

# Project-Based Learning and Numeracy Literacy in Vocational Education: A Systematic Review of Their Impact on Critical Thinking

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## Article Info

### Article History

Submitted: 29-03-2026

Revised: 26-04-2026

Accepted: 30-04-2026

### Keywords:

Project-Based Learning;  
Critical Thinking;  
Numeracy Literacy;  
Mathematics Education;  
Digital Learning Tools

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## Abstract

Despite growing interest in fostering critical thinking in mathematics education, existing studies tend to examine pedagogical approaches, cognitive competencies, and digital tools in isolation, resulting in a fragmented understanding of how these elements interact in vocational education contexts. This study addresses this gap by systematically synthesizing evidence on the interplay between Project-Based Learning (PBL), numeracy literacy, and digital tool integration in enhancing students' critical thinking skills. A systematic literature review was conducted following the PRISMA framework, analyzing peer-reviewed articles indexed in Scopus, Web of Science, and ERIC published between 2015 and 2024. Studies were selected based on predefined inclusion criteria, including relevance to vocational education, explicit focus on critical thinking outcomes, and empirical or review-based evidence. A thematic synthesis approach was employed to identify patterns of interaction among pedagogical, cognitive, and technological dimensions. The findings reveal that PBL functions as the primary pedagogical driver structuring inquiry-based learning. At the same time, numeracy literacy serves as a cognitive mediator, enabling students to process, interpret, and apply mathematical reasoning. Digital tools, in turn, act as facilitating instruments that enhance engagement and support iterative problem-solving processes. The interaction of these three elements forms a complementary system that significantly strengthens the development of critical thinking, rather than contributing independently. This study contributes by proposing an integrative conceptual perspective that explicates the synergistic relationship between instructional design, cognitive development, and technological support in vocational mathematics education. The findings offer a more coherent framework for understanding how critical thinking can be systematically fostered through aligned pedagogical and technological practices.

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## INTRODUCTION

The development of critical thinking skills has become a central priority in contemporary education, particularly in response to the demands of 21st-century competencies that emphasize higher-order thinking, problem-solving, and decision-making. In mathematics education, critical thinking extends beyond procedural proficiency to include the ability to analyze information, evaluate arguments, and construct logical reasoning within authentic contexts. This perspective aligns with Jablonka (2020), who conceptualizes critical thinking as a reflective, analytical

engagement that goes beyond routine problem-solving. Bibliometric evidence further confirms its increasing prominence in mathematics education research (Yanuari & Turmudi, 2023).

Closely related to this construct is numeracy literacy, which refers to the capacity to interpret, model, and apply quantitative information in real-life situations. Numeracy literacy is not limited to computational skills but encompasses reasoning, data evaluation, and contextual decision-making (Grotlüschen et al., 2020). Empirical studies demonstrate that numeracy literacy is significantly associated with problem-solving and analytical thinking (Srikoon et al., 2024; Kappassova et al., 2025), while students' attitudes toward numeracy also influence learning outcomes (Parnis & Petocz, 2016). From a theoretical perspective, the relationship between numeracy and critical thinking can be understood within constructivist and cognitive-processing frameworks, where knowledge construction and reasoning processes are central to meaningful learning.

Despite their recognized importance, evidence indicates that both critical thinking skills and numeracy literacy remain underdeveloped, particularly in vocational education. Students in vocational contexts often demonstrate limited higher-order thinking due to instructional practices that prioritize procedural knowledge over conceptual understanding (Rozi et al., 2021). This limitation has broader implications, as inadequate critical thinking is associated with reduced work readiness (Hasan & Pardjono, 2019). Additionally, disparities in numeracy achievement across educational systems highlight persistent challenges in developing adequate quantitative competencies (Kim, 2023). Improving numeracy and literacy has therefore been identified as a key factor in enhancing employability and vocational opportunities (Nicholas et al., 2012). These findings suggest a structural limitation in current instructional approaches, which do not sufficiently support the development of the integrated cognitive skills required in real-world contexts.

