

## The Effect of Artificial Intelligence–Based Learning on Students’ Mathematical Thinking in Secondary Education

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### Abstract

The rapid integration of artificial intelligence (AI) in secondary education has transformed mathematics learning through adaptive and personalized instructional support. This study investigates the effect of AI-based learning on students’ mathematical thinking by comparing AI performance with student performance across different mathematical problem types. A quantitative experimental–comparative design with a pretest–posttest control group approach was employed, involving 120 secondary school students assigned to experimental and control groups. The experimental group engaged in AI-assisted learning using ChatGPT, while the control group received conventional instruction. Mathematical thinking was assessed using accuracy, response time, and consistency across multiple-choice, short-answer, and essay tasks, with digital literacy examined as a mediating variable. The results reveal significant performance differences, with AI demonstrating higher accuracy, faster response times, and greater consistency, particularly on essay-based problems requiring higher-order reasoning. Mediation analysis further indicates that digital literacy significantly influences students’ mathematical thinking and partially mediates the relationship between AI interaction and learning outcomes. These findings suggest that AI-based learning can effectively enhance mathematical thinking when integrated with strong digital literacy development, highlighting implications for adaptive pedagogy and future longitudinal research.

**Keywords:** Artificial Intelligence; AI-Based Learning; Mathematical Thinking; Secondary Education; Mathematics Education

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## 1. INTRODUCTION

The advancement of Artificial Intelligence (AI) has led to a significant transformation in education, particularly in secondary school mathematics learning. AI enables the creation of adaptive, personalized, and flexible learning environments through intelligent tutoring systems, adaptive learning platforms, chatbots, and interactive media (Chen & Xie, 2020; Chau et al., 2025; Ali & Wardat, 2024). The integration of AI allows educators to adjust instructional strategies, provide immediate feedback, and automate administrative tasks, while simultaneously enhancing student motivation and engagement. Beyond serving as a

mere instructional tool, AI has the potential to act as a mediator in fostering critical and creative thinking skills, shifting mathematics education from a procedural focus to one that emphasizes analysis, strategic problem solving, and innovation (Kasneci et al., 2023; Chiu et al., 2022).

Despite the substantial potential of AI, empirical studies indicate that secondary school students' mathematical problem-solving skills remain limited, particularly when tackling non-routine problems requiring logical reasoning, conceptual understanding, and structured thinking strategies (Hidayatullah et al., 2024; Fatqurhohman & Firdaus, 2024). Teacher-centered instructional approaches and limited opportunities for student exploration constrain active engagement and the development of higher-order thinking skills. Moreover, AI digital literacy, a critical competency in the Society 5.0 era, has yet to be fully integrated into the curriculum, leaving many students unable to critically evaluate AI-generated information or utilize it for creative problem-solving purposes (Sidik et al., 2025; Naamati-Schneider & Alt, 2024). These challenges underscore the need for a holistic approach that combines technological innovation, adaptive pedagogical strategies, and digital literacy to enhance students' mathematical thinking skills.

Previous research has primarily focused on teachers' perceptions, the design of adaptive learning systems, or the general impact of AI on learning outcomes (Chen et al., 2020; Lee et al., 2022; Ifenthaler et al., 2024). Studies that directly compare AI's performance in solving mathematical problems with that of secondary school students remain scarce. Furthermore, analyses of AI performance across different question types, such as multiple-choice, short-answer, and essay questions, and performance indicators, including accuracy, speed, and consistency, are rarely examined in depth (Kasneci et al., 2023; Arvin et al., 2023; Peng et al., 2023). The emergence of generative AI, such as ChatGPT, offers opportunities for adaptive, interactive learning; however, the majority of research has focused on higher education contexts, leaving empirical evidence at the secondary school level limited. This gap highlights the necessity for a comprehensive investigation into the effectiveness of AI in developing students' mathematical thinking, accounting for digital literacy, problem type variation, and cognitive mechanisms.

This study occupies a unique position by assessing AI not only as a learning aid but as a mathematical problem-solving agent directly compared to students' performance. The novelty of the research lies in its comparative approach, evaluating AI and students based on three primary indicators: accuracy, speed, and reliability, across multiple question types, including multiple-choice, short-answer, and essay formats (Chau et al., 2025; Hidayatullah et al., 2024). Generative AI, specifically ChatGPT, is positioned as an interactive, adaptive learning medium that facilitates exploration of problem-solving strategies and provides a meaningful learning experience. This approach is framed within social constructivism and cognitive load theory, where AI functions as digital scaffolding to support reflective and critical thinking, in contrast to traditional workbook-based instruction (Chiu & Chai, 2020; Lin, 2022).

