

Evaluating Design Thinking in Mathematics Students: The Impact of AI Utilization and Digital Literacy

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Abstract

The accelerated expansion of artificial intelligence (AI) in mathematics education has transformed instructional practices; however, its effectiveness in fostering higher-order cognitive skills remains inconclusive. Although AI-enabled learning environments provide adaptive feedback and personalized support, limited student digital literacy often restricts meaningful and critical engagement with these technologies. This suggests that AI integration alone is insufficient to develop design thinking skills without adequate learner readiness. Accordingly, this study investigates the structural relationships among AI utilization, digital literacy, and design thinking in mathematics education, with particular emphasis on the mediating role of digital literacy. A quantitative research design was adopted, drawing on survey data collected from undergraduate students and analyzed using structural equation modeling. The results indicate that AI utilization explains 35% of the variance in digital literacy, while the combined effects of AI utilization and digital literacy account for 48% of the variance in students' design thinking skills. Furthermore, digital literacy exhibits a statistically significant mediating effect, strengthening the influence of AI utilization on design thinking outcomes. These findings demonstrate that the pedagogical effectiveness of AI in mathematics education depends on the development of students' digital competencies and provides a conceptual framework to guide future instructional design and research.

Keywords: Artificial Intelligence Utilization; Digital Literacy; Design Thinking; Mathematics Education; Higher-Order Thinking Skills

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1. INTRODUCTION

The transformation of 21st-century education positions higher-order thinking skills as a primary learning orientation, particularly in mathematics, which simultaneously demands analytical, reflective, and creative capabilities. This shift is closely linked to the integration of intelligent technologies within global education systems. The adoption of Artificial Intelligence (AI) drives a paradigm shift from procedural learning to adaptive learning centered on complex problem-solving (Chiu & Chai, 2020). In this context, students are expected not only to master mathematical concepts but also to explore diverse solution strategies innovatively. This perspective aligns with the need to develop AI-based 21st-century competencies within higher education curricula (Chiu et al., 2022).

Over the past decade, AI has transformed pedagogical landscapes through adaptive learning systems, data analytics, and algorithm-driven automated feedback. Implementing AI in education enables personalized learning that is more responsive to individual students' needs (Yuskovych-Zhukovska et al., 2022). In mathematics education, the use of generative AI and academic chatbots has been shown to support students in exploring a wider range of problem-solving approaches (Chau et al., 2025). Nevertheless, this transformation also raises ethical and pedagogical challenges, including the validity of information, potential technology dependency, and the evolving role of instructors in the learning process (Perrotta & Selwyn, 2020).

Although AI offers significant potential, its integration into learning does not automatically enhance students' higher-order thinking skills. Some studies highlight gaps between policy-level AI integration and classroom implementation (Abedi, 2024). The effectiveness of AI use is strongly influenced by the cognitive readiness and reflective abilities of users in critically engaging with the technology (Arvin et al., 2023). Without adequate supporting competencies, AI risks being used instrumentally, contributing little to the strengthening of analytical and creative thinking structures in mathematics learning (Egara & Mosimege, 2024).

Within this context, digital literacy emerges as a key factor determining successful AI integration in education. Digital literacy encompasses not only technical skills but also evaluative, critical, and ethical capacities in understanding algorithm-based systems (Ng et al., 2021). Systematic reviews indicate that digital literacy significantly shapes reflective attitudes toward the use of educational technologies (Audrin & Audrin, 2022). In the context of generative AI, digital literacy equips students to identify biases, evaluate the accuracy of responses, and understand the limitations of intelligent systems (Naamati-Schneider & Alt, 2024).

Design thinking-based mathematics education offers a relevant approach to developing innovative and systematic problem-solving skills. Design thinking emphasizes empathy, ideation, prototyping, and iterative reflection in discovering solutions (Sreenivasan & Suresh, 2024). The integration of AI has the potential to enrich these stages by providing alternative solutions, visual simulations, and instant feedback that support conceptual exploration (Chau et al., 2025). However, empirical research examining the direct relationship between AI use and the development of design thinking in mathematics learning remains limited and warrants further investigation (Chiu et al., 2022).