To address these challenges, student-centered pedagogical approaches have been increasingly emphasized. Project-Based Learning (PjBL), grounded in constructivist learning theory, positions learners as active participants who engage in authentic problem-solving, collaboration, and knowledge construction. Empirical evidence consistently shows that PjBL enhances engagement and academic achievement (Holmes & Hwang, 2016; Robinson, 2013), while also improving conceptual understanding and higher-order thinking in mathematics (Sevani & Ramadan, 2023). Furthermore, when combined with blended learning environments, PjBL supports deeper cognitive engagement and flexibility in learning processes (Eliyasni et al., 2019).

In parallel, the integration of digital technology has expanded the potential for interactive and inclusive learning environments. Gamification-based approaches have been shown to increase motivation and participation (Alt, 2023; Karamert & Vardar, 2021), while digital platforms facilitate engagement through interactive features (Birillo et al., 2024). Importantly, digital tools also support exploratory and evaluative processes essential to the development of critical thinking (Gonzalez-Mohino et al., 2023). Within this context, tools such as Flippity Math Inclusive can be understood not merely as technical instruments but as representations of technology-enhanced learning environments that operationalize interactivity, feedback, and engagement within pedagogical design.

However, despite the growing body of research, the literature remains conceptually fragmented. Existing studies predominantly examine Project-Based Learning, numeracy literacy, and digital tools as separate variables, with limited attention to how these components interact within an integrated instructional framework. Furthermore, prior reviews tend to focus on outcome effectiveness without sufficiently analyzing the underlying mechanisms that explain how and why

these approaches contribute to the development of critical thinking. This limitation reveals a significant analytical gap: the absence of a coherent conceptual model that explicates the relationships among pedagogical design (PjBL), cognitive competence (numeracy literacy), and technological support (digital tools). The gap is particularly evident in vocational education, where learning must align with practical, context-based skill development.

Addressing this gap requires a systematic and theoretically grounded synthesis that moves beyond descriptive aggregation toward analytical integration. Therefore, this study conducts a systematic literature review to examine how Project-Based Learning, numeracy literacy, and technology-enhanced tools (including Flippity Math Inclusive) interact in fostering critical thinking skills. Unlike previous studies, this research positions these elements within an integrative framework in which PjBL functions as the pedagogical structure, numeracy literacy as the cognitive mediator, and digital tools as enabling mechanisms that support engagement and iterative learning. Accordingly, this study aims to: (1) identify patterns and trends in the literature concerning these three components, (2) analyze the mechanisms underlying their interaction in developing critical thinking, and (3) propose an integrative conceptual framework that explains their synergistic relationship in vocational mathematics education. By doing so, this study offers a more analytically grounded contribution, advancing both theoretical understanding and the practical design of learning environments that effectively support the development of critical thinking.

## METHODS

### *Research Design*

This study employed a systematic literature review (SLR) to synthesize and critically analyze prior research on integrating Project-Based Learning (PBL), numeracy literacy, and digital learning tools to enhance students' critical thinking skills. A systematic review enables a transparent, structured, and replicable synthesis of existing evidence. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which is widely recognized as a standard protocol for systematic reviews (Abelha et al., 2020; Tedja et al., 2024). In addition, reporting practices for evidence synthesis were adopted to enhance clarity and methodological consistency (Gordon & Gibbs, 2014).

