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ORIGINAL RESEARCH REVIEW

Technology-Integrated Problem-Based Learning in Mathematics Education: A Scoping Review of Technological Trajectories, Pedagogy, Learning, and Challenges

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ABSTRACT

Technology-integrated problem-based learning (TI-PrBL) is gaining attention as an approach that combines digital tools, artificial intelligence, and real-world problems to enhance mathematics teaching and learning. This scoping review evaluates existing theoretical and empirical evidence on TI-PrBL in mathematics education to examine its pedagogical foundations, impact on students' problem-solving skills, and the challenges faced in its implementation. A scoping review design was adopted, guided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework, to identify and map relevant studies. The review revealed four key themes. First, the evolution of technology use shows a shift from tools that emphasized efficiency, such as calculators and spreadsheets, toward platforms that foster inquiry, collaboration, and visualization, including GeoGebra, Desmos, and generative AI. Second, TI-PrBL is anchored in constructivist, self-regulated, and transformative learning theories, highlighting its capacity to strengthen higher-order thinking, autonomy, and reflective engagement. Third, consistent findings point to its positive impact on mathematical problem-solving, with students demonstrating deeper conceptual understanding, flexible strategies, and collaborative reasoning in TI-PrBL environments. Finally, challenges persist, including limited teacher preparedness, an accelerating digital divide due to inequitable access to technology, and gaps in student digital literacy, which raise concerns about the long-term sustainability and inclusivity of the TI-PrBL framework. Overall, the findings suggest that TI-PrBL holds strong potential to enhance mathematical problem-solving when aligned with authentic, real-world tasks and supported by inclusive technological access, institutional investment, and hybrid instructional models that balance inquiry-based and teacher-guided learning.

Keywords: *Digital divide, Generative AI, Mathematics Education, Problem-Based Learning*

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INTRODUCTION

In the rapidly evolving educational landscape, technology has emerged as a transformative force, reshaping traditional teaching methodologies and redefining how students engage with learning materials. In fact, a specific study indicates that technology can enhance student learning outcomes by improving engagement, motivation, and academic performance when effectively integrated into teaching practices (Kumari et al., 2023). In mathematics education, integrating dynamic simulations, interactive representations, and technology-supported problem-based learning has been found to improve students' conceptual understanding, reasoning, and transfer of learning (Dockendorff, 2019). These developments have normalized learner-centered and data-informed instructional practices, creating conditions for more advanced digital innovations. Consequently, the emergence of artificial intelligence (AI) in mathematics instruction, through intelligent tutoring systems, adaptive feedback, and learning analytics, represents an evolutionary extension of earlier technology integration rather than a pedagogical rupture, offering scalable support for individualized learning and complex problem-solving (Borah and Borah, 2024; Mahmoud and Sørensen, 2024; Kanvaria and Srivastava, 2025).

Rather than being the sole cause of educational transformation, the COVID-19 pandemic served as a significant catalyst, accelerating the adoption of digital, online, and blended learning environments. This period of rapid transition compelled educators and institutions to experiment with technology-mediated instruction at an unprecedented scale, prompting stakeholders to reflect on how the competencies, pedagogical strategies, and digital infrastructures developed during this time could be sustained and further enhanced through emerging technologies such as AI (Eteokleous et al., 2023). With this, the digital revolution has introduced new ways to acquire knowledge, shifting from passive, teacher-centered instruction to dynamic, interactive, and student-driven learning experiences. Traditional classrooms, once limited to textbooks and blackboards, now incorporate multimedia resources, artificial intelligence, real-time simulations, and interactive problem-solving environments, enabling students to visualize abstract concepts and engage in more meaningful learning. This shift is particularly crucial in mathematics education, where conceptual understanding and problem-solving skills are fundamental.

Mathematics education, in particular, demands problem-solving and analytical reasoning skills that are crucial for both academic success and real-world application. However, persistent challenges hinder Filipino students' mathematical proficiency, particularly in word problem comprehension and conceptual understanding. This issue is further exacerbated by the country's consistently low performance in international assessments such as the Program for International Student Assessment (PISA), where Filipino students rank significantly below global proficiency standards. One of the reports revealed that Filipino students scored an average of 353 points in Mathematics Literacy, significantly below the OECD average of 489 points and placing them the lowest among six ASEAN countries (Golla and Reyes, 2020). Upon reviewing the questionnaires used in international assessments such as PISA, it becomes clear that there is a strong emphasis on word problems and contextualized questions, a component in which many Filipino learners consistently encounter difficulties in Mathematics.

Moreover, many Filipino students face significant challenges when solving word problems in mathematics, as these tasks require more than just numerical skills; they also demand strong reading comprehension, logical reasoning, and the ability to translate real-life situations into mathematical expressions. According to the 2024 functional literacy, education, and mass media survey (FLEMMS) conducted by the Philippine Statistics Authority (PSA), around 18 million Filipinos who have completed basic education may still be functionally illiterate (Philippine Statistics Authority, 2024). This alarming figure aligns with Jyotsana and Pavi (2024) findings, which noted that students often struggle to grasp the narrative structure of word problems, thereby hampering their ability to construct appropriate mathematical representations. These difficulties point to a deeper issue that goes beyond mathematics alone, highlighting the linguistic barriers that many learners must overcome. Thus, developing students' problem-solving abilities requires a dual focus on both linguistic and numerical literacy, ensuring they have the tools to interpret and engage meaningfully with real-world mathematical tasks.

Simultaneously, difficulties in grasping abstract mathematical concepts further impede problem-solving, as Filipino learners often rely on rote memorization rather than meaningful understanding. Research by Xin (2023) indicates that students with learning difficulties frequently apply ineffective procedures when attempting to solve math word problems, stemming from a limited grasp of the underlying concepts and problem-solving process itself. This results in a reliance on superficial strategies, such as keyword identification or pure memorization, rather than a deeper understanding of the mathematical concepts. This gap between procedural and conceptual mastery underscores the need for innovative instructional strategies that foster deeper cognitive engagement, critical thinking, and long-term retention of mathematical concepts.

A compelling strategy for addressing this challenge is Problem-Based Learning (PrBL), an instructional methodology that immerses students in the active exploration of authentic, context-rich word problems. This approach fosters collaborative problem-solving, supports the development of robust cognitive frameworks for knowledge construction, and cultivates habits of self-directed learning through iterative practice and critical reflection (Schmidt and Moust, 2000; Norman and Schmidt, 1992; Hmelo-Silver, 2004). Ideally, PrBL encourages students to construct their own knowledge through inquiry, collaboration, and reflection. By presenting learners with complex, open-ended problems, PrBL promotes critical thinking and better problem-solving skills (Mahfudhoh and Andrijati, 2024). However, despite its effectiveness, traditional mathematics education in the Philippines remains predominantly teacher-centered, limiting students' opportunities to engage in meaningful problem-solving.