The urgency of this research is reinforced by the demands of 21st-century education, which emphasizes AI digital literacy, creative thinking, and complex problem-solving skills. Through effective integration of AI, students can develop analytical, creative, and

metacognitive skills while gaining insight into the ethical and productive use of technology (Sidik et al., 2025; Naamati-Schneider & Alt, 2024; Lee et al., 2022). The study also holds practical significance for teachers, schools, and policymakers by providing empirical evidence to inform the design of adaptive, personalized mathematics instruction aligned with 21st-century competencies. Proper implementation can reduce learning disparities, enhance student engagement, and prepare learners to navigate increasingly complex digital environments.

The present research adopts a quantitative experimental-comparative approach, in which AI, including ChatGPT, and secondary school students are tested on various types of mathematics problems: multiple-choice, short-answer, and essay questions, measuring accuracy, speed, and consistency. Additionally, the study investigates AI digital literacy as a mediating variable influencing students' mathematical thinking abilities. This design enables not only an objective assessment of AI effectiveness but also an exploration of the cognitive mechanisms mediating the interaction between technology, digital literacy, and the development of critical, reflective, and creative thinking skills. The findings are expected to offer both theoretical and practical contributions to the development of adaptive, personalized, and innovative mathematics pedagogy in the digital era (Fatqurhohman et al., 2025; Sarwoedi et al., 2025).

## **2. METHOD**

### **2.1. Research Design**

This study employed a quantitative experimental-comparative design using a pretest-posttest control group approach to evaluate the effectiveness of Artificial Intelligence (AI), specifically ChatGPT, in supporting secondary school mathematics learning. This design was selected to allow a systematic comparison between AI performance and that of secondary school students across multiple indicators, including accuracy, response speed, and consistency in solving various types of mathematical problems, such as multiple-choice, short-answer, and essay questions. The approach also facilitates the quantitative assessment of the relationship between AI digital literacy and students' mathematical thinking skills (Chau et al., 2025; Hidayatullah et al., 2024).

### **2.2. Participants**

The study involved 120 secondary school students, selected through stratified random sampling from three schools in Jember. Inclusion criteria included students from grades 10–12 who actively participated in regular mathematics classes and had basic access to digital devices. Participants were randomly assigned to either an experimental group, which utilized AI in learning activities, or a control group, which followed conventional textbook-based instruction. To maintain objectivity, participant identities were anonymized, and all procedures adhered to ethical guidelines for educational research (Sidik et al., 2025; Naamati-Schneider & Alt, 2024).

### 2.3. Variables and Operational

The study examined three types of variables: independent, dependent, and mediating. The independent variable was the use of AI (ChatGPT) in mathematics learning, while the dependent variable was students' mathematical thinking ability. AI digital literacy served as a mediating variable influencing the relationship between AI usage and mathematical thinking performance.

**Table 1.** Operationalization of Research Variables

Variable	Main Indicators	Instrument
AI Usage (X)	<ol style="list-style-type: none"> <li>1. Frequency and duration of interaction with ChatGPT during problem-solving</li> <li>2. Types of mathematical problems solved (multiple-choice, short-answer, essay)</li> <li>3. Strategies employed by AI in solving problems</li> </ol>	AI activity log: <ul style="list-style-type: none"> <li>▪ Automated tracking of interactions</li> <li>▪ Problem type completion</li> <li>▪ Solution strategy</li> </ul>
Digital Literacy (M)	<ol style="list-style-type: none"> <li>1. Ability to critically evaluate AI-generated responses</li> <li>2. Application of AI tools in mathematical problem-solving</li> <li>3. Ethical and responsible use of AI in learning</li> </ol>	<ul style="list-style-type: none"> <li>▪ Standardized digital literacy questionnaire</li> <li>▪ Teacher-scored rubric for problem-solving activities</li> </ul>
Mathematical Thinking Ability (Y)	<ol style="list-style-type: none"> <li>1. Accuracy of solutions across problem types</li> <li>2. Response time for completing each problem</li> <li>3. Consistency and reliability across multiple-choice, short-answer, and essay tasks</li> <li>4. Demonstration of analytical, strategic, and creative reasoning</li> </ol>	<ul style="list-style-type: none"> <li>▪ Objective mathematics test (20 questions: 10 multiple-choice, 5 short-answer, 5 essay)</li> <li>▪ Scoring rubric aligned with curriculum standards</li> </ul>

*5-point Likert scale (1 = strongly disagree to 5 = strongly agree)*

### 2.4. Instrument Development

The research instruments included 20 mathematics problems: 10 multiple-choice, 5 short-answer, and 5 essay questions, developed according to the secondary school curriculum and validated by mathematics education experts. Both AI and students were tested using the same problem set to ensure a fair comparison. The assessment of mathematical thinking included multiple-choice, short-answer, and essay questions aligned with national curriculum standards for secondary school mathematics.

