



Digital Mathematics Learning Environments For Enhancing Conceptual Understanding And Technological Pedagogical Competence Among Pre-Service Mathematics Teachers: A Literature Review

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Abstract

The rapid development of digital technology has transformed mathematics learning environments by enabling dynamic visualization, interactive exploration, multiple representations, collaborative learning, and immediate feedback. In mathematics teacher education, digital learning environments are not only used to support students' understanding of mathematical concepts but also to prepare pre-service teachers to integrate technology meaningfully into future teaching practices. This article aims to examine the role of digital mathematics learning environments in enhancing conceptual understanding and technological pedagogical competence among pre-service mathematics teachers. This study used a literature review approach by synthesizing relevant theoretical and empirical studies on digital mathematics learning environments, GeoGebra, technology-enhanced mathematics learning, digital learning ecosystems, conceptual understanding, and technological pedagogical content knowledge. The review was guided by four questions: what are the characteristics of digital mathematics learning environments, how do they contribute to conceptual understanding, how do they support technological pedagogical competence among pre-service mathematics teachers, and what challenges affect their implementation. The findings indicate that digital mathematics learning environments can support conceptual understanding through visualization, manipulation of mathematical objects, multiple representations, exploratory tasks, collaborative interaction, and feedback. In teacher education, such environments also strengthen technological pedagogical competence through technology-rich learning experiences, digital task design, microteaching, reflection, and TPACK development. However,

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their effectiveness depends on meaningful task design, teacher educator competence, infrastructure readiness, students' digital adaptation, and assessment models that capture both conceptual and pedagogical dimensions. This review concludes that digital mathematics learning environments should be positioned as pedagogical ecosystems rather than merely as technological tools.

Keyword: digital mathematics learning environment, conceptual understanding, pre-service mathematics teachers, GeoGebra, technology-enhanced learning.

INTRODUCTION

Mathematics learning requires the ability to understand abstract concepts, interpret symbolic forms, connect multiple representations, reason logically, and solve problems systematically. These demands become more complex in mathematics teacher education because pre-service teachers are expected not only to master mathematical content but also to transform it into meaningful learning experiences for students. Therefore, mathematics teacher education should develop both conceptual understanding and pedagogical competence. Pre-service teachers need to understand mathematical ideas deeply and, at the same time, learn how to represent, explain, and teach those ideas in ways that are accessible to learners.

The development of digital technology has expanded the nature of mathematics learning environments. Digital tools such as GeoGebra, Desmos, dynamic geometry software, learning management systems, interactive videos, virtual manipulatives, digital quizzes, and web-based learning resources allow students to interact with mathematical objects more dynamically. Through these tools, students can manipulate variables, observe graphical changes, test conjectures, explore patterns, and connect symbolic, graphical, numerical, and verbal representations. Digital technology therefore has the potential to shift mathematics learning from a procedure-oriented activity into a more exploratory, visual, and conceptually meaningful process.

Previous studies have shown that digital tools can support mathematics learning when they are integrated with appropriate pedagogical strategies. Hillmayr et al. (2020) found that digital tools have positive effects on mathematics and science learning, especially when they are used to promote active learning. Cheung and Slavin (2013) and Li and Ma (2010) also reported positive effects of educational technology on mathematics achievement. More recent studies have expanded this discussion by emphasizing that the value of technology lies not only in





improving achievement but also in enriching representation, interaction, collaboration, and mathematical reasoning (Drijvers & Sinclair, 2024; Engelbrecht & Borba, 2024; St Omer et al., 2025).

GeoGebra has become one of the most widely discussed digital tools in mathematics education. Yohannes and Chen (2023) showed that GeoGebra has been used in various areas of mathematics learning because it supports dynamic visualization, exploration, and the connection of multiple representations. Ziatdinov and Valles (2022) also emphasized the importance of GeoGebra in integrating modeling, visualization, and programming for STEM-related learning. These findings are relevant for mathematics teacher education because pre-service teachers need direct experience with digital tools that can help them understand mathematical concepts and design technology-based instructional tasks.

In teacher education, digital mathematics learning environments have a dual function. First, they support pre-service teachers as learners of mathematics by helping them develop conceptual understanding. Second, they prepare pre-service teachers as future educators who need to integrate technology into mathematics instruction. This second function is closely related to technological pedagogical content knowledge, or TPACK, which emphasizes the integration of technological knowledge, pedagogical knowledge, and content knowledge (Mishra & Koehler, 2006). A pre-service teacher who can operate digital tools does not automatically possess technological pedagogical competence. Such competence requires the ability to select digital tools, design meaningful tasks, facilitate mathematical discussion, and evaluate learning outcomes in relation to specific mathematical concepts.

