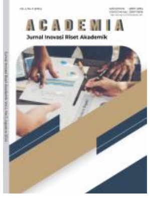

ACADEMIA: Jurnal Inovasi Riset Akademik
Vol. 6, No. 2, Maret-Mei 2026
e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

ARTIFICIAL INTELLIGENCE AND DIGITAL INNOVATION IN MATHEMATICS EDUCATION FOR CRITICAL THINKING: A SYSTEMATIC LITERATURE REVIEW

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Diterima: *28/04/2026* Direvisi: *05/05/2026*; Diterbitkan: *13/05/2026*

ABSTRACT

This study presents a systematic literature review on artificial intelligence and digital innovation in mathematics education for critical thinking. The review aimed to identify research trends, forms of implementation, major findings, and research gaps in the literature. The study employed a Systematic Literature Review design guided by the PRISMA framework. Data were collected from the Scopus database. The initial search yielded several hundred records, which were filtered based on publication years 2020–2025, English language, open access status, subject area Mathematics, and source type Journal. After the filtering and screening process, 25 articles were selected for the final synthesis. The findings show that the literature on critical thinking in mathematics education is broader than the literature directly addressing artificial intelligence. Most studies focused on pedagogical approaches such as inquiry-based learning, realistic mathematics education, proof, problem solving, and computational thinking, while only a limited number of studies explicitly examined AI or generative AI in mathematics education. The review indicates that artificial intelligence and digital innovation have strong potential to support critical thinking through interactive learning environments, AI-assisted problem solving, and digitally mediated instruction. However, their contribution depends heavily on pedagogical design, teacher mediation, and the extent to which technology supports genuine mathematical reasoning. The review concludes that the integration of artificial intelligence in mathematics education remains an emerging field and requires stronger empirical evidence, clearer conceptualization, and more context-sensitive implementation to enhance critical thinking effectively.

Keywords: artificial intelligence; digital innovation; mathematics education; critical thinking; systematic literature review

INTRODUCTION

In the digital era, mathematics education is expected not only to develop procedural competence but also to foster learners' critical thinking, logical reasoning, and informed judgment in increasingly complex and technology-mediated learning environments. This expectation is closely related to the broader transformation of education through digital innovation, including artificial intelligence (AI)-supported learning environments that are becoming more interactive, adaptive, and responsive (Zawacki-Richter et al., 2019; Chen et al., 2020; Kasneci et al., 2023). Within mathematics education, critical thinking has become a central goal because it enables students to analyze mathematical situations, evaluate strategies, construct arguments, and justify conclusions in meaningful ways (Bohlmann & Benölken, 2020; Bronkhorst et al., 2020; Nichols, 2025).

Recent literature consistently emphasizes that meaningful mathematics learning involves more than producing correct answers. It also requires students to interpret symbolic

https://doi.org/10.51878/educational.v6i2.10656

ACADEMIA: Jurnal Inovasi Riset Akademik
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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

relationships, examine assumptions, test the validity of arguments, and justify conclusions mathematically (Facione, 1990; Ennis, 2011). Studies on mathematical proof, logical reasoning, and critical mathematical thinking indicate that critical thinking in mathematics is not merely a general cognitive skill, but a discipline-specific competence grounded in analysis, evaluation, and justification within mathematical contexts (Pavitola & Rieksta, 2025; Isran et al., 2025; Monteleone et al., 2023). This perspective is important because it positions critical thinking as a substantive outcome of mathematics education rather than as a peripheral or transferable skill alone.

The literature also shows that critical thinking in mathematics does not develop automatically; rather, it depends strongly on pedagogical design. Studies on inquiry-based learning, concept-based instruction, complex tasks, and other student-centered approaches suggest that learners are more likely to develop critical thinking when they are encouraged to explore multiple strategies, interpret patterns, reflect on alternatives, and actively construct knowledge (Bohlmann & Benölken, 2020; Jeong & González-Gómez, 2021; Pokhrel et al., 2024; Doz et al., 2025; Ncube & Luneta, 2025). Similarly, research on realistic mathematics education and learning trajectory design indicates that critical thinking is strengthened when mathematics is presented through meaningful contexts and carefully structured learning experiences (Nursyahidah et al., 2025; Lestari et al., 2023; Sari et al., 2025). These studies collectively suggest that the development of critical thinking is inseparable from the quality of instructional design.

At the same time, advances in digital technology have increasingly shaped mathematics education. Digital tools are no longer used merely for presentation or routine practice; they now support dynamic visualization, adaptive interaction, automated feedback, and more sophisticated forms of cognitive support. Broader studies on artificial intelligence in education show that AI has increasingly been used to support adaptive learning, automated feedback, learner support, and data-informed educational decision-making, although its pedagogical value depends on how it is implemented within specific learning contexts (Zawacki-Richter et al., 2019; Chen et al., 2020; Jameson et al., 2022).

This transformation has become more visible with the emergence of generative AI and AI-assisted learning environments. Recent studies on ChatGPT, AI-generated mathematical responses, and digitally supported problem solving suggest that AI is beginning to reshape how mathematical tasks are interpreted, explained, and evaluated in contemporary learning settings (McGalliard & Otten, 2025; Yunianto et al., 2024; Pepin et al., 2025). Specifically, studies on ChatGPT in education and mathematics learning indicate that generative AI may support explanation, problem-solving assistance, and access to alternative solution strategies, while also requiring critical evaluation of accuracy, reasoning quality, and pedagogical appropriateness (Lo, 2023; Wardat et al., 2023). These developments raise an important question: do such innovations merely improve efficiency, or do they genuinely support deeper critical thinking in mathematics education?

This question is particularly important because the educational value of AI depends not only on the tool itself, but also on how it is integrated into mathematically meaningful learning. AI-supported environments may provide immediate responses, alternative solution paths, and interactive assistance, yet such support does not automatically promote critical thinking. Instead, its value depends on whether students are encouraged to question, verify, interpret, and evaluate digital outputs critically. In this regard, computational thinking has emerged as an important bridging concept in recent literature. Computational thinking provides an important conceptual foundation for AI-related learning because it involves problem decomposition,

https://doi.org/10.51878/educational.v6i2.10656

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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

abstraction, pattern recognition, algorithmic reasoning, and systematic problem solving, which are closely related to mathematical reasoning and critical thinking (Wing, 2006; Grover & Pea, 2013). Studies involving geometry, ethnomathematics, and GeoGebra-supported tasks further show that computational thinking includes decomposition, pattern recognition, algorithmic reasoning, and logical structuring, all of which overlap with mathematical reasoning and critical thinking (Yunianto et al., 2024; Azmi et al., 2025).