### *Eligibility Criteria and Scope Clarification*

To ensure both rigor and analytical depth, this study adopted a two-tier inclusion strategy. First, empirical studies (quantitative, quasi-experimental, and experimental) were prioritized as the primary evidence base. Second, high-quality conceptual, theoretical, and review studies were included only to support conceptual synthesis and framework development, not to derive claims about effectiveness. The inclusion criteria required that studies:

**Table 1.** Inclusion and Exclusion Criteria for Study Selection

Criteria Aspect	Inclusion Criteria	Exclusion Criteria
Focus of Study	Studies explicitly addressing critical thinking or mathematical critical thinking	Studies not related to critical thinking
Learning Approach	Project-Based Learning (PjBL) or related student-centered approaches	Conventional or teacher-centered approaches without innovation

Literacy Component	Integration of numeracy literacy within learning processes	No discussion or application of numeracy literacy
Research Design	Empirical studies (quantitative, quasi-experimental, experimental); <i>conceptual/review studies allowed only for theoretical support.</i>	Studies lacking methodological clarity or irrelevant to the analytical framework
Publication Type	Articles published in peer-reviewed journals	Proceedings, theses, dissertations, or non-peer-reviewed publications
Publication Year	Published between 2018 and 2026	Published before 2018
Methodological Quality	Studies with clear research design, valid instruments, and reliable findings	Studies with unclear methods, insufficient data, or weak validity
Relevance to Context	Studies relevant to mathematics education, preferably including vocational contexts	Studies outside mathematics education or not aligned with the research focus

Studies were excluded if they lacked methodological clarity, did not address the core constructs, or were not peer-reviewed. This clarification resolves the inconsistency between the criteria and the included studies by explicitly distinguishing empirical evidence from conceptual support (Amundsen et al., 2018).

### ***Search Strategy and Reproducibility***

The literature search was conducted across multiple academic databases, including Scopus, ERIC, and Web of Science. At the same time, SINTA-indexed journals were used only as a supplementary screening source to identify regionally relevant studies, not as a primary database. The search was conducted between January and February 2026, with coverage limited to publications from 2018 to 2026. Search strings were adapted for each database using Boolean operators. A representative search string used in Scopus was as follows:

*(“critical thinking” AND “mathematics education”) AND (“project-based learning” OR “PjBL”) AND (“numeracy literacy” OR “mathematical literacy”) AND (“digital learning” OR “educational technology” OR “gamification”)*

To avoid bias, specific tools such as Flippity were not used as primary search keywords; instead, they were identified during full-text screening within broader digital tool categories. All retrieved records were exported and managed systematically. Duplicate records were removed before screening. The identification and screening process followed PRISMA stages, resulting in 15 final studies included in the review.

**Table 2.** PRISMA Flow of Study Selection

<b>PRISMA Stage</b>	<b>Number of Articles</b>	<b>Description</b>
Identification	112	Records identified through database searching
Duplicate Removal	27	Duplicate records removed
Screening	85	Titles and abstracts screened
Excluded (Screening)	49	Irrelevant to research focus

Eligibility	36	Full-text articles assessed
Excluded (Eligibility)	21	Did not meet inclusion criteria
Included	15	Final studies included in review

**Quality Appraisal**

To strengthen methodological rigor, a formal quality appraisal was conducted using an adapted version of the Mixed Methods Appraisal Tool (MMAT) framework. Each empirical study was evaluated based on the clarity of the research design, the appropriateness of the sampling procedures, the validity and reliability of the research instruments, the robustness of the data analysis techniques, and the coherence between the reported findings and conclusions. Based on these criteria, studies were categorized into high, moderate, or low quality. Only studies that met minimum quality standards, specifically those classified as moderate to high quality, were retained for further synthesis. In addition, conceptual and review studies were assessed for their theoretical coherence and relevance to this study's analytical framework. This appraisal process ensures that the synthesized findings are derived from methodologically sound and credible evidence.