Although digital mathematics learning environments offer strong potential, their implementation still faces several challenges. Technology may be used superficially as a presentation tool, calculation aid, or decorative medium without promoting deeper conceptual understanding. Pre-service teachers may be familiar with digital devices but lack the ability to use them pedagogically. In addition, limited infrastructure, weak task design, insufficient teacher educator competence, and inappropriate assessment may reduce the effectiveness of digital learning environments. Therefore, a literature review is needed to synthesize how digital mathematics learning environments can support conceptual understanding and technological pedagogical competence among pre-service mathematics teachers.

Based on this background, this article is guided by four research questions. First, what are the characteristics of digital mathematics learning environments that are relevant to pre-service mathematics teachers? Second, how do digital mathematics learning environments contribute to students' conceptual understanding of mathematics? Third, how do digital





mathematics learning environments support technological pedagogical competence among pre-service mathematics teachers? Fourth, what challenges influence the meaningful implementation of digital mathematics learning environments in mathematics teacher education?

METHOD

This article used a literature review approach to examine, compare, and synthesize scholarly sources related to digital mathematics learning environments. The review focused on theoretical arguments, empirical findings, and conceptual discussions concerning technology-enhanced mathematics learning, GeoGebra, digital learning ecosystems, conceptual understanding, and technological pedagogical competence among pre-service mathematics teachers.

The literature was collected from international journal articles, indexed national journal articles, and relevant academic sources. The search was conducted through several academic databases and platforms, including ScienceDirect, SpringerLink, Taylor & Francis Online, Wiley Online Library, Frontiers, Emerald Insight, ERIC, Google Scholar, Garuda, and Sinta. The keywords used in the search process included “digital mathematics learning environment,” “technology-enhanced mathematics learning,” “GeoGebra in mathematics education,” “dynamic mathematics software,” “digital learning ecosystem,” “pre-service mathematics teachers,” “conceptual understanding,” “TPACK,” and “technology integration in mathematics teacher education.”

The main literature included in this review was limited to publications from 2010 to 2026. This period was selected because digital technology in mathematics education has developed rapidly during the last decade, particularly through dynamic mathematics software, online learning platforms, blended learning, mobile learning, and digital learning ecosystems. However, several foundational works published before 2010 were also included when they provided essential theoretical grounding, particularly the TPACK framework and the concept of instrumental orchestration.

The selected literature was based on several criteria. First, the sources had to be relevant to mathematics education, digital learning, technology integration, teacher education, or conceptual understanding. Second, priority was given to publications from reputable journals and academic publishers. Third, the sources had to contribute to at least one of the four main themes of this review: the characteristics of digital mathematics learning environments, conceptual understanding, technological pedagogical competence, and implementation





challenges. The analysis was conducted through repeated reading, identification of key ideas, thematic grouping, comparison of findings, and synthesis. The reviewed literature was organized into four main themes that correspond to the research questions.

RESULTS AND DISCUSSION

Characteristics of Digital Mathematics Learning Environments

A digital mathematics learning environment can be understood as a pedagogical ecosystem that integrates digital tools, mathematical tasks, learning interactions, visual representations, online resources, and instructional strategies to support the construction of mathematical knowledge. Such an environment is not defined merely by the presence of technology in the classroom. A lesson that uses slides, a projector, or online materials does not necessarily become a strong digital mathematics learning environment if technology is only used to transmit information. A meaningful digital mathematics learning environment should enable learners to explore mathematical ideas, manipulate objects, connect representations, discuss patterns, and reflect on mathematical relationships.

Nguyen et al. (2022) explain that a digital learning ecosystem consists of interconnected platforms, resources, learning activities, interactions, and actors. In mathematics education, this ecosystem has a specific character because it must support the abstract, symbolic, visual, and relational nature of mathematical knowledge. Digital tools should therefore be selected and organized not because they are modern or attractive, but because they provide specific affordances for mathematical thinking. These affordances include visualization, manipulation, representation, collaboration, and feedback.