Despite the growing visibility of AI and digital tools in education, the specific relationship between artificial intelligence, digital innovation, and critical thinking in mathematics education remains insufficiently consolidated. Existing studies have widely discussed critical thinking, mathematical reasoning, proof, problem solving, inquiry-based learning, realistic mathematics education, and computational thinking. However, these studies are often distributed across separate research strands and do not always explain how AI and digital innovation specifically contribute to the development of critical thinking in mathematics learning. As a result, the literature still lacks a focused synthesis that distinguishes between general technology-supported mathematics learning and AI-related innovation aimed at strengthening students' critical mathematical thinking.

This gap is urgent for at least three reasons. First, the rapid emergence of generative AI and AI-assisted learning tools has begun to influence how students access explanations, solve mathematical problems, and evaluate mathematical responses. Without a clear synthesis of existing evidence, AI may be used primarily to accelerate answers rather than to support reasoning, justification, and reflective problem solving. Second, mathematics education requires discipline-specific forms of critical thinking, including evaluating assumptions, validating procedures, constructing arguments, and interpreting mathematical meaning. Therefore, the contribution of AI cannot be assessed merely from technological efficiency, but must be examined in relation to the quality of mathematical reasoning it supports. Third, teachers and curriculum designers need clearer guidance on how AI and digital innovation can be pedagogically integrated to strengthen critical thinking rather than replace students' cognitive engagement.

Based on this gap, the present study conducts a systematic literature review of artificial intelligence and digital innovation in mathematics education for critical thinking. Specifically, this review aims to map publication trends, identify the forms of AI and digital innovation reported in the literature, examine how these developments are connected to critical thinking in mathematics education, and reveal specific gaps for future empirical and pedagogical research. By focusing on the intersection of artificial intelligence, digital innovation, mathematics education, and critical thinking, this review seeks to provide a more coherent basis for understanding how digital transformation can support meaningful mathematical reasoning rather than merely accelerate answer generation.

To achieve these aims, this review is guided by the following research questions:

RQ1. What publication trends characterize research on artificial intelligence and digital innovation in mathematics education for critical thinking?

RQ2. What forms of artificial intelligence and digital innovation are reported in the reviewed literature?

RQ3. How are artificial intelligence and digital innovation connected to the development of critical thinking in mathematics education?

RQ4. What research gaps and future research directions can be identified from the reviewed studies?

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By synthesizing recent studies in this area, this review seeks to contribute to a more coherent understanding of how mathematics education can respond to digital transformation while maintaining its commitment to rigorous, reflective, and meaningful mathematical thinking.

METHODS

1. Research Design

This study employed a Systematic Literature Review (SLR) to examine the role of artificial intelligence and digital innovation in mathematics education in relation to critical thinking. The SLR approach was considered appropriate because it enables the structured synthesis of dispersed studies, facilitates the identification of research trends, and reveals gaps in the literature concerning artificial intelligence, digital innovation, mathematics education, and critical thinking (Snyder, 2019). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent, systematic, and replicable process of study identification, screening, selection, and synthesis (Page et al., 2021). The analysis was organized around the four research questions formulated in the Introduction, which guided the study selection, data extraction, thematic coding, and synthesis of the reviewed articles.

2. Data Source and Search Strategy

The literature search was conducted in the Scopus database, which was selected because of its broad coverage of peer-reviewed international publications in education, mathematics, and technology-related fields. The search targeted studies situated at the intersection of artificial intelligence, digital innovation, mathematics education, and critical thinking. The search terms were derived from the main concepts of the review, namely artificial intelligence, digital innovation, mathematics education, and critical thinking. Boolean operators such as **AND** and **OR** were used to combine and refine the keywords. A representative search string was formulated as follows:

("artificial intelligence" OR AI OR ChatGPT OR "digital innovation") AND ("mathematics education" OR "mathematics learning") AND ("critical thinking")

Related constructs such as reasoning, proof, problem solving, and higher-order thinking were also considered during the screening stage because of their conceptual relevance to critical thinking in mathematics education.

3. Inclusion and Exclusion Criteria

To ensure the relevance and consistency of the selected studies, explicit inclusion and exclusion criteria were applied. Related constructs such as higher-order thinking, reasoning, proof, and problem solving were also considered during screening because they are conceptually linked to critical thinking in mathematics education.

a. the study focused on artificial intelligence and/or digital innovation within mathematics education;
b. the study addressed critical thinking, higher-order thinking, reasoning, proof, problem solving, or closely related cognitive outcomes;
c. the article was published between 2020 and 2025;
d. the article was written in English;
e. the article was available as open access;
f. the article was indexed in Scopus under the Mathematics subject area;
g. the source type was journal article.

https://doi.org/10.51878/educational.v6i2.10656

ACADEMIA: Jurnal Inovasi Riset Akademik
Vol. 6, No. 2, Maret-Mei 2026
e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

The exclusion criteria were:

a. studies not related to mathematics education;
b. studies that discussed technology in general without clear relevance to artificial intelligence or digital innovation;
c. studies that did not address critical thinking or related higher-order thinking dimensions;
d. conference papers, book chapters, reviews without sufficient relevance, editorials, and non-journal publications;
e. articles with incomplete bibliographic information or inaccessible full text.

4. Study Selection Procedure

a. The study selection process followed the PRISMA stages of identification, screening, eligibility, and inclusion. In the identification stage, several hundred records were initially retrieved from Scopus using the defined search terms. After applying the database filters, 35 articles remained.
b. In the screening stage, the titles, abstracts, and keywords of the 35 articles were examined to determine their relevance to the review topic. At this stage, studies that were clearly outside the focus of artificial intelligence, digital innovation, mathematics education, or critical thinking were excluded. In the eligibility stage, the full texts of the remaining articles were read carefully to assess whether they met all inclusion criteria and were sufficiently aligned with the purpose of the review.
c. Following the full-text assessment, 25 articles were selected for the final synthesis. These studies were considered the most relevant in addressing the intersection of artificial intelligence, digital innovation, mathematics education, and critical thinking.

5. Data Extraction

A data extraction form was used to systematically organize information from each selected article. The extracted data included the author(s) and year of publication, country or research context, research design or study type, participants or educational level, main topic or focus, the form of artificial intelligence or digital innovation discussed, mathematics education context, critical thinking dimension or related cognitive construct, and the main findings. The extracted data were organized into a review matrix to support subsequent analysis. This process enabled the review to identify both the general characteristics of the studies and their specific contributions to the research focus.