Most prior studies have focused primarily on students' perceptions of AI use or the technical effectiveness of its implementation. Recent literature reviews indicate that studies on ChatGPT and educational AI remain largely descriptive and exploratory (Albadarin et al., 2024). Other research has suggested that AI use can enhance academic creativity, yet few studies specifically examine the mediating role of digital literacy in the context of mathematics learning (Agaoglu et al., 2025). This indicates that the structural relationship between AI utilization, digital literacy, and design thinking has not yet been fully integrated into a single empirical model.

The fragmentation of the literature reveals conceptual and empirical gaps in the study of AI integration in mathematics education. Research on AI, digital literacy, and design

thinking has developed partially and is rarely examined simultaneously within a comprehensive analytical framework. Progressive education emphasizes meaningful, reflective, and transformative technology integration (Fatkurochman et al., 2026). Without an integrative approach, AI implementation risks remaining at a technical level, without significantly contributing to the development of students' higher-order thinking competencies (Cukurova et al., 2020).

Based on this background, the present study proposes an integrative model linking AI utilization, digital literacy, and design thinking in mathematics education. This model positions digital literacy as a mediating variable that explains the mechanism through which AI use influences students' design thinking abilities. This approach aligns with the perspective that the effectiveness of educational technologies is determined by the interaction between technological factors and user competencies (Ng et al., 2021). Consequently, this study evaluates not only the direct relationships among these variables but also the cognitive processes underlying AI integration in modern mathematics learning.

2. METHOD

2.1. Research Design

This study adopts a quantitative approach with an explanatory research design to examine the causal relationships among AI utilization, digital literacy, and design thinking in mathematics learning. The explanatory design is employed because the study aims to test a conceptual model that positions digital literacy as a mediating variable in the relationship between AI utilization and students' design thinking abilities. A cross-sectional survey approach is used to obtain an empirical snapshot of the relationships among the variables within a single time period. The selection of this design is consistent with prior studies that have investigated the integration of AI in education using quantitative approaches grounded in structural modeling (Chiu & Chai, 2020; Cukurova et al., 2020). Data analysis is conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM), as this method is well suited for testing predictive models and mediation effects in technology-enhanced educational contexts (Chiu et al., 2022).

2.2. Participants

The study participants were undergraduate students enrolled in mathematics education or mathematics programs who had experience using Artificial Intelligence (AI)-based technologies, such as academic chatbots or generative systems, in their learning activities. The use of AI reflects current practices of AI integration in mathematics education (Chau et al., 2025; Egara & Mosimege, 2024). A purposive sampling technique was employed with the following criteria: (1) active students in the middle or final semesters of study, (2) having at least one semester of experience using AI in learning, and (3) willingness to participate voluntarily. The determination of sample size was guided by principles of adequacy for structural model analysis in AI-based educational research (Yuskovych-Zhukovska et al., 2022).

2.3. Variables and Operational

This study involves three main variables, which are operationally defined based on a review of recent literature on AI, digital literacy, and design thinking.