The first characteristic of digital mathematics learning environments is dynamic visualization. Many mathematical concepts are difficult to understand when presented only through static symbols or diagrams. Dynamic visualization allows students to observe changes, movement, transformation, variation, and dependency. For example, students can observe how changing a parameter affects the shape of a graph, how a geometric transformation changes the position of an object, or how a secant line approaches a tangent line. This dynamic quality helps learners see mathematical relationships that are often hidden in static representations.

The second characteristic is interactivity. In a digital mathematics learning environment, students do not merely observe mathematical objects; they can manipulate them. Interactivity allows learners to drag points, adjust sliders, change variables, construct diagrams, generate graphs, and test conjectures. This interaction transforms mathematics learning into an investigative process. Students can ask “what happens if” questions and immediately observe





the consequences of their actions. Such interaction is important because mathematical understanding is strengthened when learners actively explore relationships rather than passively receive explanations.

The third characteristic is multimodal representation. Mathematics can be represented symbolically, graphically, numerically, visually, and verbally. Students often experience difficulty when they cannot connect these forms. Digital tools can display multiple representations simultaneously, allowing learners to observe the relationship between equations, graphs, tables, diagrams, and verbal explanations. GeoGebra is a strong example because it integrates algebra, geometry, graphing, calculus, and statistics in one platform (Yohannes & Chen, 2023). Through linked representations, students can understand that a mathematical concept is not limited to one symbolic form but can be interpreted through different representational systems.

The fourth characteristic is collaboration. Digital environments allow students to work together in shared documents, online platforms, discussion forums, or collaborative task spaces. In mathematics learning, collaboration is important because students need to explain ideas, compare strategies, justify claims, and negotiate meaning. Borba et al. (2016) noted that blended learning, e-learning, and mobile learning have expanded the spaces in which mathematics learning can occur. Similarly, Engelbrecht et al. (2020) argued that the internet has transformed mathematics classrooms by enabling new forms of access, interaction, and collaboration.

The fifth characteristic is exploratory task orientation. Digital tools are most powerful when they are embedded in tasks that encourage students to explore, predict, test, justify, and generalize. If technology is used only to demonstrate a formula or produce an answer, its conceptual value is limited. Drijvers and Sinclair (2024) argue that the role of digital technology in mathematics education should be understood through its purposes and pedagogical perspectives. This means that technology should be evaluated based on how it supports mathematical learning goals, not merely based on its technical sophistication.

In the Indonesian context, the need to develop interactive mathematics learning environments is also increasingly relevant. Latri and Juhari (2025) emphasized the transformation of ordinary classrooms into interactive mathematics laboratories by focusing on activity, exploration, and student engagement. Juhari and Habibah (2026) also highlighted the importance of mathematics education students' adaptation to digital learning ecosystems. These studies indicate that digital mathematics learning environments are not only a global issue but also an important concern in Indonesian mathematics education.

Therefore, digital mathematics learning environments for pre-service mathematics





teachers should be understood as learning spaces that combine technology, mathematical content, pedagogical design, and reflective practice. These environments should not only help pre-service teachers learn mathematics but also help them understand how technology can be used to teach mathematics meaningfully.

Contribution to Conceptual Understanding in Mathematics

Conceptual understanding refers to the ability to understand mathematical meanings, relationships, principles, and representations. Students with conceptual understanding do not only know how to apply formulas or procedures; they also understand why procedures work, how concepts are connected, and how mathematical ideas can be represented in different forms. In mathematics teacher education, conceptual understanding is particularly important because pre-service teachers are expected to explain concepts to future learners. A teacher who understands mathematics only procedurally may reproduce mechanical teaching practices and may find it difficult to respond to students' misconceptions.

Digital mathematics learning environments contribute to conceptual understanding through visualization of abstract concepts. Mathematical ideas such as functions, limits, derivatives, integrals, vectors, matrices, transformations, and probability often involve relationships that are not easily visible. Digital tools can make these relationships more accessible by representing them visually and dynamically. For instance, a derivative can be explored through the movement of a secant line toward a tangent line, while an integral can be represented as an accumulation of areas under a curve. These visual experiences can help students build intuitive understanding before moving toward formal definitions.

The second contribution is the manipulation of mathematical objects. Manipulation allows students to conduct mathematical experiments. When students adjust a parameter and observe its effect on a graph, they are not simply memorizing the role of coefficients; they are constructing an understanding of functional relationships. This process supports inquiry because students can test hypotheses and refine their reasoning based on visual feedback. St Omer et al. (2025) emphasized that technology-enhanced mathematics learning becomes meaningful when technological attributes such as visualization, interactivity, and feedback are connected to mathematical learning processes.