6. Data Analysis

The selected articles were analyzed using descriptive analysis and thematic synthesis. Descriptive analysis was used to summarize publication trends, study contexts, methodological approaches, and the major topics addressed in the literature. Thematic synthesis was then employed to identify recurring patterns across the studies, particularly in relation to the forms of artificial intelligence and digital innovation used in mathematics education, the role of these innovations in supporting critical thinking, the dominant pedagogical approaches associated with AI-supported mathematics learning, and the research gaps that remain in the field. The analysis was organized around the research questions, allowing the findings to be presented systematically and interpreted in relation to the broader development of mathematics education in the digital era.

7. Quality Assurance

To enhance the reliability of the study selection and data extraction process, the two authors independently reviewed the articles based on the predetermined inclusion and exclusion

https://doi.org/10.51878/educational.v6i2.10656

ACADEMIA: Jurnal Inovasi Riset Akademik
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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

criteria. Each author examined the titles, abstracts, and full texts of the selected studies and extracted relevant information using the same data extraction framework. Any differences in judgment were discussed until consensus was reached. This collaborative verification process was conducted to reduce individual bias and ensure that the final set of included studies and thematic categories were aligned with the research questions.

RESULTS AND DISCUSSION

It should be noted that not all selected studies focused exclusively on artificial intelligence. Some studies addressed digital innovation, computational thinking, technology-supported learning, inquiry-based learning, proof, reasoning, and critical thinking in mathematics education. These studies were included because they provided relevant conceptual or pedagogical connections to the broader discussion of AI and digital transformation in mathematics learning.

1. Study Selection

The study selection process followed the PRISMA framework. The initial search in the Scopus database yielded several hundred records related to artificial intelligence, digital innovation, mathematics education, and critical thinking. To improve relevance and consistency with the objectives of the review, the records were filtered by publication years (2020–2025), English language, open access status, subject area (Mathematics), and source type (Journal). After filtering, 35 articles remained for further screening.

The 35 articles were then screened based on their titles, abstracts, and keywords. Studies that did not sufficiently address mathematics education, did not clearly relate to artificial intelligence or digital innovation, or did not connect with critical thinking or related higher-order cognitive constructs were excluded. The remaining studies underwent full-text assessment to determine their eligibility for the final synthesis.

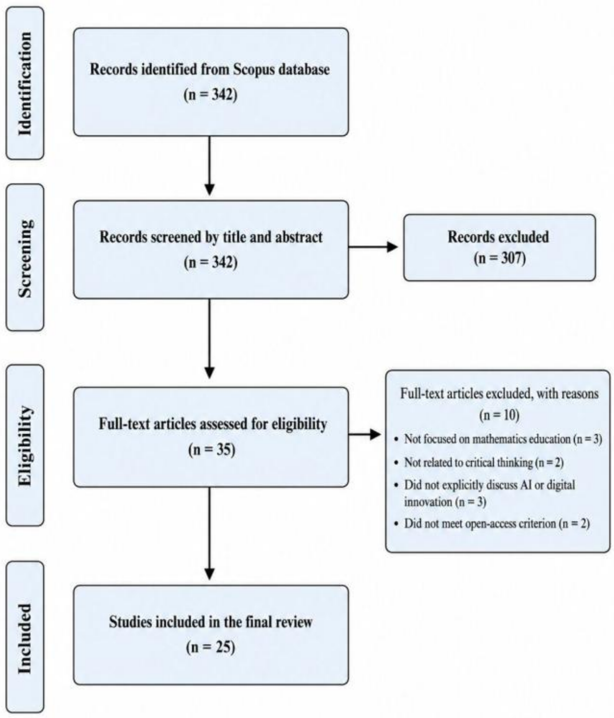

Figure 1. PRISMA's Diagram

https://doi.org/10.51878/educational.v6i2.10656

ACADEMIA: Jurnal Inovasi Riset Akademik
Vol. 6, No. 2, Maret-Mei 2026
e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

Following the full-text review, 25 articles were included in the final corpus of this systematic literature review, as they were considered the most relevant to the intersection of artificial intelligence, digital innovation, mathematics education, and critical thinking. The study selection process also showed that, although the broader literature on mathematics education and critical thinking is extensive, studies that explicitly integrate artificial intelligence and digital innovation remain relatively limited.

Although the final synthesis included 25 studies, these articles were considered sufficient and relevant for addressing the research questions because they were selected through a systematic screening process based on predetermined inclusion and exclusion criteria. The selected studies represented recent scholarly discussions on mathematics education, critical thinking, digital innovation, AI-supported learning, computational thinking, and technology-enhanced pedagogical design. Therefore, the purpose of this review was not to generalize all AI practices in mathematics education, but to synthesize the patterns, connections, and gaps emerging from the selected Scopus-indexed and open-access studies.

2. Characteristics of the Selected Studies

Table 1 presents the characteristics of the 25 selected studies. The reviewed articles were published between 2020 and 2025, with the highest concentration appearing in 2025, indicating growing recent attention to the intersection of mathematics education, critical thinking, and digital or AI-related innovation. Earlier studies published in 2020–2021 tended to provide broader conceptual or pedagogical foundations, whereas studies from 2023–2025 increasingly addressed more specific issues such as computational thinking, AI-supported problem solving, ChatGPT, critical mathematical thinking, and innovative classroom design.

In terms of geographical distribution, the studies originated from a range of countries, including Indonesia, the United States, the Netherlands, Australia, Germany, Israel, Latvia, Spain, Nepal, Japan, Slovenia, South Africa, Norway, Austria, and Sweden. Among these, Indonesia contributed the largest number of studies, suggesting strong regional interest in mathematics education innovation and critical thinking. This distribution also indicates that the topic has attracted international attention, although the focus and depth of AI integration vary across contexts.

Methodologically, the selected studies were diverse. The corpus was dominated by qualitative studies, conceptual papers, design-oriented studies, and classroom-based analyses, while a smaller number of studies employed quasi-experimental, mixed-methods, meta-analytic, and review-based approaches. This pattern suggests that the field is still in an exploratory and developmental stage, with many studies seeking to conceptualize, design, or pilot instructional innovations rather than rigorously test large-scale interventions.

The reviewed studies also covered a broad range of educational contexts, including early childhood, elementary school, secondary school, higher education, preservice teacher education, and adult education. However, a substantial proportion of the studies were situated in school mathematics and teacher education, reflecting a strong concern with how critical thinking can be fostered through classroom practice, pedagogical design, and teacher readiness.