Table 1. Operationalization of Research Variables

Variable	Operational Definition	Dimension	Key Indicators	Number of Items
AI Utilization (X)	The level of frequency, intensity, and quality of Artificial Intelligence (AI) use in supporting mathematics learning, particularly in concept exploration and problem-solving	<ol style="list-style-type: none"> Usage frequency Interaction quality Usage reflection 	<ol style="list-style-type: none"> Using AI to understand mathematical concepts Using AI to solve problems Comparing multiple solution methods provided by AI Using AI to verify answers Re-evaluating results provided by AI Using AI to reflect on problem-solving strategies 	8 item
Digital Literacy (M)	Students' ability to understand, evaluate, and use digital technologies, including AI systems, critically, reflectively, and ethically in the context of mathematics learning	<ol style="list-style-type: none"> Evaluation of digital information Understanding algorithmic systems Digital reflection and responsibility 	<ol style="list-style-type: none"> Verifying the accuracy of AI output Identifying potential bias in AI responses Comparing AI information with other sources Understanding the limitations of AI systems Using AI ethically in academic tasks Reflecting on the reliability of digital information 	8 item
Design Thinking (Y)	Students' ability to identify problems, generate creative ideas, develop alternative solutions, and conduct iterative reflection in solving mathematics problems	<ol style="list-style-type: none"> Problem identification Creative ideation Solution development/prototyping Iterative reflection 	<ol style="list-style-type: none"> Analyzing mathematical problems from multiple perspectives Generating more than one problem-solving strategy Testing and comparing alternative solutions Revising strategies based on outcome evaluation Developing innovative approaches to solve problems Reflecting on the effectiveness of chosen solutions 	10 item

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

The definition of digital literacy refers to a digital literacy framework that emphasizes cognitive and evaluative aspects in technology use (Ng et al., 2021; Audrin & Audrin, 2022). Meanwhile, the design thinking construct is adapted to the characteristics of empathy, ideation, and iterative reflection processes within an educational context (Sreenivasan & Suresh, 2024).

2.4. Instrument Development

The research instrument consisted of a structured questionnaire developed based on a synthesis of literature on AI in education (Chiu et al., 2022), digital literacy (Ng et al., 2021), and design thinking development in academic contexts (Sreenivasan & Suresh, 2024). Items were systematically constructed to ensure representation of each construct indicator: (1) AI utilization focused on the quality of students' interactions with AI systems, particularly regarding the use of generative AI in learning; (2) digital literacy encompassed cognitive, critical, and ethical aspects of technology use; and (3) design thinking emphasized exploratory processes, ideation, and reflection in solving mathematics problems. Content validity was evaluated through expert judgment by specialists in mathematics education and educational technology to ensure conceptual relevance and clarity of item wording.

2.5. Validitas dan Reliabilitas Instrumen

Validity and reliability testing were conducted through the evaluation of the outer model in PLS-SEM. Convergent validity was assessed based on factor loadings ≥ 0.70 and Average Variance Extracted (AVE) ≥ 0.50 . Discriminant validity was examined using the Fornell-Larcker criterion and HTMT (< 0.90). Construct reliability was evaluated through Composite Reliability and Cronbach's Alpha ≥ 0.70 . This approach aligns with standard practices for testing structural models in research on AI and digital education (Cukurova et al., 2020).

2.6. Data Collection Procedure

Data collection was conducted online using a digital survey platform. Respondents were provided with explanations regarding the research objectives, data confidentiality, and their participation rights through an informed consent statement. This procedure aligns with the ethical principles of technology-based educational research (Perrotta & Selwyn, 2020). The questionnaire required approximately 10–15 minutes to complete. Incomplete responses or those not meeting inclusion criteria were excluded to ensure the quality of the analysis.

2.7. Data Analysis

Data analysis was conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM), comprising:

- (1) Outer Model Evaluation: To assess convergent validity, discriminant validity, and construct reliability.
- (2) Inner Model Evaluation: To examine path coefficients, R^2 values, effect size (f^2), and predictive relevance (Q^2).

- (3) Mediation Testing: The mediating effect of digital literacy was tested using bootstrapping with 5,000 resamples to assess the significance of the indirect effect. Mediation was considered significant if $t\text{-value} > 1.96$ and $p\text{-value} < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Results

This study examined the relationships among AI utilization, digital literacy, and design thinking in mathematics learning among university students. Data were collected through a structured online questionnaire administered to students who had prior experience using artificial intelligence tools such as generative artificial intelligence systems or academic chatbots in mathematics learning activities. All responses were screened to ensure completeness, internal consistency, and compliance with the established inclusion criteria.

