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Developing Pre-Service Mathematics Teachers' TPACK Through Digital Learning Environments: A Literature Review

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Abstract

The development of pre-service mathematics teachers' competence in integrating technology has become a central issue in contemporary teacher education. One of the most widely used frameworks for understanding this competence is Technological Pedagogical Content Knowledge (TPACK), which refers to the integrated knowledge of technology, pedagogy, and subject matter. This article aims to review how digital learning environments contribute to the development of pre-service mathematics teachers' TPACK. Using a narrative literature review approach, this article synthesizes studies published between 2010 and 2025 that discuss TPACK, mathematics teacher education, digital learning environments, dynamic mathematics software, virtual simulations, technology-based microteaching, collaborative task design, online and hybrid learning, and professional development. The review indicates that digital learning environments can strengthen TPACK when technology is not treated merely as a technical tool, but is embedded in pedagogical design and mathematical representation. TPACK development is more effective when pre-service teachers engage in authentic learning experiences, such as technology-based task design, digital microteaching, virtual simulation, collaborative lesson planning, feedback, reflection, and the use of dynamic mathematics software. However, several challenges remain, including infrastructure limitations, unequal access to digital tools, variation in digital literacy, limited institutional support, and the lack of longitudinal evidence on the sustainability of TPACK development in real teaching practice. This article argues that mathematics teacher education programs need to design digital learning environments that are structured, contextual, reflective, collaborative, and sustainable so that TPACK development moves beyond technical proficiency toward meaningful pedagogical competence.

Keywords: TPACK, pre-service mathematics teachers, digital learning environment, mathematics teacher education, literature review.

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INTRODUCTION

The development of digital technology has transformed mathematics education, particularly in the ways mathematical concepts are represented, explored, communicated, and taught. Mathematics is no longer learned only through symbolic notation, manual procedures, and verbal explanation, but also through dynamic visualization, simulation, virtual manipulatives, geometry software, online platforms, and interactive applications. This transformation has important implications for mathematics teacher education because pre-service teachers are now expected to possess more complex competencies than mastery of mathematical content and conventional teaching strategies. They need to understand how digital technology can support conceptual understanding, mathematical reasoning, classroom discussion, problem solving, and active learning.

In mathematics teacher education, technology integration should not be understood merely as the ability to operate digital tools. The ability to use GeoGebra, spreadsheets, simulations, learning management systems, or other mathematical applications does not automatically mean that pre-service teachers are able to teach mathematics effectively with technology. Technology becomes pedagogically meaningful only when it is selected based on learning objectives, the characteristics of mathematical content, students' learning needs, and appropriate instructional strategies. Therefore, the development of pre-service mathematics teachers' competence should be directed toward the integrated use of technological, pedagogical, and content knowledge.

Technological Pedagogical Content Knowledge (TPACK) provides an important framework for explaining such competence. TPACK positions technology-based teaching as the intersection of technological knowledge, pedagogical knowledge, and content knowledge (Agyei & Voogt, 2012; Bowers & Stephens, 2011; Hyde & Edwards, 2011). In mathematics teacher education, this framework is particularly relevant because mathematics requires accurate representation, conceptual explanation, and pedagogical strategies that help students understand abstract mathematical objects. Through TPACK, pre-service teachers learn not only how to select digital tools, but also when, why, and how those tools should be used to support meaningful mathematics learning.

Previous studies have shown that digital learning environments can support the development of pre-service mathematics teachers' TPACK. Agyei and Voogt (2012) demonstrated that collaborative design activities help pre-service mathematics teachers develop TPACK through lesson planning, technology selection, and reflective discussion. Agyei and Voogt (2015) further found that a mathematics-specific instructional technology course

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improved pre-service teachers' competence in integrating spreadsheets into mathematics teaching. Bhagat et al. (2017) showed that GeoGebra integration can enhance teachers' professional development and TPACK. Similarly, Chai et al. (2020) reported that STEM-TPACK design-based learning strengthened pre-service teachers' efficacy in integrating science, mathematics, engineering, and technology.

Recent studies also indicate that digital learning environments are becoming increasingly diverse. TPACK development is no longer limited to training in the use of mathematics software. It also involves technology-based microteaching, technology-enhanced active learning, virtual simulation, hybrid learning, digital task design, game-based learning, digital storytelling, and artificial intelligence. Jeon and Rim (2023) showed that robot programming activities can improve pre-service mathematics teachers' TCK, TPK, and TPACK. Hai et al. (2025) found that technology-enhanced active learning environments can improve all TPACK components and strengthen pre-service teachers' technology beliefs. Ngwabe and Boateng (2025) also showed that the use of digital and non-digital visualization tools in microteaching can improve pre-service mathematics teachers' technological, technological pedagogical, and technological content knowledge.