Across the 25 studies, several recurring themes were identified, including critical thinking, critical mathematical thinking, mathematical proof, logical reasoning, problem solving, inquiry-based learning, realistic mathematics education, computational thinking, and the emerging role of artificial intelligence and ChatGPT in mathematics learning. Importantly, only a limited number of studies directly examined AI or generative AI in mathematics education. Most studies instead provided broader pedagogical, cognitive, or conceptual foundations that help explain the potential role of digital innovation in supporting critical

https://doi.org/10.51878/educational.v6i2.10656

ACADEMIA: Jurnal Inovasi Riset Akademik
Vol. 6, No. 2, Maret-Mei 2026
e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

thinking in mathematics education. These patterns provide the basis for the theoretical synthesis presented in the next section.

Table 1. Characteristics of the 25 Selected Studies

No	Author	Country	Research Design	Participant	Main Focus
1	Bohlmann & Benölken, (2020)	Germany	Conceptual/ analytical paper	Mathematics education discourse	Complex tasks, mathematical literacy, and 21st-century skills
2	Gal et al., (2020)	Israel	Survey/ conceptual paper	Adult education and vulnerable adults	Numeracy, critical numeracy, and vulnerability
3	Pavitola & Rieksta, (2025)	Latvia	Case study	Grade 9 students	Critical thinking in mathematical proof tasks
4	Jeong & González-Gómez, (2021)	Spain	Pre–post survey / classroom intervention	143 pre-service teachers	Flipped learning and attitudes toward mathematics learning
5	Pokhrel et al., (2024)	Nepal	Qualitative document analysis	School mathematics education context	Self-directed learning pedagogy in mathematics
6	Nichols, (2025)	Singapore	Commentary/conceptual article	Higher education context	Quantitative reasoning among mathematically literate students
7	Hattori et al., (2025)	Japan	Lesson design / classroom implementation study	Secondary mathematics classroom	Socially open-ended tasks and a rubric for critical thinking/social values
8	Nursyahidah et al., (2025)	Indonesia	Design Research	32 Grade 8 students	Learning trajectory on data distribution through PMRI
9	Kwon & Lee, (2025)	United States	Meta-analysis	8 studies; 13 effect sizes	Effect of STEM project-based learning on creativity
10	Bronkhorst et al., (2020)	Netherlands	Qualitative interview study	4 secondary students (ages 16–17)	Logical reasoning in formal and everyday reasoning tasks
11	Sari et al., (2025)	Indonesia	Qualitative study	30 prospective mathematics teachers	Iceberg design, RME, mathematical literacy, and SDGs
12	Utami & Pramudiani, (2024)	Indonesia	Descriptive qualitative / educational ethnography	30 Grade IV elementary students	Critical thinking in geometry through Betawi cultural context
13	Doz et al., (2025)	Slovenia	Quasi-experimental/comparative study	258 Grade 9 students	Inquiry-based learning and mathematics outcomes across Gagné's taxonomy

https://doi.org/10.51878/educational.v6i2.10656

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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
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No	Author	Country	Research Design	Participant	Main Focus
14	Isran et al., (2025)	Indonesia	Exploratory qualitative case study	Lecturers, students, and assignment documents in higher education	Lecturers, students, and assignment documents in higher education
15	McGalliard & Otten, (2025)	United States	Analytical/comparative study	AI systems (e.g., ChatGPT, Gemini) and educator responses	AI responses to challenging mathematics problems
16	Ncube & Luneta, (2025)	South Africa	Sequential explanatory mixed methods	35 Grade 11 learners; 6 interviewed	Concept-based instruction and conceptual understanding in mathematics
17	Kacerja & Julie, (2023)	Norway	Qualitative discussion analysis	Preservice mathematics teachers	Values, BMI, and critical mathematics education
18	Monteleone et al., (2023)	Australia	Conceptual + task-based interview study	16 young students (aged 5–6)	Conceptualising critical mathematical thinking in early years
19	Yunianto et al., (2024)	Austria	Education Design Research	Purposively selected postgraduate students	ChatGPT, GeoGebra, and computational thinking in geometry
20	Trisnani et al., (2024)	Indonesia	Qualitative survey study	114 elementary school mathematics teachers	Challenges in integrating critical thinking into mathematics classrooms
21	Pepin et al., (2025)	Netherlands	Scoping survey/review	Literature-based study	ChatGPT in mathematics education: benefits, challenges, and implications
22	Lestari et al., (2023)	Indonesia	Research and Development (ADDIE)	Students and expert validators	RME-based worksheets for improving students' critical thinking
23	Azmi et al., (2025)	Indonesia	Ethnographic / instructional framework study	Junior high school geometry context; local experts and documents	Computational thinking through Rumoh Aceh ethnomathematics
24	Andersson & Register, (2023)	Sweden	Interview study	Preservice mathematics teachers	Ethical reasoning in big data and access to data

https://doi.org/10.51878/educational.v6i2.10656

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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

No	Author	Country	Research Design	Participant	Main Focus
25	Geiger et al., (2023)	Australia	Survey/conceptual article	School, university, and adult education contexts	Connections between citizenship education and mathematics education

3. Theoretical Synthesis of Artificial Intelligence and Digital Innovation in Mathematics Education for Critical Thinking

The theoretical synthesis of the selected studies indicates that the literature is organized around several interconnected constructs rather than a single dominant framework. Based on the 25 reviewed articles, six major theoretical clusters were identified: (1) critical thinking as a core outcome of mathematics education, (2) critical mathematical thinking as a discipline-specific form of critical reasoning, (3) pedagogical design as a mediator of critical thinking development, (4) computational thinking as a bridge to AI-related learning, (5) artificial intelligence and digital innovation as emerging instructional resources, and (6) the social, cultural, and ethical dimensions of mathematics education.

The first cluster positions critical thinking as a central goal of mathematics education. Several studies emphasize that mathematics learning should not be limited to procedural accuracy, but should also develop students' ability to analyze, evaluate, justify, infer, and make reasoned decisions. In this view, critical thinking is expressed through activities such as interpreting mathematical situations, questioning assumptions, evaluating strategies, and constructing arguments. This cluster establishes critical thinking as the primary educational outcome against which other innovations, including AI and digital innovation, should be assessed.