To bridge this gap, technology-integrated problem-based learning (TI-PrBL) has emerged as a dynamic instructional approach that combines the principles of PrBL with digital technology to improve problem-solving skills. Digital platforms such as GeoGebra, Desmos, Wolfram Alpha, and generative AI-powered tools like ChatGPT provide interactive environments where students can visualize abstract mathematical concepts, test hypotheses, and receive instant feedback in mathematics instruction. This integration is particularly significant in STEM education, where TI-PrBL fosters dynamic learning environments that promote collaboration, critical thinking, and real-world applicability. In the context of mathematics education, technology-integrated problem-based learning (TI-PrBL) remains less explored. For this approach to be effectively implemented in Filipino classroom settings, it must be anchored in robust theoretical and empirical foundations pertinent to mathematics instruction.

Hence, this scoping review aims to synthesize theoretical and empirical literature on Technology-Integrated Problem-Based Learning (TI-PrBL) in mathematics education. The primary direction of this review is to establish a foundational basis for TI-PrBL as a practical approach for enhancing students' mathematical problem-solving skills and to offer evidence-informed recommendations for its effective implementation in educational settings.

Specifically, the study seeks to: (1) examine the evolution of technology use in mathematics education within TI-PrBL contexts, highlighting shifts in digital tools and instructional applications; (2) analyze the cognitive and pedagogical foundations underpinning TI-PrBL, with emphasis on learning theories that support inquiry, collaboration, and higher-order thinking; (3) evaluate the reported impact of TI-PrBL on students' mathematical problem-solving skills, including conceptual understanding, reasoning, and collaborative learning outcomes; and (4) identify the challenges, implementation issues, and sustainability concerns encountered in the adoption of TI-PrBL in mathematics education.

MATERIALS AND METHODS

Research design

This study employed a scoping review design to systematically identify, map, and synthesize existing theoretical and empirical literature on technology-integrated problem-based learning (TI-PrBL) in mathematics education. A scoping review was deemed appropriate given the emerging, interdisciplinary, and methodologically diverse nature of TI-PrBL research, where the primary objective is to examine the breadth, characteristics, and thematic patterns of existing studies rather than to evaluate effect sizes or establish causal relationships (Munn et al., 2018; Godfrey, 2020).

While the review followed systematic and transparent procedures, including predefined inclusion and exclusion criteria, structured database searches, and a documented screening process guided by the PRISMA framework, its intent aligns with the scoping review methodology for mapping research trends, theoretical foundations, instructional applications, and implementation challenges of TI-PrBL across educational contexts.

Literature search and theme identification

The identification of relevant research studies was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Moher et al., 2009). Multiple meta-search engines were utilized, including Crossref, Scopus, Taylor and Francis, Semantic Scholar, and OpenAlex. The literature search was facilitated using Harzing's Publish or Perish (PoP) software.

Inclusion and exclusion criteria

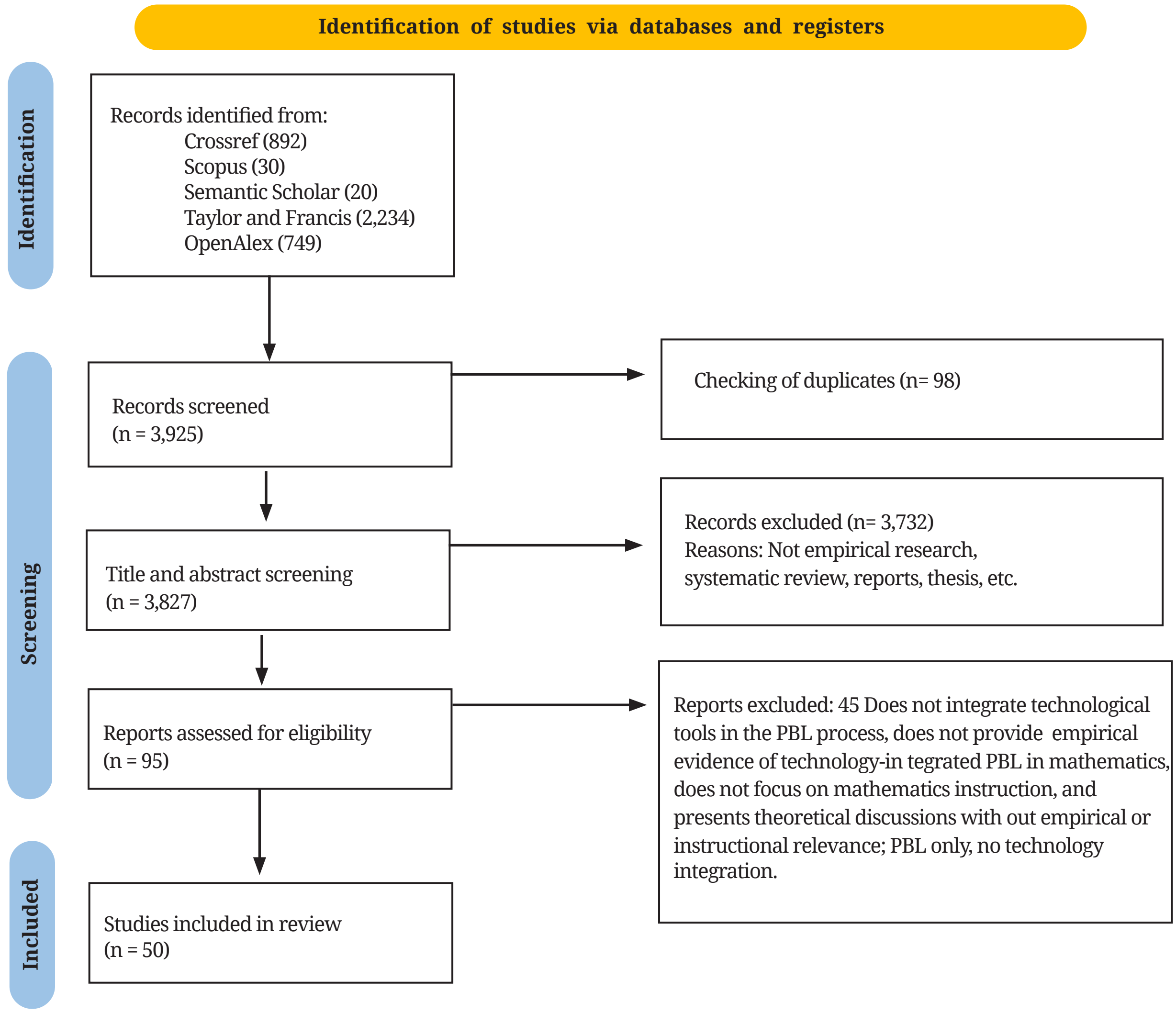

Figure 1. Flow diagram of the literature search using PRISMA protocol.