**Table 2.** Research Procedure

No	Research Stage	Description
1	AI Tool Selection	<ol style="list-style-type: none"> <li>1) Selection of ChatGPT version 4 as the AI tool for problem-solving</li> <li>2) Ensure capability for multiple problem types: multiple-choice, short-answer, essay</li> <li>3) Verify adaptive problem-solving and interactive features.</li> </ol>
2	Mathematics Problem Compilation	<ol style="list-style-type: none"> <li>1) Develop 20 mathematics problems aligned with secondary school curriculum</li> <li>2) Include 10 multiple-choice, 5 short-answer, and 5 essay questions</li> <li>3) Validate content and cognitive level through expert review.</li> </ol>
3	Sample Selection	<ol style="list-style-type: none"> <li>1) Use stratified random sampling to select 120 students from three schools</li> </ol>

		2) Divide participants into experimental group (AI-assisted learning) and control group (conventional textbook-based learning)
		3) Inclusion criteria: grades 10–12, active participation in mathematics classes, and basic digital literacy.
4	Experimental Design	1) Implement pretest-posttest control group design 2) Compare AI and student performance based on: <ul style="list-style-type: none"> <li>▪ Accuracy</li> <li>▪ Response time</li> <li>▪ Consistency</li> <li>▪ Higher-order thinking skills</li> </ul>
		3) Obtain ethical approval and participant consent.
5	Testing Implementation	1) Administer problems sequentially: AI first, then students. 2) Record AI and student responses digitally. 3) Track interaction patterns, strategies used, and time taken for each problem.
6	Data Collection	1) Collect performance metrics: <ul style="list-style-type: none"> <li>▪ Accuracy per problem type</li> <li>▪ Response time per problem</li> <li>▪ Consistency across problem types.</li> </ul>
		2) Record AI activity logs for interaction frequency and strategy analysis.
		3) Administer digital literacy questionnaire to students.
7	Data Analysis	1) Conduct descriptive statistics: mean, standard deviation. 2) Perform independent t-tests for AI vs student performance. 3) Conduct ANOVA to compare performance across problem types. 4) Conduct multiple regression to test mediating effect of digital literacy on mathematical thinking.
8	Interpretation & Conclusion	1) Evaluate AI effectiveness in mathematics problem-solving. 2) Identify relative strengths and limitations of AI and students. 3) Analyze mediating role of digital literacy in enhancing mathematical thinking. 4) Draw implications for AI integration in secondary mathematics education.

## 2.5. Validitas dan Reliabilitas Instrumen

Instrument validity was established through content validity by consulting three mathematics education experts and two AI specialists, ensuring that the mathematics problems, digital literacy questionnaire, and AI interaction metrics aligned with research objectives, cognitive levels, and problem types (multiple-choice, short-answer, essay). Reliability was assessed using Cronbach's alpha for the questionnaire and inter-rater reliability for essay scoring, with results  $\geq 0.85$  and  $\geq 0.80$ , respectively. AI activity logs were also verified for accuracy of strategies, response times, and completion. These procedures confirm the instruments were valid and reliable, supporting objective comparisons between AI and student performance and mediation analyses involving digital literacy.

## 2.6. Data Collection Procedure

Data collection was conducted in three structured phases to ensure accurate measurement of student mathematical thinking and AI performance.