The second cluster concerns critical mathematical thinking, which extends general critical thinking into the specific domain of mathematics. The reviewed studies indicate that critical thinking in mathematics is not merely a form of generic reflection, but involves discipline-specific forms of reasoning such as proof construction, logical justification, symbolic interpretation, and the evaluation of mathematical validity. This distinction is important because it clarifies that the contribution of AI in mathematics education should be assessed not only in terms of efficiency or engagement, but also in relation to the quality of students' mathematical reasoning.

The third cluster highlights pedagogical design as a crucial mediator in the development of critical thinking. Many of the selected studies focused on inquiry-based learning, realistic mathematics education, concept-based instruction, complex tasks, and other student-centered approaches. These studies consistently suggest that critical thinking does not emerge automatically from technology use; instead, it depends on how learning is designed. From this perspective, digital innovation becomes meaningful only when embedded in pedagogical structures that encourage questioning, exploration, argumentation, and reflective problem solving.

The fourth cluster identifies computational thinking as an important conceptual bridge between mathematics education and artificial intelligence. Studies in this cluster emphasize pattern recognition, decomposition, algorithmic reasoning, and logical structuring as key processes that connect mathematical activity with AI-related learning environments. Computational thinking therefore functions as a transitional construct, linking traditional mathematical reasoning with the structured and process-oriented thinking that is increasingly relevant in digitally mediated and AI-supported learning contexts.

https://doi.org/10.51878/educational.v6i2.10656

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The fifth cluster directly addresses artificial intelligence and digital innovation in mathematics education. Although only a small number of studies explicitly examined AI, ChatGPT, or AI-assisted problem solving, these studies show that AI has begun to enter mathematics education as a tool for generating responses, supporting problem solving, facilitating interaction, and expanding access to digital learning resources. At the same time, the literature suggests that AI in mathematics education remains an emerging field. Its role is still being explored, and its educational value depends heavily on task design, teacher mediation, and the extent to which AI use supports rather than replaces genuine mathematical reasoning.

The sixth cluster emphasizes the social, cultural, and ethical dimensions of mathematics education. A number of studies highlight the role of culture, citizenship, values, numeracy, and ethical reasoning in shaping meaningful mathematics learning. This cluster broadens the understanding of critical thinking by showing that mathematical reasoning also involves interpreting data, evaluating social issues, and making informed judgments in real-world contexts. In relation to digital innovation, this perspective is especially important because it reminds educators that AI integration must also be considered in terms of ethics, responsibility, and social relevance.

Overall, the theoretical synthesis shows that the literature on artificial intelligence and digital innovation in mathematics education for critical thinking remains fragmented but promising. Direct AI-based studies are still limited, while a much larger body of literature provides conceptual and pedagogical support through themes such as critical mathematical thinking, inquiry, computational thinking, and contextualized mathematics learning. This suggests that the field is currently in a transitional phase, in which digital innovation is becoming increasingly visible, but its integration into mathematics education for critical thinking still requires stronger empirical and theoretical consolidation. These six clusters also provide the conceptual basis for interpreting the main findings of the reviewed studies.

Based on the 25 selected studies, the literature can be synthesized into six major theoretical clusters that explain how artificial intelligence and digital innovation are positioned in mathematics education for critical thinking.

Table 2. Theoretical Synthesis of the Selected Studies

No	Theoretical Cluster	Core Concepts	Representative Studies	Theoretical Contribution to the Review
1	Critical thinking as a core outcome of mathematics education	Analysis, evaluation, justification, inference, reasoned decision-making	Pavitola & Rieksta, (2025); Hattori et al., (2025); Utami & Pramudiani, (2024); Lestari et al., (2023)	Establishes critical thinking as a central educational outcome in mathematics, against which the contribution of AI and digital innovation should be assessed.
2	Critical mathematical thinking as a discipline-specific form of reasoning	Mathematical proof, symbolic interpretation, logical justification, evaluation of validity	Monteleone et al., (2023); Isran et al., (2025); Bronkhorst et al., (2020); Pavitola & Rieksta, (2025)	Clarifies that critical thinking in mathematics is not merely general reflection, but involves discipline-specific reasoning processes tied to mathematical validity and argumentation.
3	Pedagogical design as a mediator of	Inquiry-based learning, realistic mathematics	Bohlmann & Benölken, (2020); Doz et al., (2025);	Shows that critical thinking does not emerge automatically from

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No	Theoretical Cluster	Core Concepts	Representative Studies	Theoretical Contribution to the Review
	critical thinking development	education, concept-based instruction, complex tasks, student-centered learning	Ncube & Luneta, (2025); Jeong & González-Gómez, (2021); Nursyahidah et al., (2025)	technology use, but depends on carefully designed pedagogical structures and meaningful learning experiences.
4	Computational thinking as a bridge to AI-related learning	Decomposition, pattern recognition, algorithmic reasoning, logical structuring, process-oriented thinking	Yunianto et al., (2024); Azmi et al., (2025)	Positions computational thinking as a conceptual bridge connecting mathematical reasoning with AI-supported and digitally mediated learning environments.
5	Artificial intelligence and digital innovation as emerging instructional resources	ChatGPT, AI-generated responses, AI-assisted problem solving, digital learning resources, interaction support	McGalliard & Otten, (2025); Pepin et al., (2025); Yunianto et al., (2024)	Indicates that AI and digital innovation are emerging as tools for supporting problem solving, interaction, and access, while their educational value depends on pedagogical design and teacher mediation.
6	Social, cultural, and ethical dimensions of mathematics education	Citizenship, values, numeracy, ethical reasoning, cultural context, socially meaningful mathematics	Gal et al., (2020); Kacerja & Julie, (2023); Geiger et al., (2023); Andersson & Register, (2023); Utami & Pramudiani, (2024)	Broadens the review by showing that critical thinking in mathematics also involves social interpretation, ethical judgment, and culturally meaningful engagement, all of which are relevant to AI integration.

As shown in Table 2, the reviewed studies do not converge around a single theoretical framework. Instead, they form an interconnected set of constructs linking critical thinking, critical mathematical thinking, pedagogical design, computational thinking, emerging AI-supported learning, and the broader social, cultural, and ethical dimensions of mathematics education.

4. Main Findings

The synthesis of the 25 selected studies reveals that the intersection of artificial intelligence, digital innovation, mathematics education, and critical thinking is characterized by both emerging technological developments and a broader pedagogical foundation. Although only a limited number of studies explicitly addressed artificial intelligence, the reviewed literature collectively provides important insights into how digital innovation can support critical thinking in mathematics education.