The search strategy was developed to capture literature on the integration of technology in problem-based learning within mathematics education. Keywords were grouped around three core concepts: (1) mathematics education ("mathematics education," "math instruction," "STEM education"), (2) problem-based learning ("problem-based learning," "PBL," "problem solving," "active learning"), and (3) technology integration ("technology integration," "educational technology," "digital technology," "AI in education," "GeoGebra," "Desmos," "gamification," "virtual reality"). These terms were combined using Boolean operators and adapted for database searches in Publish or Perish, ensuring comprehensive retrieval of both general and tool-specific studies. The review covered studies from 2005 to 2025 to capture both the early emergence of technology-enhanced approaches in mathematics education (e.g., GeoGebra, graphing tools) and the most recent innovations such as AI, gamification, and VR. This range ensures inclusion of foundational work and current developments in technology-integrated problem-based learning.

Following the literature search and screening process, the included studies were subjected to theme identification. Guided by Braun and Clarke's (2006) thematic analysis approach, each study was coded inductively and deductively based on its focus, research design, context, and outcomes. Codes were iteratively refined and clustered into higher-order categories, which were then synthesized into the four themes that structured the results. Studies were included in the synthesis if they focused on mathematics education, with particular emphasis on mathematics instruction. To be considered, studies needed to examine problem-based learning, problem-solving, or constructivist/active learning approaches relevant to PrBL, and demonstrate the integration of digital or technological tools such as graphing calculators, GeoGebra, Desmos, gamification platforms, AI applications, VR/AR, Google Jamboard, spreadsheets, or other educational technologies. Eligible studies were those conducted in formal educational settings (primary, secondary, or higher education) or those that reported implications applicable to mathematics teaching and learning. Only publications from 2005 to 2025, written in English or with an English translation, and published as peer-reviewed journal articles, conference proceedings, or book chapters were included.

Moreover, studies were excluded if they did not explicitly involve mathematics learning contexts, did not incorporate technology integration in relation to PrBL or problem-solving, or were limited to theoretical discussions without empirical or instructional relevance. Non-academic publications, editorials, opinion papers, theses, and reports outside the defined time frame or not available in English were also excluded.

As shown in figure 1 above, during the identification process, a total of 3,827 records were retrieved from Crossref (n = 892), Scopus (n = 30), Semantic Scholar (n = 20), Taylor and Francis (2, 234) and OpenAlex (n = 749). After removing 98 duplicates, 3,827 records were screened by title and abstract, of which 3,732 were excluded because they represented non-empirical research, systematic reviews, reports, theses, or other irrelevant publication types. A total of 95 full-text reports were assessed for eligibility, with 45 excluded for not integrating technological tools into the PrBL process, not focusing on mathematics instruction, or lacking instructional relevance. Finally, 50 studies met all inclusion criteria and were included in the review.

RESULTS

The graphical analysis of the indexed keywords associated with technology-integrated problem-based learning (TI-PrBL) from 2005–2025, generated through VOSviewer, is presented in Figures 2 and 3. In the co-occurrence network map, the size of each node (circle) reflects the frequency and prominence of the keyword across the included publications. At the same time, the link strength and connection density indicate how closely related these concepts are within the scholarly discourse. Larger circles, such as mathematics education, problem-based learning, and technology, are shown to be central in the literature, suggesting that these terms serve as foundational anchors in TI-PrBL research.

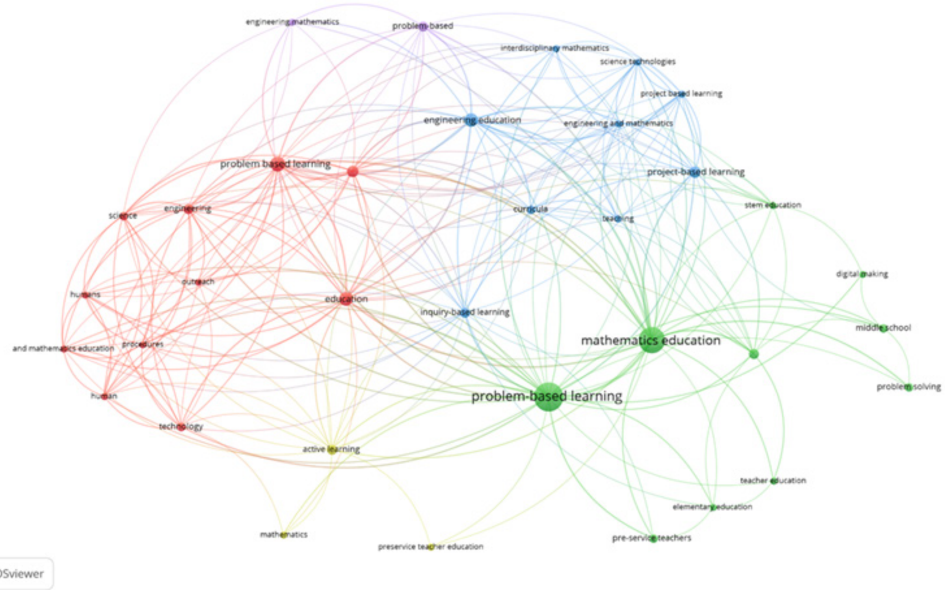

Figure 2. Co-occurrence network map of terms in the articles' abstract and title linked with "Problem-based leaning in mathematics education"

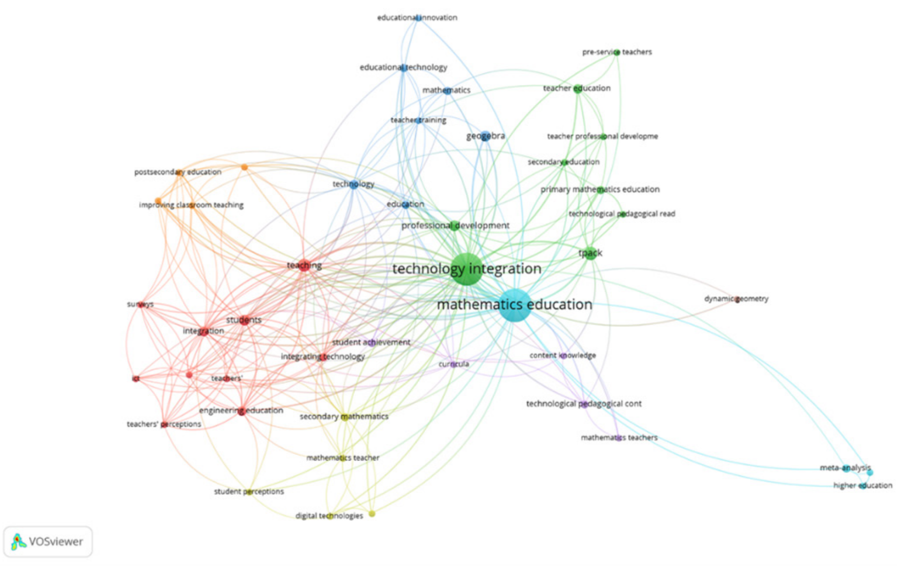

Figure 3. Co-occurrence network map of terms in the articles' abstract and title linked with "Technology integration in mathematics education"

The cluster analysis further revealed five major thematic groupings, each representing distinct but interconnected strands of research within TI-PrBL. Based on the cluster analysis of 47 index keywords associated with "Problem-based learning in Mathematics Education" studies, the most common terms mentioned in the articles' keywords are mathematics education, problem-based learning, engineering, technology (Cluster 1), digital making, elementary education, problem solving, stem education, teacher education (Cluster 2), curricula, inquiry-based learning, teaching (Cluster 3), and active learning, mathematics, pre-service teacher education (Cluster 4) and Cluster 5. However, the smallest includes terms such as engineering mathematics and problem-based, which represent specialized applications of TI-PrBL in discipline-specific contexts (see Figure 2). The network map illustrates that TI-PrBL research is not isolated within mathematics education alone but is embedded in a broad, interconnected ecosystem spanning STEM education, teacher preparation, curriculum innovation, digital making, and inquiry-based pedagogy.