The third contribution is the development of connections among multiple representations. One of the common difficulties in mathematics learning is the inability to translate between symbolic, graphical, numerical, and verbal forms. A student may be able to solve an equation algebraically but fail to explain its graphical meaning. Conversely, a student





may interpret a graph visually but fail to connect it to an equation. Digital environments can reduce this difficulty by presenting different representations simultaneously. GeoGebra, for example, allows students to see how a symbolic expression, graph, table, and geometric construction are related. Such representational connections are essential for conceptual understanding.

The fourth contribution is exploratory learning. In traditional mathematics instruction, students often receive definitions, formulas, examples, and exercises in a linear sequence. In digital environments, instructors can design tasks that ask students to observe patterns, formulate conjectures, test cases, and develop generalizations. For example, in learning quadratic functions, students can explore how changes in parameters affect the vertex, axis of symmetry, and direction of the parabola. In geometry, students can investigate which properties remain invariant when a shape is transformed. This process encourages students to construct mathematical meaning through guided inquiry.

The fifth contribution is multimodal learning. Digital environments often combine text, symbols, graphics, animation, sound, and interaction. Paivio's (2014) dual coding theory suggests that visual and verbal information can support one another in cognition. In mathematics learning, this is important because students can benefit from seeing a concept visually while also receiving verbal explanation. Takdirmin and Juhari (2026) showed that visual and auditory learning styles remain relevant in mathematics learning in the digital era. Although learning styles should not be treated rigidly, the combination of visual, verbal, and interactive experiences can enrich students' engagement with mathematical concepts.

The sixth contribution is feedback. Digital tools often provide immediate feedback when students manipulate objects, submit answers, or test constructions. Feedback helps students recognize errors, revise strategies, and compare expected outcomes with observed outcomes. However, feedback must be interpreted pedagogically. Immediate visual feedback from a tool does not automatically produce conceptual understanding unless students are guided to explain what the feedback means mathematically.

Meta-analytic evidence supports the potential of technology in mathematics learning. Li and Ma (2010) found that computer technology had positive effects on mathematics achievement, while Cheung and Slavin (2013) reported that educational technology applications could enhance mathematics achievement in K–12 classrooms. Hillmayr et al. (2020) further showed that digital tools had positive effects in mathematics and science learning when they were used in appropriate instructional contexts. These findings indicate that technology can support learning, but the quality of implementation remains crucial.





For pre-service mathematics teachers, the contribution of digital environments to conceptual understanding has a double value. First, it helps them understand mathematics more deeply. Second, it provides them with pedagogical examples of how abstract mathematical concepts can be taught through visualization, exploration, representation, and interaction. This double value makes digital mathematics learning environments important in teacher education.

Support for Technological Pedagogical Competence among Pre-Service Mathematics Teachers

Technological pedagogical competence refers to the ability to integrate technology into teaching in ways that are pedagogically meaningful and content-specific. In mathematics teacher education, this competence involves knowing which digital tools are appropriate for particular mathematical concepts, how to design technology-based tasks, how to facilitate students' exploration, and how to assess learning in digital environments. This idea is closely related to the TPACK framework, which emphasizes the integration of technological knowledge, pedagogical knowledge, and content knowledge (Mishra & Koehler, 2006).

Pre-service mathematics teachers may possess technological familiarity, but this does not automatically lead to pedagogical competence. Many students are comfortable using smartphones, applications, and online platforms in daily life, but they may not know how to use digital tools to support mathematical reasoning. Technological pedagogical competence requires a shift from using technology as a general tool to using technology as a mathematical and pedagogical tool.

Digital mathematics learning environments can support this competence through direct learning experiences. When pre-service teachers experience digital mathematics learning as students, they gain concrete examples of how technology can support visualization, exploration, discussion, and reflection. Such experiences can shape their beliefs about mathematics teaching. If pre-service teachers only experience procedural instruction, they may reproduce procedural teaching in their future classrooms. Conversely, if they experience meaningful digital learning, they are more likely to design active and conceptually oriented lessons.

Digital environments also support competence through task design. Designing digital mathematics tasks requires pre-service teachers to consider learning objectives, mathematical concepts, tool affordances, student difficulties, representations, guiding questions, and assessment. For example, designing a GeoGebra task for functions is not simply a matter of generating graphs. It requires decisions about which variables students will manipulate, what patterns they should notice, what questions will guide their thinking, and how they will explain their findings. Through task design, pre-service teachers learn to connect technology, pedagogy,



and content.