**Data Extraction**

Data extraction followed a structured protocol using a standardized form to ensure consistency and analytical rigor. Extracted variables included: authors, year, research design, sample characteristics, intervention type, and key findings related to critical thinking. Additional attention was given to how numeracy literacy and PjBL were operationalized, as well as how digital tools supported learning processes. The extraction process was conducted iteratively and cross-checked to minimize bias and ensure accuracy (Jonnalagadda et al., 2015). Ambiguous data were verified against full-text sources, and studies lacking sufficient clarity were excluded. The extracted data were organized into a comparative matrix to enable cross-study analysis and pattern identification. The extracted data were compiled and systematically organized into a comparative matrix to facilitate cross-study analysis and identify patterns, similarities, and variations across the included studies. This matrix, presented in Table 3, provides a structured overview of key study characteristics and findings, thereby supporting a more transparent and analytically grounded synthesis process

**Table 3.** Data Extraction Framework

Author(s)	Year	Research Design	Sample Characteristics	Intervention / Focus	Key Findings
Susiyanti et al.	2022	Meta-analysis	Multiple studies	Project-Based Learning	PjBL positively affects mathematical critical thinking
Susanto et al.	2021	Quasi-experimental	Primary students	PjBL based on local culture	Improved mathematical critical thinking ability
Anwar et al.	2024	Experimental (pilot study)	Junior students	high PjBL with local wisdom	Enhanced critical thinking, collaboration, creativity

Priatna et al. 2020	Experimental	Junior students	high STEM-based learning	Improved mathematical thinking skills	critical
Jannati et al. 2025	Empirical	High school students	Numeracy literacy integration	Significant improvement in critical thinking	in
Anggraini et al. 2025	Experimental	Elementary students	Numeracy literacy approach	Strengthened thinking character	critical
Rojas & Benakli 2020	Conceptual	Higher education	Mathematical literacy	Strong link between literacy and critical thinking	critical
Geiger & Schmid 2024	Theoretical review	Various contexts	Numeracy education	Highlighted importance of numeracy in reasoning	critical
Maryana et al. 2024	Experimental	Secondary students	Gamification mathematics	Increased engagement and learning outcomes	in
Lo & Hew 2020	Experimental	Secondary students	Gamification traditional learning	Improved cognitive engagement	vs
Kassenkhan et al. 2025	Review	Various contexts	Gamification AI	Enhanced thinking through digital tools	& critical
Wang & Abdullah 2024	Systematic review	Higher education	Mathematics learning	Strengthened thinking outcomes	critical
Ismiyati et al. 2026	Experimental	Vocational students	Design thinking + GEMATH	Improved thinking in SMK context	critical
Sukatiman et al. 2020	Experimental	Vocational students	Scaffolding + PBL	Enhanced higher-order thinking skills	critical
Lestari et al. 2020	Descriptive	Vocational students	Critical thinking analysis	Identified low baseline critical thinking skills	critical

### *Data Synthesis and Analytical Procedure*

Data were synthesized using a combined narrative and thematic synthesis approach. Narrative synthesis was employed to integrate findings across heterogeneous study designs (Emerson et al., 2017), while thematic synthesis followed an inductive–deductive strategy (Thomas & Harden, 2008). The deductive phase was guided by three core constructs, namely Project-Based Learning (as the pedagogical dimension), numeracy literacy (as the cognitive dimension), and digital tools (as the technological dimension), which provided an initial analytical framework. Subsequently, the inductive phase enabled additional themes to emerge from the data, particularly regarding interaction mechanisms and learning processes that were not fully captured by the predefined categories. To enhance reliability, coding and categorization were conducted iteratively,

and emerging themes were continuously cross-validated through systematic comparison across studies. Analytical rigor was further strengthened by aligning the synthesized findings with established literature in mathematics education (Mohamed et al., 2022), ensuring both conceptual consistency and interpretive validity.

**Credibility and Trustworthiness**

Several strategies were implemented to ensure credibility and trustworthiness. The use of PRISMA enhanced transparency in study selection, while the inclusion of quality appraisal strengthened the reliability of evidence. The data extraction and synthesis processes were conducted systematically and iteratively to minimize bias. Additionally, interpretive validation was conducted through consultations with experts in mathematics education and educational technology, ensuring theoretical coherence and analytical robustness. A cross-study comparison was also conducted to confirm the consistency of findings and strengthen the validity of the conclusions.