Meanwhile, the cluster analysis of the 64 keywords revealed eight thematic groupings that outline the structure of research on technology integration in mathematics education (see Figure 3). The most common terms clustered around ICT use, teaching practices, and teachers' perceptions (Cluster 1); pre-service teachers and TPACK-oriented professional development (Cluster 2); educational innovation and teacher training (Cluster 3); and digital technologies within secondary mathematics contexts (Cluster 4). Additional clusters emphasized curriculum, content knowledge, and student achievement (Cluster 5); flipped classroom models and evidence-based evaluations (Cluster 6); instructional improvement and teacher education (Cluster 7); and specialized tools such as dynamic geometry (Cluster 8).

Table 1. General study characteristics of the included studies on technology-integrated problem-based learning (TI-PrBL) in mathematics education.

Author/s (Year)	Country	Educational level	Technology integration	Learning approach / pedagogy
Canonigo (2024)	Philippines	Secondary education (Grade 10)	AI tools (GeoGebra, ChatGPT, adaptive learning platforms, intelligent tutoring systems, data-driven instruction)	Collaborative learning, teacher-led discussion, problem-solving
Silva et al. (2025)	Ecuador	Primary/Elementary Education (Grade 5)	Gamification tools (Kahoot!, Prodigy Math, virtual badges, leaderboards, points/rewards systems)	Gamification (interactive digital games, rewards, badges, leaderboards), compared with conventional teaching
Filiz and Gür (2025)	Turkey	Higher Education (Pre-service teachers, 4th year)	ChatGPT (AI tool for problem-solving support)	Problem-solving with AI support; Metacognitive awareness development
Govender et al. (2024)	Nigeria	Primary Education (Grades 5–6)	Digital tools integrated in ACT model (curation, conversation, correction, creation, chaos)	Activated classroom teaching (ACT) pedagogy; Design-based research
Korenova et al. (2024)	Czech Republic	Higher Education (Pre-service teachers, Faculty of Education)	GeoGebra (dynamic geometry), Kahoot (e-testing), learning Apps, AR/VR tools	Digital technology integration in teacher education; reflective practice; innovative teaching strategies
Körtesi et al. (2022)	Slovakia	Higher Education (First-year university students)	Computer algebra systems (CAS), Dynamic geometry systems (DGS), symbolic calculators	Mixed teaching methods; active and innovative strategies; sustainability of math knowledge through test–retest design
Mollakuqe and Mollakuqe (2025)	North Macedonia	Secondary (High School, ages 15–18)	GeoGebra software (interactive visualization tool)	Experimental vs. traditional teaching; 8-week intervention; focus on engagement, active participation, and conceptual understanding
Schmid and Korenova (2024)	Czech Republic	Tertiary (Pre-service teacher education, 1st–2nd year)	GeoGebra (dynamic applets), AR, VR, 3D printing	Design-based research (DBR); iterative teaching model blending traditional methods (paper-pencil) with digital tools; emphasis on engagement, spatial reasoning, algorithmic/critical thinking
Supiter and Rabut (2025)	Philippines	Secondary (Grade 10)	Desmos graphing calculator	Student-centered learning; Use of interactive visualization tools; Phenomenological exploration of learner experiences
van Borkulo et al. (2023)	Netherlands	Upper Secondary (Grade 11)	Spread sheets	Design-based research; Computational thinking framework (Brennan and Resnick); Authentic data exploration
Dani and Ashok (2025)	Malaysia	Secondary	DESMOS (online graphing calculator, virtual manipulative)	5E model (Engage, explore, explain, elaborate, evaluate); Design-based research
Leong and Parrot (2018)	Malaysia	Secondary	Graphing calculator	Problem-solving based
Shadaan and Leong (2013)	Malaysia	Secondary	GeoGebra	Technology-assisted learning
Arirao (2025)	Philippines	Secondary (Grade 9)	AI-powered tools (Cici, Photomath, ChatGPT)	Mixed-method; AI-assisted learning with surveys, interviews, pre-/post-tests, classroom observations