**Table 3.** Data Collection Procedure

Phase	Description	Key Measures & Records
Pretest	1) Administered to all participants before intervention	1) Accuracy across problem types (MCQ, short-answer, essay)
	2) Assess baseline mathematical thinking abilities and digital literacy.	2) Response time
		3) Higher-order thinking indicators
		4) Digital literacy questionnaire

<b>Experimental Phase (4 weeks)</b>	1) Experimental group engaged with ChatGPT v4; control group used conventional textbook-based learning.	1) Frequency and duration of AI engagement 2) Types of problems solved 3) Problem-solving strategies used by AI and students 4) Engagement levels
	2) AI-student interactions logged digitally.	
<b>Posttest</b>	Administered after intervention to assess development in mathematical thinking.	1) Accuracy, response time, and consistency across problem types 2) Analytical, strategic, and creative reasoning 3) Integration with AI activity logs and digital literacy data for mediation analysis

## 2.7. Data Analysis

Data were analyzed using descriptive statistics (mean, standard deviation) and inferential statistics, including independent t-tests for comparing AI and student performance and ANOVA for identifying performance differences across problem types (multiple-choice, short-answer, essay). Additionally, multiple regression was employed to assess the mediating effect of AI digital literacy on mathematical thinking ability. The analysis provided a comprehensive evaluation of AI effectiveness and its role in enhancing students' mathematical reasoning skills.

## 3. RESULTS AND DISCUSSION

### 3.1. Results

The study examined the effectiveness of AI-based learning, specifically ChatGPT v4, in supporting secondary school students' mathematical thinking skills. A total of 120 students participated, divided into experimental (AI-assisted learning) and control (conventional instruction) groups. The instruments included a 20-item mathematics test (10 multiple-choice, 5 short-answer, 5 essay) and a digital literacy questionnaire, while AI performance was logged via system activity logs capturing accuracy, response time, and problem-solving strategies. Data were analyzed to compare AI and student performance across problem types and to assess the mediating role of digital literacy in students' mathematical thinking development.

Table 4 summarizes the descriptive statistics of accuracy, response time, and consistency for AI and student performance across problem types.

**Table 4.** Descriptive Statistics of AI and Student Performance

Problem Type	Group	Mean Accuracy (%)	Mean Response Time (s)	Consistency (SD)
Multiple-choice	AI	96.2	12.3	1.2
Multiple-choice	Students	78.5	54.6	6.5
Short-answer	AI	92.8	18.5	1.5
Short-answer	Students	70.4	63.2	7.2
Essay	AI	89.6	35.8	2.0
Essay	Students	65.3	78.4	8.1
Multiple-choice	AI	96.2	12.3	1.2

The descriptive data show that AI consistently outperformed students in accuracy and speed across all problem types, while students exhibited greater variability in performance, particularly on essay and short-answer questions.

**Table 5.** Instrument Validity and Reliability

Instrument	Type of Test	Validity Assessment	Reliability Measure	Result
Digital Literacy Questionnaire	Likert-scale self-report	Content validity by 3 mathematics education experts & 2 AI specialists	Cronbach's alpha	0.87 (high)
Mathematics Test (20 items: MCQ, Short-answer, Essay)	Objective test	Content validity by 3 mathematics education experts & 2 AI specialists	Inter-rater reliability (essay scoring)	0.82 (high)
AI Activity Log	System-generated log	Checked for completeness and accuracy of recorded problem-solving strategies, response time, and completion	System reliability (internal consistency of recorded metrics)	Verified consistent

### Instrument Testing

To ensure the robustness of the mathematics test, item-level analysis was conducted prior to hypothesis testing. The analysis included item difficulty, item discrimination, and overall test reliability across different problem types.

**Table 6.** Quantitative Results of Mathematics Test Item Analysis

Problem Type	Number of Items	Difficulty Index (Mean)	Discrimination Index (Mean)	Reliability Coefficient
Multiple-choice	10	0.62	0.41	0.84
Short-answer	5	0.58	0.44	0.81
Essay	5	0.55	0.47	0.82
<b>Overall Test</b>	<b>20</b>	<b>0.59</b>	<b>0.44</b>	<b>0.86</b>

### Assumption Testing

Prior to inferential statistical analysis, assumption testing was conducted to ensure the suitability of parametric tests. The assumptions of normality and homogeneity of variance were examined for pretest and posttest scores of mathematical thinking in both experimental and control groups.

Normality was tested using the Shapiro–Wilk test, as the sample size in each group was below 200. A significance value greater than 0.05 indicates normally distributed data.

**Table 7.** Results of Normality Test (Shapiro–Wilk)

Group	Test Phase	N	W Statistic	Sig. (p)
Experimental	Pretest	60	0.972	0.124
Experimental	Posttest	60	0.968	0.087
Control	Pretest	60	0.975	0.156
Control	Posttest	60	0.971	0.102

All significance values exceeded 0.05, indicating that pretest and posttest scores were normally distributed in both groups. These results support the use of parametric statistical analyses for subsequent hypothesis testing.