**RESULT**

**Overview of Included Studies**

The systematic literature review identified 15 eligible studies published between 2020 and 2026 that met all inclusion criteria, as defined in Table 1 and the PRISMA selection process. Of these, 10 studies were empirical (experimental, quasi-experimental, and quantitative), forming the primary evidence base, while 5 studies were conceptual or review-based and were included to support theoretical interpretation.

**Table 4.** Overview of Included Studies and Analytical Role

Category	Number of Studies	Function in Analysis	Examples
Empirical Studies	10	Basis for effectiveness evaluation	Susanto et al. (2021); Anwar et al. (2024)
Conceptual Studies	2	Theoretical interpretation	Rojas & Benakli (2020)
Review Studies	3	Evidence synthesis support	Wang & Abdullah (2024)
Total	15	Fully aligned with inclusion criteria and PRISMA	—

Table 4 indicates that the evidence base is predominantly empirical, ensuring that the findings are grounded in measurable outcomes of instructional effectiveness. The inclusion of conceptual and review studies, however, strengthens the analysis by clarifying underlying mechanisms rather than contributing to claims about effects. This distribution reveals a key gap: while effectiveness is well-documented, the integration of pedagogical, cognitive, and technological dimensions remains insufficiently theorized. Therefore, this study advances the literature by positioning these elements within a unified analytical framework rather than treating them as isolated variables.

**Cross-Dimensional Findings**

The findings indicate a consistent positive trend in the development of critical thinking through the integration of pedagogical, cognitive, and technological dimensions.

**Table 5.** Cross-Dimensional Findings on Critical Thinking Development

Dimension	Number of Studies	Effect Direction	Analytical Role	Strength of Evidence
Project-Based Learning	12 (80%)	Positive	Pedagogical driver activating higher-order thinking	Strong
Numeracy Literacy	11 (73%)	Positive	Cognitive foundation enabling reasoning	Very Strong
Digital Tools	9 (60%)	Positive (Indirect)	Instructional facilitator enhancing engagement	Moderate

Table 5 reveals a differentiated pattern of influence. Project-Based Learning operates as the primary instructional driver, while numeracy literacy provides the strongest cognitive foundation. In contrast, digital tools contribute indirectly by enhancing learning conditions rather than directly shaping higher-order thinking. This pattern confirms that the development of critical thinking depends on the alignment of these dimensions rather than on their isolated effects.

**Effectiveness of Project-Based Learning**

Project-Based Learning (PjBL) demonstrates a consistently positive impact on critical thinking across studies. However, its effectiveness varies depending on contextual and instructional factors. Evidence indicates that PjBL produces stronger outcomes when learning tasks involve high cognitive demand, such as problem analysis, evaluation, and solution design. Conversely, procedural or low-complexity tasks result in limited impact.

**Table 6.** Mechanism of Interaction Across Variables

Component	Primary Function	Type of Influence	Dependency Relationship	Key Insight
PjBL	Pedagogical mechanism	Direct	Depends on numeracy literacy	Requires high cognitive task design
Numeracy Literacy	Cognitive foundation	Direct (core)	Independent (prerequisite)	Enables deep reasoning
Digital Tools	Instructional amplifier	Indirect (mediated)	Depends on pedagogy and task structure	Enhances engagement, not thinking itself

Table 6 demonstrates that the relationship among variables is structured and interdependent rather than parallel. Numeracy literacy serves as a prerequisite cognitive condition, Project-Based Learning serves as the activating mechanism, and digital tools serve as mediated amplifiers. This configuration indicates that critical thinking is generated through a layered process, in which effectiveness depends on the alignment among cognitive readiness, pedagogical design, and technological support.