Song et al. (2025)	Malaysia	Elementary	Artificial intelligence (AI) tools	Mixed-methods: Quasi-experimental (pre/post-tests), traditional vs AI-supported instruction, qualitative interviews
Llorente and Tado (2024)	Philippines	Higher Education (College, 1st year)	Technology-enhanced learning (general integration of digital tools)	Problem-based learning (PBL); mediation model linking technology integration and student engagement
Boom-Cárcamo et al. (2024)	Colombia	Higher Education	Gamification tools integrated in instruction	Problem-based learning (PBL) + Gamification
Santoso and Sedjoko (2019)	Indonesia	Junior High School (Grade 7)	Mobile learning application (MMLA – Android app "Learning rectangle")	Problem-based learning (PBL)
Segal and Biton (2024)	Israel	Higher Education	Generative AI (ChatGPT) for problem posing and refinement	Problem posing approach; TPACK Framework; AI-supported pedagogy
Mengyao and Ismail (2025)	Malaysia	Secondary level (Mathematics classes)	Technology-enhanced SDG contextual real-life problems; ADDIE instructional design	Sustainable development goals problem-based learning (SDG-PBL); real-life problem integration mixed-method instructional evaluation
Amalia et al. (2023)	Indonesia	Senior High School	GeoGebra	Problem-based learning with focus on representation, simulations, problem exploration, and inquiry learning
Amallya et al. (2025)	Indonesia	Senior High School (Grade XI)	GeoGebra	Problem-based learning (PBL) with emphasis on mathematical communication and problem-solving
Noviyana et al. (2025)	Indonesia	Elementary Education (Grade 5)	AI-assisted instruction and PBL environment	AI-Integrated problem-based learning using polya's problem-solving stages
Araiza-Alba et al. (2021)	Australia	Elementary (Ages 7–9.9)	Immersive virtual reality (IVR) for problem-solving games	Problem-solving skills development through IVR; comparison with tablet and board game; includes engagement and knowledge transfer assessment
Essuman and Wilmot (2024)	Ghana	Tertiary (Pre-service math teacher education)	General digital tools for algebra instruction	Technology-supported mathematics teaching; descriptive survey on perceptions and challenges
Ye et al. (2024)	China	Higher Education / Applied Mathematics	Large language models (LLM), automated reasoning chain and personalized explanation systems	AI-assisted problem solving with adaptive personalization; intelligent tutoring system framework
Rahmah and Zahra (2025)	Indonesia	Not explicitly stated (general student population)	AI-powered chatbots and virtual assistants for real-time math problem support	Technology-supported interactive and adaptive learning; student-centered assistance
Lê et al. (2025)	Vietnam	Secondary (10th Grade Algebra) and Teacher Professional Development	ChatGPT used to generate real-world algebra problems	Training-based adoption of AI for generating authentic PBL tasks; grounded in Technology Acceptance Model
Sinuraya (2023)	Indonesia	Senior High School (Grade X)	Digital problem-based learning student worksheets (Electronic LKPD) developed using ADDIE	Problem-based learning (PBL) supported by digital worksheets; development-evaluation research
Gorev and Gurevich-\ Leibman (2015)	Israel	Tertiary (Mathematics teacher education)	Dynamic geometry software, hypertexts, applets, videos	Technology-integrated mathematics instruction emphasizing inquiry and tool adaptation to tasks
Triwahyun-ingtyas et al. (2020)	Indonesia	Elementary School (Grade 3)	Kvisoft flipbook maker for digital PBL e-module	Problem-based learning using digital interactive e-modules; ADDIE model development
Sukkamart et al. (2024)	Thailand	Middle School (Mathayom 2)	Blended learning digital platforms supporting online + face-to-face instruction	Problem-based blended learning (PBBL) to enhance computational thinking and academic achievement
Harini et al. (2023)	Indonesia	Not explicitly stated (K–12 level; topic: ratios)	Digital E-worksheets for mathematics	Technology-supported problem-based learning emphasizing self-directed learning and independent problem solving
Pitorini et al. (2024)	Indonesia	Not explicitly stated (school-level application)	E-module integrating PBL elements and Socratic questioning	Problem-based learning combined with structured socratic dialogue for developing critical thinking
Choirunisa and Susanti (2024)	Indonesia	Senior High School (Grade X)	Photomath app used to assist in solving SPLTV problems	Problem-based learning enhanced by AI-assisted solution checking and guided reasoning

Laksmiwati (2018)	Indonesia	Junior Secondary School (Grade 8 / Year 2)	GeoGebra used to support learning of Pythagorean theorem	Problem-based learning supported by action research cycles focused on improving student self-confidence
Suratno and Waliyanti (2023)	Indonesia	Junior High School (Grade 8)	GeoGebra integrated into mathematics lessons	Problem-based learning approach emphasizing problem-solving enhancement
Bellatama et al. (2025)	Indonesia	Junior High School	Wordwall digital gamified activities embedded in PBL module	Problem-based learning integrated with gamification to improve engagement, mastery, and practicality
Chaiarwut et al. (2025)	Thailand	Secondary School Level	Constructivist digital learning platform with interactive tools	Constructivist problem-based digital learning model supporting executive mathematical problem-solving
Martínez-Gómez and Nicolalde (2025)	Ecuador	Secondary School	Mobile learning application providing digital access to math resources	Problem-based learning facilitated through mobile learning to develop collaborative, decision-making, and problem-solving skills
Yang et al. (2025)	China	Vocational High School	Digital learning platform enabling problem-based digital learning (PBDL)	Problem-based digital learning focusing on improving mathematics proficiency and creative problem solving
Biton and Segal (2025)	Israel	Pre-Service Teacher Education	Generative AI (ChatGPT) used to craft, refine, and analyze mathematical prompts	Inquiry-based and problem-posing learning supported by AI to enhance TPACK and problem development skills
Segal et al. (2025)	Israel	Teacher Educator Professional Development	Generative AI (ChatGPT) used to analyze pedagogical and mathematical scenarios	AI-supported professional learning to enhance TPACK through problem analysis and pedagogical decision-making
Handayani et al. (2022)	Indonesia	Junior High School	GeoGebra applied in creative problem-solving learning model	GeoGebra-supported CPS approach to develop mathematical problem-solving and improve learning interest
Safira and Darmawan (2025)	Indonesia	Undergraduate Mathematics Education	Physical statistical board as a technology-based concrete instructional aid	Problem-based learning enhanced with hands-on visualization tools to develop critical thinking and conceptual understanding
Nurmanita et al. (2019)	Indonesia	Senior High School (Grade XI)	GeoGebra integrated in developed lesson plans, teacher's book, student book, worksheets, and assessments	Problem-based learning using the 4-D development model to improve mathematical critical thinking
Muchlis et al. (2021)	Indonesia	University (Plane Geometry Course)	Web-based worksheet integrating GeoGebra exploration for concept discovery	Project-based learning (PjBL) supported by GeoGebra, emphasizing independent exploration and conceptual understanding
Binri and Hidayati (2022)	Indonesia	Junior High School (Grade VIII)	Developed lesson plans and student worksheets (technology-mediated learning materials)	Problem-based learning oriented toward improving problem-solving skills, validated for practicality and effectiveness
Dahal et al. (2022)	Nepal	Junior High School (Grade IX)	GeoGebra used to visualize geometric transformations through digital objects, images, and animations	Problem-based and discovery learning supported by GeoGebra for collaborative exploration of transformation concepts
Septian et al. (2020)	Indonesia	High School (not explicitly specified; likely secondary level)	GeoGebra used for visualization and problem-solving activities involving 3D mathematics concepts	GeoGebra-assisted problem-based learning shown to improve problem-solving ability and positive student attitudes

Encompassing Asia (Philippines, Malaysia, Indonesia, Thailand, Vietnam, China), Europe (Turkey, Slovakia, Czech Republic, Netherlands, North Macedonia), Latin America (Colombia, Ecuador), Africa (Nigeria, Ghana), and Oceania (Australia). Regarding educational levels, secondary education remains the most frequently examined stage, reflecting its critical role in developing mathematical reasoning and problem-solving skills. A substantial portion of research also targeted higher education, particularly pre-service teacher education programs and professional development for mathematics teacher educators. However, fewer studies focused on primary and elementary levels.

The technologies integrated across studies vary considerably, ranging from established platforms such as GeoGebra, Desmos, spreadsheets, and graphing calculators, to newer tools like artificial intelligence (ChatGPT, Photomath, adaptive learning platforms, LLMs), gamification applications (Kahoot!, Prodigy Math, Wordwall), mobile learning applications, and immersive technologies (IVR, AR/VR, 3D printing). Pedagogically, the integration of technology was primarily framed within problem-based learning (PrBL) and related active learning strategies. Many studies employed experimental and quasi-experimental designs to compare TI-PrBL with traditional approaches, reporting improvements in student engagement, conceptual understanding, problem-solving performance, and positive attitudes toward mathematics. Other studies adopted design-based research (DBR) or development-evaluation frameworks, emphasizing iterative refinement of technology-enhanced learning materials and pedagogical strategies. Several studies also explored teacher-focused applications, including pre-service teacher training, problem-posing with AI, and professional development for teacher educators, highlighting reflective practice and enhancement of Technological Pedagogical Content Knowledge (TPACK) as critical components.