Açıkgül and Aslaner (2020) found that GeoGebra-supported microteaching and TPACK-based practices can improve the TPACK levels of prospective teachers. Agyei and Voogt (2012) also showed that collaborative design can support the development of TPACK among pre-service mathematics teachers. These studies suggest that technological pedagogical competence is best developed through active design, practice, and reflection rather than through theoretical instruction alone.

Microteaching is another important strategy. Through microteaching, pre-service teachers can practice using digital tools in teaching situations, receive feedback, and revise their instructional strategies. This process helps them understand that teaching with technology is not simply operating software. It requires classroom orchestration, questioning, explanation, and responsiveness to students' ideas. Trouche (2004) introduced the concept of instrumental orchestration to explain how teachers manage the interaction between students, tools, and mathematical knowledge. This concept remains relevant because digital learning requires teachers to organize tools and tasks in ways that promote mathematical thinking.

Digital mathematics learning environments also support reflective practice. Reflection allows pre-service teachers to analyze whether technology actually helped students understand the concept, whether the task encouraged reasoning, whether students focused too much on technical operations, and whether the digital tool added pedagogical value. Valtonen et al. (2019) argued that pre-service teachers' TPACK develops as evolving knowledge domains. This means that competence is not built through a single course or workshop but through repeated cycles of experience, design, implementation, feedback, and reflection.

Technology acceptance is also important. Yıldız and Arpacı (2024) found that pre-service mathematics teachers' TPACK influenced their intention to use GeoGebra. This finding indicates that pre-service teachers are more likely to use digital tools when they understand their pedagogical value and feel competent in using them. Dinçer (2025) also showed that digitalization, distance education, and online learning shape pre-service mathematics teachers' career perceptions, including their awareness of digital content creation as a professional skill. These findings suggest that technological pedagogical competence is related not only to skill but also to professional identity.

In higher education, digital pedagogical strategies can also strengthen students' engagement and conceptual learning. Hevardani et al. (2026) emphasized the importance of digital pedagogical strategies in mathematics learning in higher education, particularly when technology is integrated with conceptual exploration, collaborative dialogue, lecturer



facilitation, and reflection. This is relevant for pre-service mathematics teachers because they need to learn how to transform digital tools into pedagogically purposeful learning experiences.

Therefore, digital mathematics learning environments support technological pedagogical competence through four main pathways. First, they allow pre-service teachers to experience technology-rich mathematics learning. Second, they provide opportunities to design digital mathematical tasks. Third, they support practice through microteaching and simulation. Fourth, they encourage reflection on the relationship between technology, pedagogy, content, and student learning. These pathways are essential for preparing pre-service mathematics teachers for digital-era classrooms.

Challenges in Implementing Digital Mathematics Learning Environments

Despite their potential, digital mathematics learning environments face several challenges. The first challenge is the gap between technical skill and pedagogical skill. Pre-service teachers may know how to use digital devices, but they may not know how to use them to teach mathematical concepts. Technical skill answers the question of how to operate a tool, while pedagogical skill answers why, when, and how the tool should be used to support learning. This distinction is important because technology integration in mathematics education must be guided by mathematical and pedagogical purposes.

The second challenge is superficial technology use. Technology is sometimes used merely to present slides, display videos, or produce answers more quickly. Although these uses may be helpful, they do not necessarily promote conceptual understanding. Digital tools should help students explore relationships, justify claims, connect representations, and develop mathematical reasoning. Drijvers and Sinclair (2024) argue that the role of digital technologies in mathematics education should be evaluated based on the purposes they serve. If technology does not support mathematical thinking, its instructional value remains limited.

The third challenge is task design. A digital task is not automatically meaningful because it uses technology. A strong digital mathematics task should include a mathematical problem, exploration, guiding questions, opportunities for explanation, and reflection. For example, a task on derivatives should not only ask students to draw graphs but should guide them to explain the relationship between the slope of a curve and the derivative function. A task on geometry should not only ask students to construct shapes but should guide them to investigate invariant properties. Designing such tasks requires both content knowledge and pedagogical creativity.