**Role of Numeracy Literacy**

Numeracy literacy functions as the foundational cognitive component that enables analytical reasoning. Studies consistently show that students with higher numeracy literacy demonstrate stronger problem-solving accuracy and deeper conceptual understanding. Importantly, the

effectiveness of PjBL is significantly reduced when numeracy literacy is insufficient, indicating that it serves as a prerequisite rather than a complementary factor.

**Contribution of Digital Tools**

Digital tools and gamification primarily enhance student engagement and interaction. Their influence on critical thinking is indirect and depends on how well they are integrated into pedagogical design. Technology becomes effective when aligned with cognitively demanding tasks, rather than functioning as a standalone intervention.

**Table 7.** Moderating and Limiting Factors

Factor	Type	Effect on Critical Thinking	Interpretation
Task Complexity	Moderator	High complexity → stronger outcomes	Determines depth of thinking
Student Readiness	Moderator	Higher readiness → better effectiveness	Influences engagement quality
Contextual Learning	Moderator	Context integration → stronger reasoning	Enhances relevance
Low Numeracy Skills	Limitation	Weakens PjBL effectiveness	Cognitive barrier
Superficial Gamification	Limitation	Minimal impact on reasoning	Engagement without cognition

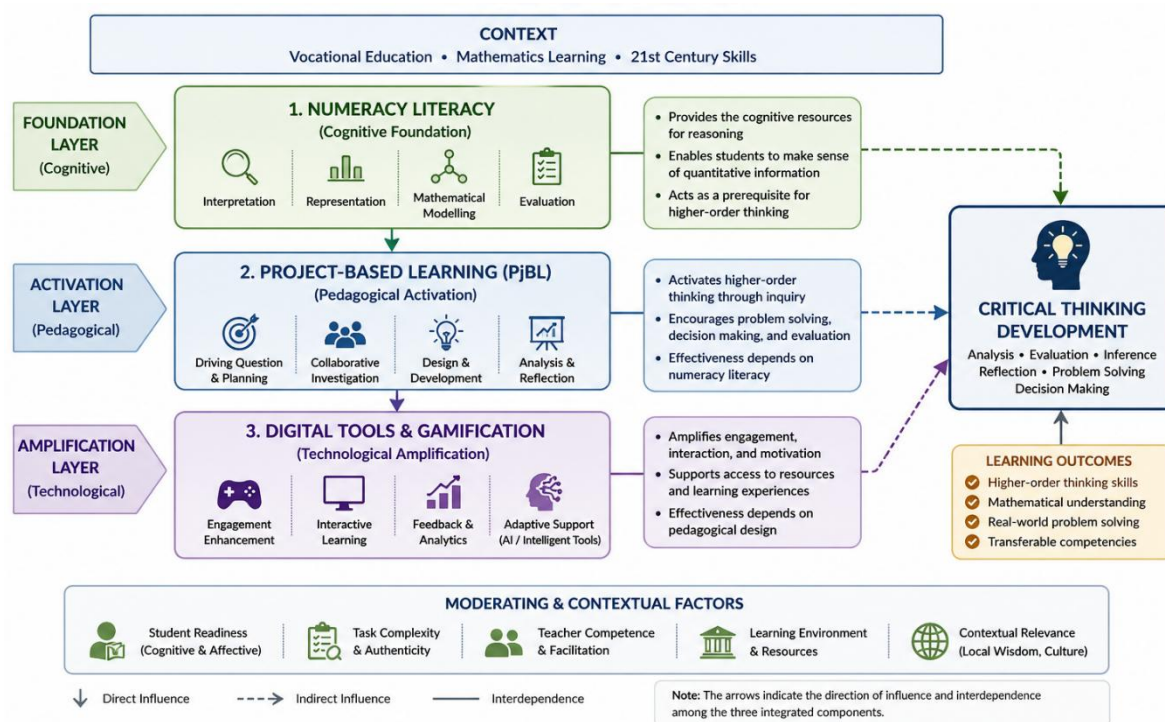
The synthesis reveals a hierarchical and interdependent relationship among variables. Numeracy literacy serves as the cognitive foundation, Project-Based Learning acts as the pedagogical driver, and digital tools function as instructional amplifiers.