After the data screening process, the final dataset was analyzed using Partial Least Squares Structural Equation Modeling. This analytical approach was selected due to its suitability for predictive modeling, mediation analysis, and the examination of complex structural relationships in educational research. The results are presented sequentially, beginning with descriptive statistics, followed by measurement model evaluation, structural model assessment, and hypothesis testing, in alignment with the research objectives.

Descriptive statistical analysis was conducted to provide an overview of students responses to each construct examined in the study. Mean values represent the central tendency of participants perceptions, while standard deviation values indicate the variability of responses. All constructs were measured using a five point Likert scale ranging from strongly disagree to strongly agree.

Table 2. Descriptive Statistics of Research Variables

Variable	Number of Items	Mean	Standard Deviation
AI Utilization	8	3,92	0,58
Digital Literacy	8	4,01	0,55
Design Thinking	10	3,88	0,60

As shown in Table 2, all variables demonstrate mean scores above the midpoint of the measurement scale, indicating generally positive perceptions among students. Digital literacy shows the highest mean value, suggesting that students perceive themselves as relatively competent in evaluating, understanding, and using digital and artificial intelligence technologies. Design thinking and AI utilization also demonstrate moderate to high mean scores, reflecting active engagement with AI tools and participation in problem identification, ideation, and reflective solution development during mathematics learning.

Measurement Model Evaluation (Outer Model)

The measurement model evaluation aimed to assess the adequacy of the research instruments in measuring the intended latent constructs. This evaluation included tests of convergent validity, discriminant validity, and construct reliability.

Convergent validity was evaluated by examining indicator loadings and Average Variance Extracted (AVE). The findings indicate that all indicator loadings exceeded the

recommended cutoff value of 0.70, demonstrating adequate item reliability. In addition, the AVE values for all constructs were greater than 0.50, indicating that each construct accounts for more than 50% of the variance in its indicators and therefore satisfies the criteria for convergent validity.

Table 3. Convergent Validity Results

Variable	Range of Factor Loadings	Average Variance Extracted (AVE)
AI Utilization	0,72 – 0,86	0,61
Digital Literacy	0,74 – 0,88	0,64
Design Thinking	0,71 – 0,85	0,60

Discriminant validity was assessed using the Fornell Larcker criterion, which compares the square root of the Average Variance Extracted of each construct with its correlations with other constructs. Discriminant validity is established when the square root of Average Variance Extracted is greater than the interconstruct correlations.

Table 4. Discriminant Validity Results

Variable	AI Utilization	Digital Literacy	Design Thinking
AI Utilization	0,78	-	-
Digital Literacy	0,59	0,80	-
Design Thinking	0,55	0,62	0,77

Internal consistency reliability was assessed using Cronbach's alpha and Composite Reliability (CR). The results show that all constructs achieved Cronbach's alpha and CR values above the recommended threshold of 0.70, confirming acceptable reliability and consistency of the measurement scales.

Table 5. Construct Reliability Results

Variabel	Cronbach's Alpha	Composite Reliability
AI Utilization	0,88	0,91
Digital Literacy	0,90	0,93
Design Thinking	0,89	0,92

Structural Model Evaluation (Inner Model)

The explanatory power of the structural model was assessed by examining the coefficient of determination values. These values indicate the proportion of variance explained by the predictor variables.

Table 6. Coefficient of Determination Results (R²)

Endogenous Variable	R ²
Digital Literacy	0,35
Design Thinking	0,48

The coefficient of determination indicates that AI utilization accounts for 35% of the variance in digital literacy. Furthermore, the combined effects of AI utilization and digital literacy explain 48% of the variance in students' design thinking. These R² values reflect a moderate explanatory power of the proposed structural model.

Hypothesis testing was conducted using a bootstrapping procedure with five thousand resamples to assess the significance of the structural relationships among variables.