One major finding concerns the forms of artificial intelligence and digital innovation reported in the literature. Direct references to AI were found mainly in studies discussing ChatGPT, AI-generated responses to mathematical problems, and broader reviews of generative AI in mathematics education. In addition, several studies examined digital innovation more broadly through GeoGebra-based tasks, flipped learning, digital worksheet design, and pedagogical approaches that integrate technology-supported reasoning and

https://doi.org/10.51878/educational.v6i2.10656

ACADEMIA: Jurnal Inovasi Riset Akademik
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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

exploration. This suggests that digital innovation in mathematics education is currently broader than AI alone and that AI should be understood as one part of a wider transformation of digital learning environments.

A second major finding is that the reviewed studies consistently positioned critical thinking as a key outcome of mathematics education. Across the literature, critical thinking was associated with students' ability to analyze mathematical situations, justify procedures, evaluate strategies, construct arguments, solve non-routine problems, and reflect on the validity of mathematical reasoning. In many cases, the studies did not use artificial intelligence directly, yet they contributed important theoretical and pedagogical foundations showing what kinds of classroom activities are most likely to foster critical thinking. These activities included mathematical proof, problem solving, inquiry-based learning, realistic mathematics education, concept-based instruction, and complex task design.

A third important finding is that AI and digital innovation appear to support critical thinking only when combined with strong pedagogical design. The literature does not suggest that technology automatically improves students' reasoning. Rather, its contribution depends on how it is embedded in instruction. For example, studies involving ChatGPT or AI-generated mathematical responses indicate that AI may help generate explanations, alternative solution paths, or immediate responses to mathematical tasks. However, these benefits become educationally meaningful only when learners are encouraged to question, verify, interpret, and evaluate the outputs critically. In this sense, digital innovation functions best as a supportive resource, not as a replacement for reasoning.

Another major finding is the central role of computational thinking as a bridge between mathematics education and AI-related learning. Studies involving geometry, GeoGebra, and computational thinking indicate that processes such as decomposition, pattern recognition, algorithmic reasoning, and structured problem solving are highly relevant to digitally supported mathematics learning. These processes also overlap with critical thinking because they require students to examine relationships, justify choices, and evaluate logical steps. Thus, computational thinking appears to be an important mediating construct that connects mathematical reasoning with digital innovation.

The review also shows that teacher mediation remains essential. Several studies emphasized the challenges faced by teachers in integrating critical thinking into classroom practice, while AI-related studies highlighted the need for human oversight in interpreting and validating AI-generated outputs. This indicates that the educational value of AI depends not only on the technology itself, but also on teachers' ability to design meaningful tasks, guide students' reflection, and prevent superficial dependence on automated responses. Therefore, the contribution of AI to critical thinking is inseparable from the pedagogical competence of teachers.

In addition, the review identified the importance of social, cultural, and ethical dimensions in mathematics education. Some studies linked critical thinking to citizenship, numeracy, values, cultural context, and ethical reasoning. These findings suggest that critical thinking in mathematics education is not limited to formal symbolic reasoning but also involves interpreting data, assessing real-world issues, and making informed judgments. From this perspective, digital innovation and AI in mathematics education should be evaluated not only in terms of technical efficiency, but also in terms of their social meaning, ethical implications, and relevance to learners' lived experiences.

Overall, the main findings suggest that the literature is currently stronger in explaining the pedagogical and conceptual foundations of critical thinking in mathematics education than

https://doi.org/10.51878/educational.v6i2.10656

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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
Online Journal System: https://jurnalp4i.com/index.php/academia

in providing direct empirical evidence on the effects of artificial intelligence. AI-related studies are still relatively few, but they indicate growing interest in the role of generative AI, digital platforms, and intelligent support systems in mathematical learning. The available evidence points to a promising but still developing field, in which digital innovation has clear potential to support critical thinking, provided that it is integrated through thoughtful pedagogy, disciplinary reasoning, and teacher guidance.

Table 3. Summary of the Main Findings of the Reviewed Studies

No	Main Finding Theme	Summary of Findings	Representative Studies	Implication for the Review
1	Forms of artificial intelligence and digital innovation	The reviewed studies show that AI-related innovation in mathematics education mainly appears through ChatGPT, AI-generated mathematical responses, AI-assisted problem solving, GeoGebra-supported tasks, digital worksheets, and other technology-enhanced learning environments.	McGalliard & Otten, (2025); Yunianto et al., (2024); Pepin et al., (2025); Jeong & González-Gómez, (2021); Lestari et al., (2023)	Indicates that digital innovation in mathematics education is broader than AI alone, and that AI should be understood as part of a wider digital transformation in teaching and learning.
2	Critical thinking as a key outcome of mathematics education	Across the studies, critical thinking is consistently associated with analysis, justification, evaluation of strategies, argument construction, non-routine problem solving, and reflection on mathematical validity.	Pavitola & Rieksta, (2025); Isran et al., (2025); Utami & Pramudiani, (2024); Hattori et al., (2025); Lestari et al., (2023)	Confirms that critical thinking is a central outcome in mathematics education and an appropriate lens for examining the role of AI and digital innovation.
3	Pedagogical design determines the effectiveness of AI and digital innovation	Technology does not automatically improve reasoning. Its contribution depends on how it is embedded in inquiry, realistic mathematics education, concept-based instruction, proof, problem solving, and other well-designed learning environments.	Bohlmann & Benölken, (2020); Doz et al., (2025); Ncube & Luneta, 2025); Nursyahidah et al., (2025); Jeong & González-Gómez, (2021)	Shows that pedagogical design is the main condition under which AI and digital innovation can meaningfully support critical thinking.
4	Computational thinking as a mediating construct	Computational thinking emerges as an important bridge linking mathematical reasoning with AI-related learning through decomposition, pattern recognition, algorithmic reasoning, and logical structuring.	Yunianto et al., (2024); Azmi et al., (2025)	Suggests that computational thinking provides a conceptual pathway for understanding how AI can be integrated into mathematics education.
5	Teacher mediation remains essential	The reviewed studies highlight that teachers play a central role in guiding reflection, evaluating AI-generated outputs,	Trisnani et al., (2024); McGalliard & Otten, (2025);	ndicates that the educational value of AI depends not only on the tool itself, but also on

https://doi.org/10.51878/educational.v6i2.10656

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No	Main Finding Theme	Summary of Findings	Representative Studies	Implication for the Review
		preventing superficial dependence on automated responses, and maintaining meaningful mathematical reasoning.	Pepin et al., (2025)	teacher readiness, classroom orchestration, and pedagogical judgment.
6	Social, cultural, and ethical dimensions broaden the meaning of critical thinking	A number of studies connect mathematics education with citizenship, values, numeracy, cultural context, and ethical reasoning, showing that critical thinking also involves interpreting data, evaluating social issues, and making informed judgments.	Gal et al., (2020); Kacerja & Julie, (2023); Geiger et al., (2023); Andersson & Register, (2023); Utami & Pramudiani, (2024)	Expands the review beyond formal reasoning by showing that AI and digital innovation in mathematics education should also be considered in relation to ethics, responsibility, and social relevance
7	Direct AI-based evidence is still limited	Although interest in AI is growing, only a small proportion of the reviewed studies directly investigate AI or generative AI in mathematics education, while most studies provide broader pedagogical or conceptual support.	McGalliard & Otten, (2025); Pepin et al., (2025); Yunianto et al., (2024)	Reveals that the field is still emerging and that stronger empirical evidence is needed to clarify the role of AI in enhancing critical thinking.