DISCUSSION

The findings of this scoping review demonstrate how technology-integrated problem-based learning (TI-PrBL) has evolved in mathematics education, the cognitive and pedagogical foundations underpinning its use, its reported impact on students' problem-solving skills, and the challenges and sustainability concerns shaping its implementation across diverse contexts.

1. Evolution of technology use in mathematics education

Across the reviewed studies, the progression of technology use in mathematics education demonstrates a clear shift from basic digital tools toward advanced, intelligent, and immersive learning environments. Analysis of the 44 relevant studies reveals three chronological phases: (1) foundational digital tools, (2) interactive and multimodal platforms, and (3) AI-driven personalized systems. This evolution reflects a broader pedagogical transition from technology as a productivity aid toward technology as a cognitive partner in mathematical inquiry, aligning with contemporary goals of conceptual understanding, epistemic agency, and authentic problem solving.

Early studies (2013–2019) primarily documented the use of calculators, spreadsheets, dynamic geometry software, and mobile applications to improve computational efficiency, visualization, and basic problem-solving. Tools such as GeoGebra, graphing calculators, digital worksheets, and mobile learning apps were widely adopted to support procedural fluency and conceptual exploration. Studies involving GeoGebra (e.g., Shadaan and Leong, 2013; Laksmiwati, 2018; Nurmanita et al., 2019) consistently reported improvements in visualization, confidence, and foundational problem-solving skills. Similarly, Picaza et al. (2024) reported that the experimental group, which received traditional instruction integrated with GeoGebra, demonstrated a statistically significant improvement in trigonometry performance among Filipino college students in Southern Mindanao. While these tools enhanced representational access and learner engagement, most implementations remained teacher-directed and skill-oriented, suggesting that early digital integration primarily reinforced procedural and conceptual efficiency rather than epistemic inquiry.

By the early to mid-2020s, research showed increasing adoption of multimodal platforms, including gamification tools, blended learning systems, digital e-modules, augmented/virtual reality, and web-based learning environments. Studies integrating game-based approach and gamification components (e.g., Silva et al., 2025; Boom-Cárcamo et al., 2024; Bellatama et al., 2025; Payot et al., 2025) reported enhanced performance, engagement, motivation, and participation. Likewise, immersive and interactive platforms, such as VR-based problem-solving (Araiza-Alba et al., 2021), AR tools for geometric reasoning, and blended learning systems (Sukkamart et al., 2024), enable learners to manipulate digital objects, explore mathematical relationships, and collaborate more effectively. This phase marks a pedagogical shift toward active, student-centered learning, supported by diverse digital modalities. Teacher education programs also reflected this evolution, with studies showing integration of GeoGebra, Kahoot, AR/VR, and 3D technologies in developing future teachers' technological and pedagogical competencies (Korenova et al., 2024; Muchlis et al., 2021). However, although these tools expanded representational fluency and engagement, their pedagogical impact depended heavily on task design and instructional framing, with inquiry-oriented gains emerging primarily when technologies were embedded within problem-based and collaborative learning structures.

Recently, the most relevant studies (2024–2025) illustrate a transition toward AI-enhanced mathematics instruction, including tools such as ChatGPT, AI chatbots, adaptive learning systems, and large language model (LLM) based tutoring environments. These technologies provided personalized feedback, automated reasoning chains, step-by-step guidance, and context-aware problem-solving support. Studies using ChatGPT and related generative AI tools (Canonigo, 2024; Filiz and Gür, 2025; Arirao, 2025; Segal and Biton, 2024; Lê et al., 2025) emphasized improvements in explanation quality, mathematical reasoning, task generation, and student support. AI-powered instructional systems for elementary and secondary learners (Song et al., 2025; Rahmah and Zahra, 2025) highlighted benefits in real-time assistance, error correction, and scaffolding of complex tasks. More advanced applications, such as LLM-based automated reasoning systems (Ye et al., 2024), demonstrated capabilities for adaptive personalization and intelligent tutoring, representing the newest stage in technological evolution. In contrast, Roquero et al. (2025) found that the relationship between AI utilization and mathematics achievement was weak and statistically non-significant. Furthermore, the mediation analysis indicated that AI utilization did not exert a significant mediating effect among BSED Mathematics students in a Philippine state college in Southern Mindanao.

Taken all these accounts, these only reveal that technological advancement alone does not guarantee pedagogical transformation. Rather, the trajectory of technology integration in mathematics education reflects a gradual shift from representational enhancement toward epistemic participation, where tools increasingly mediate reasoning, explanation, and problem formulation rather than merely solution execution. This evolution points to the importance of aligning emerging technologies with inquiry-oriented pedagogies such as TI-PrBL, ensuring that intelligent systems amplify mathematical meaning-making rather than encourage cognitive offloading, procedural dependence and overreliance.

2. Cognitive and pedagogical foundations of TI-PrBL

The reviewed studies indicate that technology-integrated problem-based learning (TI-PrBL) is grounded in multiple theoretical and pedagogical frameworks. These foundations are synthesized and visually represented in a researcher-developed conceptual diagram (see Figure 4). Across the literature, TI-PrBL is most consistently situated within Constructivist, Self-Regulated Learning, and Transformative Learning traditions, with technology functioning not merely as an instructional aid but as a mediational tool that reshapes how learners engage in mathematical inquiry, reasoning, and meaning-making.

Many studies situated TI-PrBL within Constructivist perspectives, drawing from both Social and Cognitive Constructivism to create active, socially mediated learning environments where knowledge is built through collaboration and exploration (Wood, 2008; Abbas et al., 2013; Vygotsky, 1978; Waite-Stupiansky and Cohen, 2023). Technology serves as a cognitive extension of these constructivist principles by enabling manipulation of mathematical representations, facilitating collaborative inquiry, and creating interactive learning spaces. For example, tools such as GeoGebra, dynamic geometry environments, interactive e-modules, and mobile learning applications have been shown to support conceptual exploration, real-time visualization, and student-driven discovery (e.g., Amalia et al., 2023; Suratno and Waliyanti, 2023; Dahal et al., 2022). Immersive platforms such as VR-based environments (Araiza-Alba et al., 2021) and blended digital systems (Sukkamart et al., 2024) further reinforced constructivist learning by enabling students to engage with mathematical ideas through manipulation, simulation, and collaborative problem-solving. These environments reflect a consistent pattern across the literature that technology amplifies the exploratory nature of PrBL by expanding opportunities for interaction, interpretation, and meaning-making. However, the review also suggests that constructivist gains are contingent on instructional design quality, as technologically rich environments can devolve into procedural tool use when inquiry framing, justification, and collaborative meaning-making are insufficiently foregrounded.