Table 7. Structural Path Coefficients

Relationship	Path Coefficient	t-value	p-value
AI Utilization to Digital Literacy	0,59	8,42	< 0,001
Digital Literacy to Design Thinking	0,41	6,15	< 0,001
AI Utilization to Design Thinking	0,32	4,87	< 0,001

The results demonstrate that all hypothesized direct relationships are positive and statistically significant, indicating meaningful associations among AI utilization, digital literacy, and design thinking in mathematics learning.

The mediating role of digital literacy in the relationship between AI utilization and design thinking was examined through indirect effect analysis using bootstrapping.

Table 8. Indirect Effect Analysis

Mediation Path	Indirect Effect	t-value	p-value
AI Utilization through Digital Literacy to Design Thinking	0,24	5,36	< 0,001

The results indicate that the indirect effect is statistically significant, confirming that digital literacy mediates the relationship between AI utilization and design thinking in mathematics learning.

3.2. Discussion

This study provides empirical evidence on the interrelationships between artificial intelligence utilization, digital literacy, and students' design thinking skills in mathematics education. The findings align with prior research emphasizing that AI integration in education must be understood as a pedagogical and cognitive process rather than merely a technological intervention (Perrotta & Selwyn, 2020; Ali & Wardat, 2024). Moreover, the results support systematic reviews indicating that AI tools influence learning outcomes most effectively when embedded within well-structured instructional designs and supported by learner competencies (Albadarin et al., 2024; Yuskovych-Zhukovska et al., 2022). This study extends existing literature by empirically validating these relationships within the context of mathematics education, a domain that demands high levels of abstraction and problem-solving.

AI Utilization as a Determinant of Digital Literacy

The finding that AI utilization accounts for a substantial proportion of variance in students' digital literacy provides empirical support for the argument that sustained engagement with intelligent systems functions as a catalyst for advanced digital competence development. Digital literacy in contemporary education extends beyond operational skills to include critical evaluation of information, ethical awareness, and adaptive decision making in technology use (Audrin & Audrin, 2022; Ng et al., 2021). Interaction with AI-

supported learning environments requires students to interpret algorithmic feedback, assess the reliability of AI-generated outputs, and regulate their own learning strategies. These processes position learners as active agents within digital ecosystems, thereby strengthening higher-order digital literacy skills that are essential in mathematics learning contexts characterized by abstraction and problem solving (Naamati-Schneider & Alt, 2024).

Within the broader landscape of educational transformation, this relationship underscores the role of AI as an enabler of progressive learning practices. Fatkurochman et al. (2026) argued that modern education systems must integrate intelligent technologies to promote learner autonomy, adaptability, and reflective thinking. However, such integration is not value neutral. Abedi (2024) emphasized that misalignment between technology integration policies and pedagogical practices can limit the developmental potential of digital tools. The present findings suggest that when AI utilization is meaningfully embedded in mathematics instruction, it can act as a practical mechanism for enhancing students' digital literacy rather than merely serving as a technical supplement. This reinforces the importance of pedagogically grounded AI use that aligns technological affordances with instructional goals.

Moreover, the results resonate with recent conceptualizations that frame digital literacy in the era of AI-powered assistants as an advanced cognitive and ethical competence. Naamati-Schneider and Alt (2024) highlighted a shift from basic digital operation toward skills related to judgment, self-regulation, and responsible technology engagement. The positive association between AI utilization and digital literacy observed in this study supports this shift, indicating that frequent and purposeful interaction with AI tools encourages students to develop a more sophisticated understanding of digital systems. Consistent with findings by Agaoglu et al. (2025) in other disciplinary contexts, these results demonstrate that AI-driven digital literacy development is not domain specific, but also highly relevant in mathematics education, where critical evaluation and adaptive reasoning are central to meaningful learning.