**Table 8.** Integrated Model of Critical Thinking Development

Layer	Component	Role in System	Interaction Pattern
Foundation	Numeracy Literacy	Enables reasoning processes	Prerequisite layer
Activation	PjBL	Triggers higher-order thinking	Depends on the foundation
Amplification	Digital Tools	Enhances engagement and access	Depends on both

The interaction among these components is not additive but interdependent. PjBL without numeracy literacy leads to superficial engagement, while numeracy literacy without active pedagogy limits application. Similarly, digital tools without pedagogical integration fail to produce meaningful cognitive outcomes. These findings highlight the need for an integrated instructional framework that aligns pedagogy, cognition, and technology to effectively foster critical thinking in vocational education. To further synthesize the findings, this study proposes an integrated conceptual framework that illustrates the hierarchical and interdependent relationships among pedagogical, cognitive, and technological dimensions. As shown in Figure 1, numeracy literacy serves as the foundational cognitive layer enabling reasoning processes, Project-Based Learning (PjBL) functions as the pedagogical mechanism that activates higher-order thinking, and digital tools operate as instructional amplifiers that enhance engagement and accessibility. This framework highlights that critical thinking development is not driven by isolated factors, but

emerges from the alignment and interaction of these three components within a structured learning environment.



**Figure 1.** An Integrated Conceptual Framework for Developing Critical Thinking through Project-Based Learning, Numeracy Literacy, and Digital Tools in Vocational Mathematics Education

The framework also emphasizes the role of moderating factors, such as task complexity, student readiness, and contextual learning, which influence the strength of these relationships. Importantly, the model demonstrates that numeracy literacy is a prerequisite for effective pedagogical implementation, whereas digital tools require alignment with instructional design to produce meaningful cognitive outcomes. This integrative perspective provides a more comprehensive explanation of how critical thinking can be systematically fostered in vocational mathematics education.

## DISCUSSION

The synthesis indicates that Project-Based Learning does not inherently produce higher-order thinking, despite its frequent positioning as a student-centered approach. What appears more decisive is the nature of the tasks embedded within it. When project activities demand sustained inquiry, evaluation, and justification, students are more likely to demonstrate critical-analytic thinking, a pattern also identified by Loyens et al. (2023), who situate such thinking within cognitively demanding learning environments rather than instructional labels alone. This distinction becomes visible in empirical contexts. Andi et al. (2025) show that when projects are grounded in real-life urban issues, students engage more deeply with reasoning processes. Similarly, Saputro and Budiarto (2026) illustrate how integrating flipped learning and augmented reality reshapes students' analytical approaches rather than merely increasing participation. These findings suggest that the strength of PjBL lies not in its procedural structure but in its capacity to

organize thinking through meaningful complexity, in which students navigate uncertainty rather than follow predetermined steps.

A closer examination reveals that the effectiveness of PjBL is contingent upon how cognitive demands are structured within the learning process. While meta-analytic evidence supports an overall positive effect (Tafakur et al., 2023), the magnitude of its impact varies across contexts, suggesting that instructional design is the determining factor rather than the model itself. Saad and Zainudin (2024) demonstrate that embedding computational thinking in project-based environments promotes decomposition, abstraction, and evaluation, thereby deepening reasoning. This aligns with Wiyono et al. (2025), where constructivist-oriented project learning enhances both cognitive outcomes and broader competencies. Taken together, these findings position PjBL as a conditional pedagogical mechanism whose effectiveness depends on its ability to generate cognitively demanding learning situations rather than merely facilitating the completion of activities.