Self-regulated learning (SRL) theory was also widely applied in TI-PrBL research, emphasizing students' development of metacognitive awareness, strategic action, and motivational regulation (Winne and Perry, 2000; Zimmerman, 2008). Many TI-PrBL studies highlight how technology supports metacognitive monitoring, strategic decision-making, and motivational regulation as students navigate open-ended mathematical tasks. Digital tools such as GeoGebra, Desmos, AI chatbots, Photomath, ChatGPT, and automated feedback systems were frequently used to scaffold learners' reasoning processes, allowing them to test hypotheses, receive immediate feedback, revise strategies, and reflect on their solutions (Arirao, 2025; Noviyana et al., 2025; Choirunisa and Susanti, 2024; Filiz and Gür, 2025). Digital learning modules developed using ADDIE and 4-D instructional design models (Triwahyuningtyas et al., 2020; Sinuraya, 2023; Nurmanita et al., 2019) also provided structured SRL-aligned environments that guided students through cycles of exploration, evaluation, and refinement. These studies consistently showed that technology not only supported students' problem-solving performance but also strengthened autonomy, persistence, and the regulation of learning strategies, hallmarks of SRL aligned with PrBL pedagogy. At the same time, the review highlights a tension between scaffolding and cognitive offloading, particularly when automated systems provide rapid solutions without transparent reasoning pathways, underscoring the importance of pedagogical orchestration that cultivates epistemic agency rather than procedural dependence.

In addition, several studies referenced Transformative Learning Theory (TLT) as a foundation for TI-PrBL (Mezirow, 1991; Christie et al., 2015). Within this lens, advanced technologies such as generative AI and automated reasoning systems were incorporated. TI-PrBL designs that included tools like ChatGPT, LLM-based reasoning assistants, or AI-driven feedback systems encouraged learners to critically evaluate generated solutions, compare strategies, and engage in reflective judgment before accepting or modifying outputs (Canonigo, 2024; Segal and Biton, 2024; Ye et al., 2024). These reflective cycles contributed to deeper shifts in learners' understanding, prompting them to interrogate assumptions, refine interpretations, and adopt more sophisticated mathematical reasoning strategies. The literature also points to pedagogical models such as the Activated Classroom Teaching (ACT) framework (Govender et al., 2024) and creative problem-solving models (Handayani et al., 2022), which position technology as a mechanism for promoting active engagement, disciplined inquiry, and higher-order thinking.

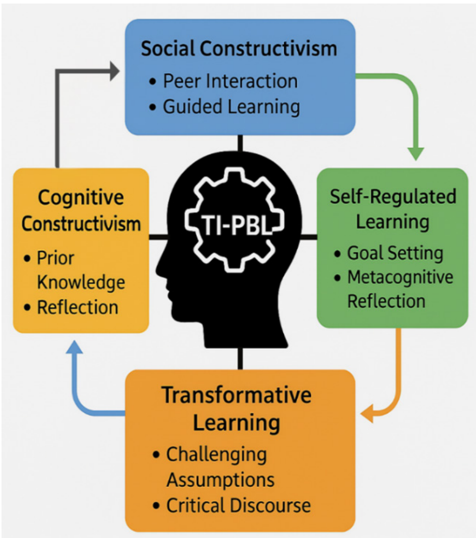

Figure 4. Theoretical anchor of technology-integrated problem-based learning (TI-PrBL).

Despite these strengths, the review reveals notable theoretical gaps. Influential integrative frameworks such as technological pedagogical content knowledge (TPACK) and situated learning theory (SLT) are largely limited, limiting conceptualization of how disciplinary knowledge, pedagogy, and technological affordances co-evolve within TI-PrBL designs. Without a TPACK lens, studies risk treating technology as an additive enhancement rather than as a constitutive element of mathematical representation and pedagogical reasoning. Similarly, the limited use of situated learning perspectives constrains analysis of how learners participate in disciplinary practices, transfer knowledge across contexts, or develop durable mathematical identities through authentic problem engagement. These omissions contribute to a broader pattern in the literature: strong evidence of short-term instructional effectiveness but limited explanatory power regarding mechanisms of learning, durability of outcomes, and scalability across diverse educational systems.

3. Impact of TI-PrBL on students' problem-solving skills

The reviewed studies consistently demonstrate that technology-integrated problem-based learning (TI-PrBL) exerts a substantial positive influence on students' mathematical problem-solving abilities. In fact, a wide range of digital tools was shown to contribute to these gains. GeoGebra, one of the most frequently studied tools, consistently supported students' visualization, conceptual reasoning, and structured problem-solving processes (Amalia et al., 2023; Amallya et al., 2025; Suratno and Waliyanti, 2023; Handayani et al., 2022; Dahal et al., 2022). Studies incorporating GeoGebra in PrBL and inquiry-based tasks reported enhanced representation skills, improved spatial reasoning, and greater confidence in tackling multi-step problems (Septian et al., 2020; Nurmanita et al., 2019; Muchlis et al., 2021; Binri and Hidayati, 2022). Similarly, digital worksheets, e-modules, and blended learning materials built through systematic design models (e.g., ADDIE, 4-D) facilitated scaffolded learning pathways that strengthened students' ability to analyze problems, test hypotheses, and refine solutions (Triwahyuningtyas et al., 2020; Sinuraya and Frisnoiry, 2023; Harini et al., 2023). These tools collectively demonstrate that interactive visualizations and structured digital environments deepen students' engagement with problem-solving cycles, particularly when embedded within inquiry-rich and collaborative pedagogical contexts.

More recent studies have extended these findings by integrating artificial intelligence, gamified PrBL, blended digital environments, and mobile learning applications. AI-assisted learning tools, including ChatGPT, Photomath, AI chatbots, and LLM-based reasoning systems, were found to support real-time feedback, guided reasoning, and strategic decision-making, strengthening students' problem-solving accuracy and self-regulated learning processes (Arirao, 2025; Noviyana et al., 2025; Choirunisa and Susanti, 2024; Song et al., 2025; Rahmah and Zahra, 2025; Ye et al., 2024). Immersive and blended PrBL environments such as VR, gamification-enhanced modules, and problem-based digital learning platforms similarly improved students' computational thinking, creativity, decision-making, and collaborative problem-solving (Araiza-Alba et al., 2021; Bellatama et al., 2025; Sukkamart et al., 2024; Chaiarwut et al., 2025;

Martínez-Gómez and Nicolalde, 2025; Yang et al., 2025). Teacher education studies further demonstrated that technology-supported inquiry and problem-posing tasks strengthened pre-service teachers' abilities to analyze, refine, and design mathematical problems, thus reinforcing the pedagogical foundations of problem-solving instruction (Schmid and Korenova, 2024; Korenova et al., 2024; Biton and Segal, 2025; Segal and Biton, 2024; Segal et al., 2025).