Despite these positive contributions, the implementation of digital learning environments still faces several challenges. Infrastructure limitations, internet access, device availability, teacher educator readiness, students' digital literacy, and institutional support remain major issues in mathematics teacher education (Ahmad, 2025; Hidayat & Chao, 2024; Zulu, 2025). Moreover, the availability of technology does not necessarily lead to meaningful mathematics learning if it is not supported by strong pedagogical design. Edson and Thomas (2019) emphasized that digital resources alone are insufficient; teachers need to transform their knowledge so that digital materials can be used pedagogically. Thus, the central issue is not simply whether technology is available, but how it is integrated into the design of mathematics learning.

Based on this background, this article aims to review the development of pre-service mathematics teachers' TPACK through digital learning environments. The review focuses on four main questions: first, how TPACK functions as a core competence in mathematics teacher education; second, what forms of digital learning environments support TPACK development; third, what strategies can strengthen TPACK through design, practice, collaboration, and reflection; and fourth, what challenges remain in developing TPACK through digital learning environments. This article is expected to provide a conceptual synthesis for mathematics teacher education programs in designing digital learning environments that are not limited to

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technical training, but also strengthen pedagogical competence, mathematical content knowledge, and technology-based teaching readiness.

METHOD

This article employed a narrative literature review approach. This approach was selected because the purpose of the article was to synthesize theoretical ideas and empirical findings related to the development of pre-service mathematics teachers' TPACK through digital learning environments. A narrative literature review allows the researcher to organize previous studies thematically, identify recurring patterns across the literature, and construct conceptual arguments based on relationships among key findings. Unlike meta-analysis, this review did not aim to calculate statistical effect sizes. Instead, it focused on interpreting and integrating relevant studies to explain how digital learning environments contribute to TPACK development in mathematics teacher education.

The literature reviewed in this article was limited primarily to studies published between 2010 and 2025. This period was selected because research on TPACK, digital mathematics learning environments, online learning, virtual simulation, and technology-enhanced teacher education has expanded significantly during this timeframe. Publications before 2010 were not included in the main analysis, except where they were necessary to provide foundational theoretical context. The selected literature consisted of journal articles, conference papers, book chapters, and theoretical studies that addressed TPACK, mathematics teacher education, technology integration, digital learning environments, dynamic mathematics software, virtual simulation, online and hybrid learning, technology-based microteaching, digital task design, and professional development for mathematics teachers.

The selection of literature was guided by several inclusion criteria. First, the study had to discuss technology integration in mathematics education or mathematics teacher education. Second, it had to address TPACK or components related to technological, pedagogical, and content knowledge. Third, it had to provide insights into digital learning environments, instructional strategies, teacher competence development, or challenges in technology integration. Fourth, the study had to present conceptual or empirical information that could be synthesized to explain the development of pre-service mathematics teachers' TPACK. Studies were excluded when they focused only on general educational technology without a clear connection to mathematics education, did not discuss teacher knowledge or teacher preparation, or did not provide sufficient conceptual or methodological information for synthesis.

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The analysis was conducted in three stages. The first stage involved identifying and reading relevant studies to determine their main focus, theoretical framework, educational context, and contribution to TPACK development. The second stage involved grouping the literature into four thematic categories: TPACK as a core competence in digital mathematics teaching, forms of digital learning environments that support TPACK, strategies for developing TPACK through design and practice, and challenges in implementing digital learning environments. The third stage involved narrative synthesis, in which findings from different studies were compared, connected, and interpreted to identify common patterns, differences, and implications for mathematics teacher education. Through this process, the review did not merely summarize individual studies, but developed a broader conceptual explanation of how digital learning environments can strengthen pre-service mathematics teachers' TPACK.

RESULTS AND DISCUSSION

TPACK as a Core Competence for Pre-Service Mathematics Teachers in Digital Learning

TPACK is a central framework for understanding the competence required by pre-service mathematics teachers in the digital era. It emphasizes that technology-based teaching is not simply a matter of using digital devices, but involves the integration of technological, pedagogical, and content knowledge. In mathematics education, this integration is particularly important because mathematical concepts are often abstract, symbolic, and dependent on appropriate representation. Pre-service mathematics teachers therefore need to be able to select technologies that are suitable for specific mathematical topics, design pedagogical strategies that support conceptual understanding, and guide students in using technology to explore mathematical ideas.