The fourth challenge is teacher educator readiness. Teacher educators play a central role in modeling digital pedagogy, designing tasks, facilitating discussion, and guiding reflection. If





teacher educators lack technological pedagogical competence, digital tools may be used only as supplementary media. Engin et al. (2023) emphasized the importance of systematic TPACK development for pre-service mathematics teachers. This implies that teacher education programs should also strengthen the competence of teacher educators who guide technology integration.

The fifth challenge is infrastructure and access. Digital mathematics learning requires devices, internet connection, software access, and technical support. In some contexts, unequal access to technology can limit students' participation. However, limited infrastructure does not mean that digital learning should be abandoned. Instructors can use free applications, offline resources, shared devices, low-bandwidth platforms, and blended strategies. The key issue is not always the sophistication of the technology but the appropriateness of the tool for the learning context.

The sixth challenge is students' adaptation to digital learning ecosystems. Juhari and Habibah (2026) emphasized the need for mathematics education students to adapt to digital learning environments. Adaptation includes managing learning time, using digital platforms, accessing resources, collaborating online, and developing self-regulated learning habits. Without adaptation, digital environments may become burdensome rather than supportive.

The seventh challenge is assessment. If digital mathematics learning is intended to develop conceptual understanding and technological pedagogical competence, assessment should not focus only on final answers or procedural accuracy. Assessment should also capture students' explanations, representations, reasoning, digital task design, microteaching performance, and reflective ability. Possible assessment forms include digital portfolios, GeoGebra task analysis, lesson plans, video-based microteaching, reflective journals, and TPACK-based rubrics.

The eighth challenge is the risk of cognitive overload. Digital tools provide many features, but too many features may distract students from mathematical goals. Students may focus on clicking, dragging, formatting, or exploring visual effects without understanding the mathematics behind the activity. Therefore, digital tasks should be carefully structured. Scaffolding is needed so that students know what to observe, what to manipulate, what to explain, and what conclusion to draw.

Based on these challenges, the implementation of digital mathematics learning environments should be systematic. Technology should be selected based on mathematical goals. Digital tasks should be designed to promote conceptual reasoning. Pre-service teachers should be involved as learners, designers, practitioners, and evaluators. Teacher educators





should model meaningful technology integration. Assessment should measure both conceptual and pedagogical dimensions. In this way, digital mathematics learning environments can become spaces for developing both mathematical understanding and teaching competence.

CONCLUSION

This literature review shows that digital mathematics learning environments have important potential for enhancing conceptual understanding and technological pedagogical competence among pre-service mathematics teachers. Such environments are characterized by dynamic visualization, interactivity, multimodal representation, collaboration, exploratory tasks, and feedback. These characteristics make digital mathematics learning environments different from conventional learning environments that rely heavily on static explanation and procedural practice.

Digital mathematics learning environments contribute to conceptual understanding by making abstract mathematical concepts more visible, manipulable, and connected across representations. Through tools such as GeoGebra, Desmos, simulations, digital worksheets, and online platforms, students can explore mathematical relationships, test conjectures, observe patterns, and construct meaning. However, technology supports conceptual understanding only when it is integrated into meaningful tasks that promote reasoning, discussion, and reflection.

In mathematics teacher education, digital learning environments also support technological pedagogical competence. Pre-service mathematics teachers need to experience digital mathematics learning, design technology-based tasks, practice digital instruction through microteaching, and reflect on the relationship between technology, pedagogy, and mathematical content. The TPACK framework provides a strong theoretical foundation for understanding this competence because it emphasizes the integration of technological, pedagogical, and content knowledge.

Several challenges must be addressed to implement digital mathematics learning environments effectively. These challenges include the gap between technical and pedagogical skills, superficial use of technology, weak task design, teacher educator readiness, infrastructure limitations, students' adaptation to digital ecosystems, assessment issues, and cognitive overload. Addressing these challenges requires systematic planning, appropriate tool selection, strong pedagogical design, reflective practice, and assessment models that capture both conceptual understanding and technological pedagogical competence.

This review concludes that digital mathematics learning environments should be positioned not merely as technological tools but as pedagogical ecosystems. Their main value





lies not in the presence of digital devices but in their ability to support mathematical thinking, conceptual exploration, representation, collaboration, and teacher preparation. Future research may examine the implementation of digital mathematics learning environments in specific university mathematics courses, such as calculus, geometry, algebra, statistics, and discrete mathematics. Empirical studies are also needed to investigate how digital task design influences pre-service teachers' conceptual understanding, TPACK development, and readiness to teach mathematics in technology-rich classrooms.

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