Beyond performance outcomes, the review indicates that TI-PrBL environments foster important metacognitive and dispositional dimensions of problem solving. Students exposed to technology-mediated inquiry demonstrate increased persistence, strategic experimentation, and reflective monitoring of their reasoning processes, aligning with self-regulated learning accounts of mathematical cognition. Visual modeling tools, adaptive feedback systems, and collaborative platforms enable learners to externalize thinking, test assumptions, and refine arguments through peer dialogue. These affordances contribute not only to improved solution accuracy but also to greater epistemic agency, as learners increasingly justify methods, evaluate alternatives, and negotiate meaning within problem-solving communities.

However, the review also identifies important boundary conditions. While most studies report strong short-term gains, interventions are typically classroom-bound, technologically scaffolded, and limited in duration, raising unresolved questions about durability and transfer. Few studies examine whether students who demonstrate strong performance in technology-rich PrBL environments sustain comparable reasoning in non-digital contexts or in everyday problem situations. Moreover, the increasing use of generative AI introduces risks of cognitive offloading and surface-level engagement, particularly when automated tools provide rapid solutions without transparent reasoning pathways. These findings suggest that the impact of TI-PrBL on problem-solving skills depends not merely on access to advanced tools but on instructional designs that foreground explanation through mathematical discourse, validation, reflection through meaning-making, and metacognitive control.

4. Challenges, issues, and sustainability concerns in implementing TI-PrBL

The reviewed studies consistently highlighted a range of challenges that constrain the effective implementation of technology-integrated problem-based learning (TI-PrBL) in mathematics education. A recurring issue concerns the pedagogical complexity of designing technology-enhanced problem-based lessons, as teachers often struggled to balance real-world problem contexts with the cognitive demands introduced by digital tools. Studies revealed that poorly aligned technological features, such as dynamic geometry environments, VR/AR tools, spreadsheets, and AI-supported platforms, sometimes increased students' cognitive load or fragmented the learning process when design scaffolds were insufficient (Korenova, Krpec and Barot, 2024; Schmid and Korenova, 2024; van Borkulo et al., 2023). Several teacher-focused studies emphasized the need for structured support strategies, such as mini-lessons, formative check-ins, and guided modelling, as educators reported difficulties adapting their instructional practices to technology-enhanced PrBL without sustained mentorship and iterative refinement (Segal and Biton, 2024; Biton and Segal, 2025; Segal, Biton and Alush, 2025). There is also a limited TPACK preparation; pre-service teacher studies further indicated that educators required more extensive professional development to effectively plan, implement, and troubleshoot TI-PrBL environments (Essuman and Wilmot, 2024).

Student-related challenges echoed these instructional concerns. Several studies documented that when expectations for technology use in problem-based tasks were unclear, students experienced confusion, disengagement, and difficulty managing the multiple steps required in exploratory digital environments. This was particularly evident in studies involving visualization tools, blended platforms, and VR applications, where insufficient teacher scaffolding led students to focus more on navigating the tool than on solving the mathematical problem itself (Mollakuqe and Mollakuqe, 2025; Sukkamart et al., 2024). Barriers related to unequal access to devices and unstable connectivity were also evident, especially in studies conducted in rural or resource-constrained contexts, where student participation in technology-enhanced tasks was limited by infrastructural disparities (Canonigo, 2024; Supiter and Rabut, 2025). Even when access was available, digital literacy gaps hindered effective engagement, with students in AI- and app-supported environments sometimes relying excessively on automated features rather than developing conceptual understanding (Rahmah and Zahra, 2025; Ye et al., 2024). These patterns reflect broader risks of cognitive offloading and surface-level engagement, particularly in technology-rich environments where reasoning processes are not made transparent.

Systemic and sustainability challenges further reinforced these difficulties. Studies highlighted that schools, particularly in developing countries, faced persistent shortages of digital resources, insufficient funding, and infrastructural limitations that restricted sustained implementation of TI-PrBL, aligning with the realities of underfunded and high-needs educational contexts (Canonigo, 2024; Martinez-Gómez and Nicolalde, 2025). Other studies developing digital worksheets, e-modules, and gamified PrBL tools reported concerns about practicality, scalability, and long-term maintenance, noting that many innovations remained at the pilot level due to limited institutional capacity (Binri and Hidayati, 2022; Bellatama et al., 2025; Sinuraya, 2023). Sustainability concerns also extended to teachers' ability to keep pace with rapidly evolving technologies, dependence on external platforms that required periodic updates, and variable school-level support for continuous teacher upskilling (Biton, 2024; Segal, Biton and Segal, 2025).

Taken together, these findings suggest that the effectiveness of TI-PrBL depends not only on pedagogical design and technological affordances but also on systemic conditions that support teacher learning, infrastructural stability, and institutional coherence. Without sustained investments in professional development, curriculum redesign, and equitable access to digital resources, TI-PrBL risks remaining a collection of short-term innovations rather than evolving into a durable instructional paradigm. These challenges are particularly pronounced in low-resource and Global South contexts, where structural inequities may limit the scalability and inclusivity of technology-mediated inquiry. Thus, the long-term viability of TI-PrBL hinges on coordinated efforts to align pedagogy, technology, and policy in ways that sustain epistemically rich learning environments while mitigating inequities in access and opportunity.

CONCLUSION

This scoping review highlights the transformative potential of technology-integrated problem-based learning (TI-PrBL) for strengthening students' mathematical problem-solving skills and identifies critical conditions for its sustainable implementation. The findings indicate that TI-PrBL supports higher-order thinking by engaging learners in authentic, complex tasks that promote reasoning, application, and conceptual understanding.

First, more substantial alignment with international benchmarks such as the Program for International Student Assessment (PISA) is essential. Designing TI-PrBL tasks around real-world and situational problems can better cultivate higher-order thinking skills than an overreliance on multiple-choice formats, which have shown limited effectiveness in developing mathematical problem-solving competencies. Second, the persistent digital divide remains a significant barrier. Effective implementation of TI-PrBL requires access to reliable technology, digital infrastructure, and learner digital literacy. Without inclusive strategies such as low-bandwidth, offline, or mobile-first solutions, TI-PrBL risks exacerbating existing educational inequities. Third, sustained investment in educational infrastructure and policy support is critical. Classroom-level innovation alone is insufficient without systemic efforts to address device and connectivity shortages and secure long-term institutional backing. Finally, the findings suggest the need to explore hybrid instructional models. While TI-PrBL is effective for applied and collaborative learning, certain abstract mathematical concepts may benefit from structured, teacher-guided instruction. A balanced approach that integrates traditional methods with technology-enhanced, inquiry-driven learning offers a pragmatic pathway for diverse educational contexts.

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AUTHOR CONTRIBUTIONS

D. C. M: Conceptualization, development of research questions, drafting and writing the manuscript. C. R. B: Scoping review and literature search, methodology design. R. A. N: Analysis of results, writing of discussion, validation of themes

DECLARATION

Informed consent statement

This study is a scoping review of existing literature and did not involve human participants, animals, or the collection of primary data. Therefore, ethical approval was not required. All sources included in this review were cited correctly and acknowledged to ensure academic integrity.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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