Digital Literacy as a Cognitive Enabler of Design Thinking

The significant effect of digital literacy on students' design thinking skills highlights its function as a core cognitive enabler rather than a peripheral technical competence. Design thinking is inherently complex, requiring learners to identify and frame problems, generate and evaluate ideas, construct and test solutions, and engage in iterative reflection based on feedback. These processes rely heavily on advanced information processing, critical evaluation, and metacognitive regulation (Sreenivasan & Suresh, 2024; Sriwisathiyakun, 2023). Students with higher levels of digital literacy are better positioned to navigate digital environments, integrate multiple representations of mathematical problems, and critically reflect on solution pathways. Consequently, digital literacy provides the cognitive infrastructure that allows design thinking to emerge and develop in technology-mediated mathematics learning contexts.

From the perspective of mathematics education, this relationship addresses long-standing challenges associated with students' problem-solving development. Fatqurhohman and Firdaus (2024) emphasized that weaknesses in mathematical problem solving often stem

from fragmented mathematical identity and limited reflective capacity. Digital literacy, particularly when cultivated through AI-supported learning environments, can mitigate these limitations by offering structured feedback, opportunities for self-monitoring, and spaces for iterative refinement of ideas. In parallel, Audrin and Audrin (2022) argued that higher-order digital literacy promotes metacognitive engagement, which is essential for evaluating assumptions, monitoring progress, and revising strategies during problem solving. The present findings therefore suggest that digital literacy serves as a cognitive bridge that links technological engagement with deeper creative and analytical thinking in mathematics.

Theoretically, design thinking requires learners to explore alternative solutions, assess constraints, and refine ideas through continuous feedback cycles. Digital literacy enables these processes by equipping students with the skills to access diverse digital resources, simulate problem scenarios, and critically evaluate information quality and relevance. Empirical evidence from Darmawan and Widiastuti (2025) similarly demonstrated that digital literacy strengthens design thinking by supporting analytical reasoning and creative exploration in technology-rich learning environments. In line with this view, the current results indicate that digital literacy operates not merely as a functional skill set, but as an integrative cognitive capability that connects AI utilization with design thinking outcomes. This reinforces the position articulated by Ng et al. (2021) that digital literacy should be conceptualized as a multidimensional construct encompassing technical, cognitive, and ethical dimensions essential for higher-order thinking development.

Synergistic Effects of AI Utilization and Digital Literacy on Design Thinking

The combined influence of AI utilization and digital literacy on design thinking demonstrates a clear synergistic relationship, indicating that neither variable operates effectively in isolation. AI-based learning tools provide adaptive scaffolding, personalization, and real-time feedback that can support complex problem-solving processes. However, the extent to which these affordances translate into meaningful learning outcomes depends on learners' capacity to interpret, evaluate, and strategically apply AI-generated input. Digital literacy enables students to engage critically with intelligent systems, transforming technological support into cognitively productive design thinking practices (Agaoglu et al., 2025; Chau et al., 2025). This finding reinforces the argument that AI-driven learning environments are most effective when learners possess sufficient digital competence to interact with technology in reflective and purposeful ways.

This synergistic relationship is consistent with empirical evidence reported by Darmawan and Widiastuti (2025), who demonstrated that digital literacy mediates the effect of AI usage on design thinking skills in higher education contexts. Their findings suggest that AI contributes to higher-order thinking primarily through the learner's ability to process and evaluate technological input. Similarly, Sreenivasan and Suresh (2024) emphasized that the integration of AI and design thinking requires continuous reflection on both technological affordances and cognitive outcomes. The present study extends these insights to mathematics education, confirming that AI utilization enhances design thinking not directly, but through its interaction with students' digital literacy. This highlights the

importance of positioning digital literacy as a central component in AI-supported instructional design.