**Table 8.** Results of Homogeneity of Variance Test (Levene's Test)

Test Phase	Levene Statistic	df1	df2	Sig. (p)
Pretest	1.214	1	118	0.273
Posttest	0.946	1	118	0.333

The Levene's test results showed non-significant values ( $p > 0.05$ ) for both pretest and posttest scores. This indicates that the variances between the experimental and control groups were homogeneous.

Based on the results of the normality and homogeneity tests, all required statistical assumptions were met. Therefore, independent sample t-tests and ANOVA were deemed appropriate for analyzing differences in mathematical thinking performance between groups and across problem types.

### Descriptive Statistics of Mathematical Thinking Scores

This section presents descriptive statistics of students' mathematical thinking scores in the experimental and control groups based on pretest and posttest results. The analysis focuses on mean scores, standard deviations, and gain scores to provide an overview of performance changes following AI-based learning implementation.

**Table 9.** Descriptive Statistics of Mathematical Thinking Scores

Group	Test Phase	N	Mean	SD
Experimental	Pretest	60	62.45	8.12
Experimental	Posttest	60	78.63	7.45
Control	Pretest	60	61.87	8.35
Control	Posttest	60	69.14	7.98

### Gain Score

Analysis To further describe learning improvement, gain scores were calculated as the difference between posttest and pretest scores.

**Table 10.** Gain Scores of Mathematical Thinking Ability

Group	N	Mean Gain	SD
Pretest	1.214	1	118
Posttest	0.946	1	118

The experimental group achieved a substantially higher mean gain score than the control group. The relatively similar standard deviations indicate comparable score dispersion across groups.

**Table 11.** Posttest Scores by Problem Type

Problem Type	Group	Mean	SD
Multiple Choice	Experimental	82.14	6.88
	Control	73.52	7.14
Short Answer	Experimental	78.36	7.25
	Control	68.94	7.62
Essay	Experimental	75.38	8.04
	Control	64.95	8.31
Multiple Choice	Experimental	82.14	6.88
	Control	73.52	7.14

Overall, descriptive statistics indicate that students who participated in AI-based learning demonstrated higher posttest performance and greater learning gains in mathematical thinking compared to those receiving conventional instruction. These results provide a quantitative basis for subsequent inferential and hypothesis testing.

**Table 12.** Independent t-Test Results for Accuracy: AI vs. Students by Problem

Problem Type	Group	Mean Accuracy (%)	SD	t-value	p-value	Cohen's d
Multiple Choice	AI	95.20	2.10	12.84	< 0.001	1.95
	Students	76.35	7.14			
Short Answer	AI	93.48	2.85	14.22	< 0.001	2.13
	Students	70.12	7.62			
Essay	AI	91.76	3.12	15.87	< 0.001	2.41
	Students	64.95	8.31			

### Mediation Analysis: Role of Digital Literacy

Multiple regression analyses were conducted to assess the mediating effect of digital literacy on students' mathematical thinking outcomes.

**Table 13.** Multiple Regression Results for Digital Literacy as a Mediator

Dependent Variable	Predictor	$\beta$	SE	t-value	p-value
Accuracy	Digital Literacy	0.42	0.09	4.67	< 0.01
Response Time	Digital Literacy	-0.38	0.08	-4.25	< 0.01
Mathematical Thinking (Overall)	AI Interaction	0.51	0.07	7.29	< 0.001
Mathematical Thinking (with Mediator)	AI Interaction	0.34	0.08	4.18	< 0.01

\* Digital literacy significantly predicted higher accuracy and lower response time.

\*The reduction in the  $\beta$  coefficient for AI interaction indicates partial mediation.

### 3.2. Discussion

The findings of this study provide strong empirical evidence that Artificial Intelligence-based learning significantly enhances students' mathematical thinking in secondary education, particularly when supported by adequate digital literacy. The experimental group exposed to AI-assisted learning demonstrated substantially higher posttest scores and learning gains compared to the control group, confirming the effectiveness of AI integration in mathematics instruction. These results align with prior studies indicating that AI-supported environments can promote deeper cognitive engagement, adaptive feedback, and personalized learning pathways (Chen & Xie, 2020; Chiu et al., 2022; Kasneci et al., 2023).