Several studies indicate that pre-service mathematics teachers' TPACK develops more effectively when learning experiences go beyond technical training. Agyei and Voogt (2012) found that collaborative design activities helped pre-service mathematics teachers develop TPACK because they were directly involved in selecting technologies, designing learning activities, connecting digital tools with mathematical concepts, and reflecting on instructional decisions. This finding is supported by Agyei and Voogt (2015), who showed that a mathematics-specific instructional technology course improved pre-service teachers' competencies in integrating spreadsheets into mathematics instruction. These findings suggest that TPACK development requires learning experiences that are closely connected to mathematics teaching practice.

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TPACK does not develop automatically when pre-service teachers are introduced to digital tools. It develops when they engage in pedagogical reasoning: why a particular technology should be used, what mathematical concept can be clarified through that technology, how the learning activity should be structured, and how students can be guided toward conceptual understanding. Hyde and Edwards (2011) emphasized that pre-service teachers need to understand technology use in flexible and reflective ways. This means that TPACK is not merely technical competence, but a professional form of knowledge that requires simultaneous consideration of pedagogy, mathematics, and context.

Forms of Digital Learning Environments that Support TPACK Development

Digital learning environments in mathematics teacher education take various forms. These include dynamic mathematics software, virtual simulations, digital manipulatives, online learning platforms, hybrid courses, technology-based microteaching, digital task design, digital storytelling, game-based learning, and artificial intelligence-supported learning. Each form contributes differently to the development of pre-service mathematics teachers' TPACK.

Table 1. Forms of Digital Learning Environments and Their Contributions to Pre-Service Mathematics Teachers' TPACK Development

Form of Digital Learning Environment	Examples of Technology or Activity	Dominant TPACK Components Developed	Contribution to Pre-Service Mathematics Teachers
Dynamic mathematics software	GeoGebra, dynamic geometry software, Desmos	TK, TCK, TPACK	Helps pre-service teachers understand visual representation, relationships among concepts, and dynamic mathematical exploration.
Virtual simulation	Virtual classroom, digital simulation, practice-based simulation	TPK, TPACK	Trains pedagogical decision-making, teacher noticing, and readiness to respond to classroom situations.
Online and hybrid learning	LMS, discussion forums, instructional	TK, TPK	Supports interaction, flexibility, reflection, and digital classroom management.

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	videos, blended courses		
Technology-based microteaching	Teaching practice using digital visualization tools	TK, TPK, TCK, TPACK	Provides opportunities for practice, feedback, and revision of technology-based teaching strategies.
Collaborative digital task design	Collaborative design, digital task design, lesson redesign	TCK, TPK, TPACK	Develops the ability to design technology-based mathematical activities pedagogically.
Games, digital storytelling, and AI	Game-based learning, digital storytelling, AI-assisted learning	TK, TPK, TPACK	Enhances motivation, creativity, real-world contextualization, and personalized learning.

The table shows that digital learning environments do not develop TPACK components in the same way. Dynamic mathematics software, such as GeoGebra and dynamic geometry software, is particularly powerful in connecting technology with mathematical content. Bhagat et al. (2017) showed that GeoGebra integration can improve mathematics teachers' TPACK because it enables visual and interactive representations of mathematical concepts. Segal et al. (2021) also found that dynamic geometry software can strengthen specialized content knowledge and pedagogical reasoning among pre-service mathematics teachers. In this sense, digital technology helps pre-service teachers understand how mathematical ideas can be represented and explored more dynamically.

Virtual simulation contributes to TPACK development in a different way. Davis et al. (2022) showed that practice-based virtual simulations can improve pre-service mathematics teachers' teaching efficacy. Schwarts et al. (2024) argued that asynchronous digital simulations can support teacher noticing and pedagogical decision-making. Zhou (2024) also demonstrated that virtual simulation can help pre-service teachers develop mathematical discourse. These findings suggest that simulation not only develops technological knowledge, but also enables pre-service teachers to practice responding to the complexity of classroom interaction.