As shown in Table 3, the reviewed studies suggest that the field is currently stronger in its pedagogical and conceptual foundations than in direct empirical evidence on AI. Nevertheless, the available studies indicate that AI and digital innovation have considerable potential to support critical thinking when integrated through meaningful pedagogical design, teacher mediation, and mathematically rigorous tasks.

5. Research Gaps and Future Directions

The review identifies several important research gaps in the literature on artificial intelligence and digital innovation in mathematics education for critical thinking. These gaps indicate that, although the topic is receiving increasing attention, the field remains conceptually and empirically underdeveloped. Based on the synthesis of the selected studies, several research gaps were identified regarding the integration of artificial intelligence and digital innovation in mathematics education for critical thinking. These gaps are summarized in Table 4.

Table 4. Research Gaps and Future Directions in Artificial Intelligence and Digital Innovation in Mathematics Education for Critical Thinking

No	Research Gap	Description of the Gap	Future Direction
1	Limited number of direct AI-based studies	Only a small proportion of the reviewed studies explicitly examined artificial intelligence, generative AI, or ChatGPT in mathematics education, while most studies focused on broader pedagogical or conceptual themes.	Future studies should conduct more direct investigations of AI-supported mathematics learning across different educational levels and contexts.
2	Lack of strong empirical evidence	Existing AI-related studies are largely exploratory, conceptual,	More empirical, intervention-based, and mixed-methods studies are

https://doi.org/10.51878/educational.v6i2.10656

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e-ISSN: 2807-1808 | p-ISSN: 2807-2294
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No	Research Gap	Description of the Gap	Future Direction
		analytical, or review-based, with limited large-scale classroom interventions or experimental evidence.	needed to examine the actual effects of AI on students' critical thinking in mathematics education.
3	Limited conceptual clarity of digital innovation	The reviewed literature uses the term digital innovation in various ways, including AI tools, digital platforms, GeoGebra-supported learning, flipped classrooms, and digital worksheets, without consistent conceptual boundaries.	Future research should develop clearer theoretical frameworks that distinguish general educational technology, digital pedagogy, and AI-driven innovation in mathematics education.
4	Weak integration between AI and discipline-specific mathematical reasoning	Many studies on critical thinking in mathematics focus on proof, reasoning, conceptual understanding, and problem solving without involving AI, while AI-related studies often emphasize tool use more than mathematical depth.	Future studies should examine how AI can support critical mathematical thinking, especially in proof, justification, argumentation, and evaluation of mathematical validity.
5	Insufficient attention to teacher readiness and classroom implementation	The literature highlights teacher challenges, but still offers limited evidence on how teachers design AI-supported tasks, evaluate AI-generated mathematical content, and scaffold students' critical engagement.	More research is needed on teacher professional development, classroom orchestration, and pedagogical models for integrating AI responsibly into mathematics instruction.
6	Limited focus on specific mathematics domains	Current studies often discuss AI or innovation at a general level, with fewer studies targeting specific mathematical domains such as geometry, algebra, proof, statistics, or mathematical modeling.	Future research should investigate domain-specific applications of AI to determine where and how it can most effectively support critical thinking in mathematics.
7	Scarcity of ethical, cultural, and contextual perspectives in AI-supported mathematics education	Although some reviewed studies address ethics, culture, citizenship, and values, these dimensions are rarely connected directly to AI integration in mathematics classrooms.	Future studies should explore fairness, bias, data ethics, cultural relevance, access, and educational equity in AI-supported mathematics learning.
8	Limited longitudinal and developmental evidence	Most studies provide cross-sectional or short-term insights, making it difficult to determine how AI-supported mathematics learning influences critical thinking over time.	Longitudinal studies are needed to examine the sustained impact of AI and digital innovation on students' critical thinking development.
9	Fragmentation of the field	The literature remains distributed across separate	Future research should build more integrative models that connect these

https://doi.org/10.51878/educational.v6i2.10656

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No	Research Gap	Description of the Gap	Future Direction
		traditions such as critical thinking, computational thinking, mathematical proof, inquiry, digital innovation, and AI, with limited integrative synthesis.	strands into a coherent framework for mathematics education in the digital era.

The research gaps presented in Table 4 indicate that the existing literature has not yet fully explained how artificial intelligence and digital innovation can be systematically integrated into mathematics learning to foster critical thinking. Although the reviewed studies highlight the potential of digital tools, AI-supported learning, and innovative pedagogical approaches, most of them remain fragmented in terms of theoretical grounding, empirical validation, and classroom implementation. In particular, limited attention has been given to how AI-based learning environments influence students' mathematical reasoning, argumentation, problem-solving processes, and critical evaluation of mathematical ideas. Therefore, future studies need to move beyond general discussions of digital innovation and provide stronger empirical evidence on how AI can be pedagogically designed, implemented, and evaluated in mathematics classrooms.

Discussion

The findings of this review indicate that research on artificial intelligence and digital innovation in mathematics education is still developing unevenly. Previous studies have emphasized critical thinking as an important outcome of mathematics learning, particularly in relation to reasoning, proof, problem solving, and argumentation. However, the present review shows that the connection between AI-supported learning and critical thinking in mathematics has not yet been fully established through strong empirical evidence. This suggests that AI should not be viewed merely as a technological tool, but as part of a broader pedagogical system that requires meaningful mathematical tasks, teacher guidance, and opportunities for students to analyze, justify, and evaluate mathematical ideas.