A key contribution of this study lies in the direct comparison between AI and student performance across problem types. The results showed that AI consistently outperformed students in accuracy, speed, and consistency, with the largest performance gap observed in essay-based tasks requiring higher-order reasoning. This finding supports previous research suggesting that generative AI systems are particularly effective in tasks involving logical structuring, pattern recognition, and multi-step reasoning (Arvin et al., 2023; Peng et al., 2023). However, rather than positioning AI as a replacement for students' cognitive processes, these results highlight AI's potential role as a cognitive scaffold that models expert-level reasoning strategies.

The superior performance of AI in essay tasks is especially noteworthy, as such tasks demand conceptual understanding, analytical reasoning, and coherent mathematical communication. From the perspective of cognitive load theory, AI may reduce extraneous cognitive load by providing structured problem-solving pathways, allowing students to focus on intrinsic cognitive processes (Sweller et al., 2019; Lin, 2022). This mechanism may explain why AI-based learning environments are more effective in supporting complex mathematical thinking than traditional textbook-centered instruction.

Importantly, the mediation analysis revealed that digital literacy plays a partial but significant mediating role in the relationship between AI interaction and students' mathematical thinking outcomes. Students with higher digital literacy were better able to evaluate AI-generated information, select appropriate strategies, and apply AI support ethically and effectively. This finding reinforces the argument that AI effectiveness in education is not solely determined by technological sophistication, but also by learners' competencies in navigating, interpreting, and critically assessing AI outputs (Naamati-Schneider & Alt, 2024; Sidik et al., 2025).

These results extend earlier studies that primarily focused on teachers' perceptions or general learning outcomes by empirically demonstrating how digital literacy functions as a cognitive facilitator in AI-based mathematics learning (Lee et al., 2022; Ifenthaler et al., 2024). Without sufficient digital literacy, students may become passive recipients of AI-generated solutions, limiting opportunities for reflective thinking and metacognitive regulation. Therefore, integrating AI into mathematics education must be accompanied by explicit instruction in AI literacy, critical evaluation, and ethical use.

From a pedagogical perspective, the findings support a social constructivist view of learning, where AI serves as an interactive learning partner that stimulates dialogue, exploration, and reflection rather than a mere answer-providing tool (Chiu & Chai, 2020). When used appropriately, AI can facilitate meaningful learning experiences by prompting students to justify reasoning, explore alternative strategies, and refine conceptual understanding. This approach contrasts sharply with traditional instructional models that emphasize procedural repetition over conceptual depth.

Despite its contributions, this study also highlights important considerations for educational practice. While AI demonstrated superior performance, students required more time and exhibited greater variability in solving higher-order problems, particularly essays. This suggests that AI should be integrated as a supportive learning aid, not as a benchmark for student performance. Overreliance on AI without pedagogical guidance may risk reducing students' productive struggle, which is essential for developing robust mathematical reasoning skills.

In conclusion, this study confirms that AI-based learning, when combined with strong digital literacy, can significantly enhance students' mathematical thinking in secondary education. The findings contribute to both theory and practice by elucidating the mechanisms through which AI influences learning outcomes and by providing empirical guidance for educators and policymakers. Future research should explore longitudinal effects, classroom-based implementations, and the role of teacher mediation in optimizing AI-supported mathematics learning.

#### 4. CONCLUSION

This study provides strong quantitative evidence that Artificial Intelligence–based learning positively affects students’ mathematical thinking in secondary education. The findings demonstrate that students who engaged in AI-assisted learning environments achieved higher accuracy, faster response times, and greater consistency across multiple problem types compared with those taught using conventional methods. The comparative analysis further revealed that AI outperformed students, particularly in essay-based tasks requiring higher-order reasoning, analytical structuring, and coherent mathematical explanations. These results suggest that AI has substantial potential to function as an effective cognitive scaffold that supports complex mathematical problem-solving rather than merely serving as an auxiliary instructional tool.

Additionally, the mediation analysis highlights digital literacy as a critical factor in maximizing the effectiveness of AI-based learning. Students with higher levels of digital literacy were better able to evaluate AI-generated information, apply appropriate problem-solving strategies, and engage in reflective and critical thinking. This finding underscores that the educational impact of AI is not solely determined by technological access but also by learners’ cognitive readiness and evaluative competencies. Therefore, effective integration of AI in secondary mathematics education should be accompanied by systematic development of digital literacy and ethical awareness. Overall, this study contributes both theoretically and practically by clarifying the mechanisms through which AI influences mathematical thinking and by providing empirical guidance for educators and policymakers seeking to design adaptive, learner-centered, and future-oriented mathematics learning environments.

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