Online and hybrid learning environments also play an important role in TPACK development. Larkin and Jamieson-Proctor (2015) showed that the design of online mathematics education courses should consider structure, dialogue, and transactional distance. Retnowati et al. (2018) found that an e-learning approach can support the improvement of pre-

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service mathematics teachers' pedagogical competence. These findings indicate that digital learning environments are not limited to mathematical software, but also include the ways teaching and learning are organized, communicated, and reflected upon in digital spaces.

Recent studies in the Indonesian context also support the importance of designing digital learning environments that are adaptive, interactive, and responsive to students' learning characteristics. Juhari and Habibah (2026) found that mathematics education students' adaptation to the digital learning ecosystem is shaped by their ability to engage with digital platforms, manage learning autonomy, and adjust to technology-mediated academic activities. This finding suggests that digital learning environments in mathematics teacher education should not only provide access to technological tools, but also support students' gradual adaptation to digital academic culture. In a related study, Latri and Juhari (2025) emphasized that ordinary elementary school classrooms can be transformed into interactive mathematics laboratories through effective strategies that promote visualization, hands-on exploration, and student engagement. Although the study focused on elementary classroom transformation, its implication is highly relevant to mathematics teacher education because pre-service teachers need to experience and design learning environments that make mathematics visible, interactive, and conceptually meaningful. Furthermore, Takdirmin and Juhari (2026) highlighted the relevance of visual and auditory learning styles in mathematics learning in the digital era among college students. Their findings indicate that digital mathematics learning environments should accommodate diverse modes of learning, particularly through visual representation, audio-supported explanation, interactive media, and multimodal instructional design. These studies strengthen the argument that TPACK development requires digital learning environments that are not only technology-rich, but also pedagogically responsive to learners' adaptation, interaction, and learning preferences.

Strategies for Developing TPACK through Design, Practice, Collaboration, and Reflection

The development of pre-service mathematics teachers' TPACK requires authentic learning strategies. One important strategy is technology-based mathematical task design. Pre-service teachers need to be trained to design tasks that do not use technology merely as an additional medium, but use the affordances of technology to strengthen conceptual exploration. Ku (2025) showed that designing and revising dynamic geometry tasks is related to pre-service teachers' ability to notice the relationship between technology, pedagogy, and content. Thus, digital task design can serve as a powerful learning space for developing TPACK.

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Another important strategy is technology-based microteaching. Through microteaching, pre-service teachers have opportunities to test instructional designs, use technology in teaching situations, receive feedback, and revise their teaching strategies. Ngwabe and Boateng (2025) found that microteaching experiences using digital and non-digital visualization tools improved pre-service teachers' technological knowledge, technological pedagogical knowledge, and technological content knowledge. Fitriawan et al. (2025) also showed that the integration of TPACK and deep learning in microteaching improved pre-service teachers' competence, particularly in technological and pedagogical aspects. These findings suggest that microteaching can bridge theoretical understanding of TPACK and practical teaching experience.

Collaboration is also a crucial strategy in TPACK development. Agyei and Voogt (2012) showed that collaborative design helped pre-service teachers develop technological and pedagogical knowledge through teamwork, discussion, and shared reflection. McCulloch et al. (2020) introduced the idea of a third space, which connects university coursework, school practice, and the design of technology-based mathematics tasks. Such collaborative spaces are important because pre-service teachers can compare ideas, test the feasibility of lesson designs, and understand how technology is used in more authentic teaching contexts.

Reflection is inseparable from TPACK development. Without reflection, technology use may become merely technical and lack pedagogical depth. Ku (2025) emphasized the importance of design, implementation, and redesign cycles in developing teachers' design capacity. Such cycles help pre-service teachers evaluate whether the technology they use truly supports conceptual understanding, whether the selected pedagogical strategy is appropriate, and whether students experience meaningful mathematics learning. Therefore, TPACK develops through a gradual process involving experience, evaluation, and continuous improvement.

Challenges and Future Directions for Strengthening Pre-Service Mathematics Teachers' TPACK

Although digital learning environments offer significant potential, the development of pre-service mathematics teachers' TPACK still faces several challenges. The first major challenge is infrastructure and access to technology. Zulu (2025) showed that pre-service teachers working in resource-constrained schools face obstacles such as limited devices, electricity problems, and inadequate access to technological resources. Hidayat and Chao (2024) also identified access, cost, and technological familiarity as continuing issues in digital mathematics learning. These conditions indicate that TPACK development cannot be separated from institutional readiness and the socio-economic context in which pre-service teachers learn and teach.