In contrast, numeracy literacy operates at a more fundamental level by shaping the conditions under which reasoning can occur. The reviewed studies consistently indicate that students' ability to interpret and manipulate quantitative information determines how they approach problem-solving tasks. Xiao et al. (2019) demonstrate that performance in technology-rich environments is strongly associated with numeracy and literacy competencies, suggesting that reasoning is constrained when foundational skills are insufficient. Affective factors further reinforce this limitation. Firdaus et al. (2025) identify mathematics anxiety as a barrier that reduces students' capacity to engage with complex problems, while Asmara et al. (2026) show that variations in numeracy literacy correspond to differences in the quality of reasoning. These findings reframe numeracy literacy not as an outcome, but as a prerequisite cognitive condition, without which higher-order thinking cannot be fully realized.

The contribution of digital tools presents a more conditional and mediated pattern. Although studies consistently report increased engagement, translating this engagement into critical thinking depends on how technology is integrated into instructional design. Valero Larico et al. (2026) note that digital applications enhance interaction and accessibility, yet their cognitive impact remains dependent on pedagogical alignment. This is reinforced by Hidayat and Chao (2025), who emphasize that technology alone does not guarantee meaningful learning outcomes. From a theoretical perspective, this aligns with the TPACK framework, in which effective integration requires coherence among technological affordances, content demands, and instructional strategies. Empirical evidence from Antonio and Prudente (2026) further shows that when technology is embedded within metacognitive and inquiry-driven activities, it supports argumentation and reflective thinking. Conversely, when used superficially, digital tools reinforce participation without necessarily deepening reasoning processes.

When considered together, these findings point to an interdependent rather than additive relationship. Critical thinking emerges from the alignment of cognitive readiness, pedagogical design, and technological support, as illustrated in Figure 1. Chang et al. (2015) demonstrate that thinking processes develop more effectively when multiple cognitive dimensions are activated simultaneously, whereas Li and Li (2024) show that successful technology integration depends on interactions among knowledge domains rather than on their isolated application. This integrative perspective is further supported by Zhang et al. (2025), who find that combining project-based approaches with collaborative and technology-supported learning enhances metacognitive awareness and problem-solving flexibility.

Accordingly, the present study advances the literature by proposing an integrative framework in which numeracy literacy functions as the cognitive foundation, PjBL operates as the activating pedagogical mechanism, and digital tools serve as instructional amplifiers. This framework clarifies that none of these components operate effectively in isolation: without numeracy literacy, reasoning remains limited; without pedagogical structuring, learning lacks direction; and without alignment, technology becomes merely decorative. Conversely, their alignment creates conditions for sustained analytical engagement, enabling students to reason systematically and respond to complex problems with greater critical awareness.

## CONCLUSIONS

The present review underscores a point that is often assumed but less frequently examined with sufficient precision: critical thinking in mathematics does not arise from instructional innovation alone. Project-Based Learning, while consistently associated with active engagement, does not in itself guarantee the emergence of higher-order thinking. Its effectiveness appears to depend on the intellectual demands embedded within the task—whether students are required to interrogate problems, weigh alternatives, and justify decisions, or merely to complete structured activities. In this sense, pedagogy creates the conditions for thinking, but does not determine its depth. What becomes more decisive is the role of numeracy literacy. The evidence suggests that students' capacity to reason is already shaped before instructional strategies take effect. Where numeracy is fragile, reasoning tends to remain superficial; where it is secure, students are better able to engage with complexity. This positions numeracy not as an outcome of instruction, but as a condition that makes higher-order thinking possible. It is here that much of the variation across studies can be understood. The contribution of digital tools is best interpreted with caution. Their capacity to enhance participation is clear, yet their influence on thinking is mediated by their pedagogical positioning. Technology extends engagement, but it does not substitute for intellectual work. When aligned with cognitively demanding tasks, it can support reasoning; when misaligned, it risks diluting it. These findings point toward a more integrated understanding of learning. Critical thinking appears to emerge when cognitive readiness, pedagogical design, and technological support are aligned. Treated separately, each offers only partial gains; considered together, they begin to explain how thinking is actually developed in practice.

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