OR+%22generative+AI%2 2)+AND+(%22mathematics+education%22+OR+%22mathematics+teaching%2 2)&pr=on&ff1=dtySince_ 2022&ff2=eduSecondary+ Education&ff3=pubJourna l+Articles	AI, math education, secondary school, 2022-2026, article, social sciences & humanities, English