The moderate explanatory power of the combined model further indicates that AI utilization alone is insufficient to fully account for students' design thinking development. Instead, its effectiveness is contingent upon learners' ability to interpret feedback, regulate learning strategies, and integrate multiple sources of information, all of which are core dimensions of digital literacy. This observation aligns with Chau et al. (2025), who reported that AI-enhanced mathematics instruction produces stronger problem-solving outcomes when students demonstrate adequate digital competencies. In addition, Perrotta and Selwyn (2020) cautioned against framing AI as an autonomous determinant of educational outcomes, emphasizing its relational nature within pedagogical systems. The current findings empirically support this perspective by demonstrating that human capabilities, particularly digital literacy, remain central to realizing the educational potential of AI in fostering design thinking.

Implications for Mathematics Education and AI Integration

The findings of this study carry significant implications for instructional design in mathematics education, particularly in relation to the integration of AI technologies. Prior research has emphasized that innovative digital learning environments must be accompanied by the deliberate cultivation of students' digital competencies to ensure pedagogical effectiveness. Fatqurhohman, et al., (2025) argued that digital instructional innovation without parallel development of learners' digital literacy risks reducing technology to a superficial add-on rather than a meaningful cognitive support. The present findings reinforce this position by demonstrating that AI utilization alone does not automatically enhance design thinking unless students possess adequate digital literacy. In line with this, Chiu and Chai (2020) highlighted that sustainable AI-oriented curriculum design requires a balance between technological innovation, learner autonomy, and cognitive readiness, all of which are closely tied to students' digital competencies.

At a broader systemic level, the results underscore the need for alignment among technology, pedagogy, and learner development in mathematics education. Fatkurochman et al. (2026) emphasized that educational transformation in the modern era depends on the coherent integration of intelligent technologies with pedagogical goals and learner characteristics. Similarly, Abedi (2024) identified persistent gaps between policy-driven expectations for technology integration and actual classroom practices, noting that such misalignment can constrain the educational value of advanced technologies. The current findings suggest that AI implementation in mathematics education should be guided by instructional frameworks that explicitly integrate digital literacy and design thinking as complementary learning objectives, rather than treating AI as an independent instructional solution.

These implications also extend to issues of equity, sustainability, and pedagogical readiness in AI-supported mathematics learning. Chiu and Chai (2020) emphasized that effective AI adoption must support students' sense of competence and agency, which presupposes sufficient digital literacy. Without this foundation, AI integration may produce

uneven learning outcomes, as also cautioned by Abedi (2024). Ali and Wardat (2024) further noted that generative AI tools introduce both opportunities and challenges, particularly when learners and teachers are inadequately prepared to engage with them critically. In addition, Yuskovych-Zhukovska et al. (2022) argued that the benefits of AI in education are contingent upon learners' capacity to meaningfully interact with technology. Collectively, these perspectives highlight digital literacy as a critical lever for ensuring that AI integration in mathematics education promotes inclusive, effective, and cognitively meaningful learning experiences.

4. CONCLUSION

This study examined the relationships among artificial intelligence utilization, digital literacy, and design thinking in mathematics education and provides empirical evidence supporting an integrated explanatory model. The findings demonstrate that AI utilization contributes significantly to the development of students' digital literacy, which in turn plays a pivotal role in enhancing design thinking skills. Moreover, the combined influence of AI utilization and digital literacy explains a substantial proportion of variance in students' design thinking, highlighting the importance of considering both technological engagement and learner competence in AI-supported learning environments.

The results confirm that AI tools alone are insufficient to foster higher-order cognitive skills unless accompanied by adequate digital literacy. Digital literacy functions as a critical enabling mechanism that allows students to critically interpret AI-generated feedback, regulate their learning processes, and engage in reflective problem-solving. Within the context of mathematics education, this interaction supports students' ability to identify problems, generate innovative solutions, and iteratively refine their reasoning. Future research is recommended to explore longitudinal designs and domain-specific instructional strategies to further examine the dynamic interplay between AI, digital literacy, and higher-order thinking skills.

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