Theoretically, this review contributes by positioning AI and digital innovation within the broader relationship between mathematical reasoning, computational thinking, and critical thinking. The reviewed studies suggest that digital tools may support critical thinking when they encourage students to decompose problems, recognize patterns, compare solution strategies, evaluate arguments, and reflect on mathematical validity. Therefore, the theoretical contribution of this review lies in showing that the value of AI in mathematics education depends not only on automation or feedback, but also on its ability to support disciplinary forms of thinking that are central to mathematics.

The specific contribution of this review is that it consolidates fragmented studies on AI, digital innovation, computational thinking, and critical thinking into a more coherent synthesis for mathematics education. Rather than claiming that AI directly improves students' critical thinking, this review highlights that AI and digital innovation have potential when they are integrated with appropriate pedagogical design. This finding is important for mathematics educators, curriculum designers, and future researchers because it emphasizes the need to design AI-supported learning environments that promote reasoning, justification, reflection, and critical evaluation, rather than simply providing fast answers or procedural assistance.

TheoreticalContribution

This review provides a theoretical contribution by consolidating fragmented research on artificial intelligence, digital innovation, computational thinking, and critical thinking within

https://doi.org/10.51878/educational.v6i2.10656

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the specific context of mathematics education. The findings show that AI should not be understood merely as a technological tool for providing quick answers or automated feedback, but as part of a broader pedagogical and cognitive ecosystem that can support mathematical reasoning when used appropriately. By synthesizing the selected studies, this review clarifies that the contribution of AI to critical thinking in mathematics depends on its ability to support discipline-specific processes such as analysing mathematical situations, evaluating solution strategies, constructing arguments, interpreting representations, and justifying conclusions.

This review also contributes by positioning computational thinking as a conceptual bridge between traditional mathematical reasoning and AI-supported learning. Processes such as decomposition, pattern recognition, algorithmic reasoning, and logical structuring help explain how digital innovation may support critical thinking in mathematics education. Therefore, this study offers a conceptual synthesis that connects AI, digital innovation, computational thinking, and critical mathematical thinking into a more coherent framework for future research.

Practical Implication

Practically, the findings suggest that the integration of AI and digital innovation in mathematics education should be guided by clear pedagogical purposes. Teachers should not use AI merely as a tool for generating answers, simplifying procedures, or accelerating task completion. Instead, AI-supported learning should be designed to encourage students to question mathematical outputs, compare alternative solution strategies, evaluate the validity of explanations, and justify their reasoning.

For mathematics teachers, this implies the need to design tasks that require students to interact critically with digital tools and AI-generated responses. For curriculum designers, the findings highlight the importance of embedding AI literacy, computational thinking, and mathematical reasoning into learning activities. For future researchers, this review indicates the need for more empirical studies that examine how AI-supported mathematics learning affects students' critical thinking, especially in classroom contexts where teacher mediation, task design, and students' reasoning processes can be observed directly.

CONCLUSION

This systematic literature review examined the role of artificial intelligence and digital innovation in mathematics education for critical thinking. Based on the analysis of 25 selected studies, the review shows that critical thinking has become a central objective of mathematics education, particularly through approaches such as mathematical proof, inquiry-based learning, realistic mathematics education, complex tasks, and concept-based instruction. However, studies that directly investigate artificial intelligence in relation to critical thinking in mathematics education remain limited.

The findings indicate that artificial intelligence and digital innovation have considerable potential to support critical thinking in mathematics education through interactive learning environments, AI-assisted problem solving, computational thinking activities, and digitally mediated instructional resources. Nevertheless, this potential is not automatic. Its educational value depends on meaningful pedagogical design, the quality of mathematical tasks, and the ability of teachers to guide students in questioning, evaluating, and interpreting digital outputs critically.

This review also shows that the current literature is stronger in providing pedagogical and conceptual foundations than in offering direct empirical evidence on the effects of AI on critical thinking in mathematics learning. In addition, digital innovation in mathematics

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education should be understood broadly, not only as the use of AI tools, but also as the transformation of learning through interactive, adaptive, and context-sensitive digital environments.

Overall, this review contributes to the growing discourse on digital educational innovation by showing that the future integration of artificial intelligence in mathematics education should prioritize critical mathematical reasoning rather than mere task completion. Future studies are encouraged to provide stronger empirical evidence, develop clearer conceptual frameworks, and explore how AI can be integrated responsibly, ethically, and effectively across diverse mathematics learning contexts.

Implications

The findings of this review imply that the integration of artificial intelligence and digital innovation in mathematics education should be approached pedagogically rather than merely technologically. AI-based tools and digital environments are most valuable when they are embedded in learning designs that promote reasoning, justification, reflection, and the evaluation of mathematical ideas. For educational practice, this means that teachers should not use AI simply to increase efficiency or provide quick answers, but to create opportunities for students to engage critically with mathematical tasks and digital outputs. For curriculum development, the review suggests the need to align digital innovation with the broader goal of fostering critical mathematical thinking in meaningful and context-sensitive ways.

Research Contribution

This review contributes to the literature by synthesizing studies at the intersection of artificial intelligence, digital innovation, mathematics education, and critical thinking. It highlights that the field is currently supported more strongly by pedagogical and conceptual foundations than by direct AI-based empirical evidence. In addition, this review identifies six major theoretical clusters that help explain how AI and digital innovation are positioned within mathematics education for critical thinking. By doing so, the study provides a clearer conceptual map for future research and offers a more integrated understanding of the opportunities and limitations of AI-supported mathematics learning.

Limitations

This review has several limitations. First, the literature search was limited to the Scopus database, which may have excluded relevant studies indexed in other databases. Second, the review included only articles published in English, open access, within the Mathematics subject area, and in journal format, which may have narrowed the range of potentially relevant literature. Third, although the review focused on artificial intelligence and digital innovation, only a small proportion of the selected studies directly examined AI in mathematics education, which limits the strength of conclusions regarding AI-specific effects. Therefore, the findings should be interpreted as a synthesis of an emerging field rather than as definitive evidence of the impact of AI on critical thinking in mathematics learning.

Suggestions for Future Research

Future research should conduct more empirical and intervention-based studies to examine the effects of AI-supported mathematics learning on students' critical thinking across different educational levels and mathematical domains. More attention is also needed to develop clearer theoretical distinctions between general digital technology, digital pedagogy, and AI-driven innovation in mathematics education. In addition, future studies should investigate how AI can support discipline-specific mathematical reasoning, including proof, justification, argumentation, and problem solving. Research on teacher readiness, classroom implementation, and ethical issues such as fairness, access, cultural relevance, and responsible

https://doi.org/10.51878/educational.v6i2.10656

AI use is also needed to ensure that digital innovation contributes meaningfully and equitably to mathematics education

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