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The second challenge is the risk of superficial technology use. Edson and Thomas (2019) emphasized that digital resources alone are insufficient to produce effective mathematics teaching. Teachers need to transform their knowledge so that digital resources can be used meaningfully. Kohen (2023) also showed that technology use may become more content-oriented than inquiry-oriented when it is not supported by strong pedagogical design. Therefore, teacher education programs need to ensure that technology is not taught merely as a tool, but as an integral part of mathematics learning design.

The third challenge concerns the sustainability of TPACK development. Many studies report improvements in TPACK after specific interventions, but fewer studies examine whether these improvements are sustained in long-term teaching practice. Kartal and Çinar (2018) showed that pre-service teachers' beliefs about TPACK may change across coursework and field experience. Zambak and Tyminski (2022) also showed that teachers' beliefs are related to the development of technology-enhanced specialized content knowledge. Thus, TPACK development should be understood as a long-term process shaped by experience, beliefs, institutional support, and teaching context.

In the Indonesian higher education context, the challenge of TPACK development is also closely related to students' adaptation to the broader digital learning ecosystem. Juhari and Habibah (2026) showed that mathematics education students need to develop adaptive capacities in navigating digital platforms, managing online learning demands, and participating in technology-mediated learning activities. This indicates that strengthening TPACK should not be limited to training pre-service teachers to use digital applications, but should also include the development of digital learning habits, self-regulation, and readiness to participate in evolving digital ecosystems. In addition, Takdirmin and Juhari (2026) suggest that the diversity of students' learning styles, particularly visual and auditory preferences, should be considered in designing digital mathematics learning. Therefore, future mathematics teacher education programs need to integrate multimodal digital resources that combine visualization, explanation, interaction, and reflection. Latri and Juhari's (2025) work on transforming ordinary classrooms into interactive mathematics laboratories further implies that the future direction of TPACK development should emphasize the creation of learning spaces where technology supports exploration, experimentation, and meaningful mathematical engagement.

Based on this synthesis, several directions can be proposed for strengthening pre-service mathematics teachers' TPACK. Mathematics teacher education programs should provide authentic digital learning environments rather than merely offering application-based training. Pre-service teachers need to be involved in digital task design, microteaching, simulation,

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collaboration, feedback, and reflection. In addition, institutions need to provide technological support, teacher educator guidance, access to devices, and curricula that systematically integrate technology. Strong TPACK development will occur when pre-service teachers not only know how to use technology, but also understand how technology can strengthen mathematics learning conceptually, pedagogically, and contextually.

CONCLUSION

First, TPACK is a core competence that needs to be developed in mathematics teacher education in the digital era. TPACK does not only indicate pre-service teachers' ability to use technology, but also reflects their ability to connect technology with pedagogical strategies and mathematical content. Therefore, pre-service mathematics teachers need to understand technology as part of instructional design rather than merely as a technical tool. Strong TPACK enables them to select technologies that align with mathematical topics, learning objectives, and students' needs.

Second, digital learning environments play an important role in supporting the development of pre-service mathematics teachers' TPACK. Dynamic mathematics software, virtual simulation, learning management systems, online and hybrid learning, technology-based microteaching, digital task design, game-based learning, digital storytelling, and AI-supported learning can strengthen the relationship among technological, pedagogical, and content knowledge. Although each form contributes differently, they generally help pre-service teachers understand how mathematical concepts can be represented, taught, and explored more interactively and meaningfully.

Third, TPACK development is more effective when supported by authentic, collaborative, and reflective learning strategies. Technology-based mathematical task design, digital microteaching, virtual simulation, collaborative lesson planning, feedback, and design-implementation-redesign cycles help pre-service teachers develop a deeper understanding of technology integration in mathematics teaching. Through these strategies, pre-service teachers do not merely learn how to use digital applications, but also learn how to make pedagogical decisions that support meaningful mathematics learning.

Fourth, despite the potential of digital learning environments, several challenges remain. These include infrastructure limitations, unequal access to technology, variation in digital literacy, limited institutional support, and insufficient longitudinal research on the sustainability of TPACK development in teaching practice. Future research should examine the long-term development of pre-service teachers' TPACK after entering professional teaching, the

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effectiveness of digital learning models in resource-constrained contexts, and the integration of emerging technologies such as AI, virtual simulation, and digital assessment in mathematics teacher education.

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