Journal of Computers for Science and Mathematics Learning
ISSN 3047-4876 (online) & 3047-6755 (print)
February 2026, Vol. 3, No. 1, pp. 60–73

Review Article

Equipping Mathematics Pre-Service Teachers for the Digital Classroom: Research on Tools, Pedagogies, and Instructional Design

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Abstract
This systematic literature review (SLR) synthesizes research published between 2014 and 2024 on preparing pre-service mathematics teachers (PSTs) for technology-enhanced classrooms. The study addresses the growing global expectation for teacher education programs to integrate digital tools and constructivist pedagogies while promoting equity and conceptual understanding in mathematics instruction. Despite these demands, PSTs often struggle to balance technological, pedagogical, and content knowledge, relying on traditional methods that limit authentic technology use. Guided by three research questions, the review examined: (a) how digital tools such as GeoGebra, 3D printing, and collaborative platforms influence PSTs' mathematical understanding and real-world application; (b) how constructivist, technology-based strategies like flipped classrooms and peer learning affect engagement, confidence, and instructional planning; and (c) what factors shape PSTs' ability to evaluate and integrate digital resources into student-centered, standards-aligned instruction. Using a rigorous SLR process across five major databases (Google Scholar, Scopus, Web of Science, ERIC, JSTOR), 24 peer-reviewed studies were analyzed through Garrard's Matrix Method and thematic coding. Findings reveal that digital tools enhance representational fluency, problem-solving, and Technological Pedagogical Content Knowledge (TPACK), while constructivist approaches foster engagement, autonomy, and reflective practice. However, persistent challenges, such as inequitable access to technology, limited interdisciplinary training, and entrenched procedural teaching beliefs, constrain integration. Factors influencing adoption include pedagogical orientations, institutional support, and collaborative opportunities. The review concludes that the intentional, scaffolded integration of emerging technologies within constructivist frameworks strengthens PSTs' readiness for 21st-century classrooms. However, the small sample of 24 articles and the exclusion of sources like gray literature limit the study's generalizability. Nevertheless, the findings can guide teacher educators, curriculum designers, and education ministries in promoting equitable, technology-rich mathematics education through authentic digital inquiry and targeted professional development.

Keywords: Constructivist Pedagogy, Digital Tools, Mathematics Education, Pre-service Mathematics Teachers, Student-Centered Instruction, Technology Integration

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Received
September 2, 2025
Accepted
December 21, 2025
Published
February 16, 2026

Citation: Wekullo, B. J., Montano Ramos, R., & Castillo, A. H. (2026). Equipping mathematics pre-service teachers for the digital classroom: Research on tools, pedagogies, and instructional design. *Journal of Computers for Science and Mathematics Learning, 3*(1), 60–73.

DOI: 10.70232/jcsml.v3i1.51

1. INTRODUCTION

The preparation of mathematics PSTs is a central concern for educators and policymakers seeking to equip future teachers with the skills required for 21st-century classrooms. Globally, PSTs face growing expectations to integrate technology while promoting conceptual understanding, problem-solving, and equity in mathematics learning (Gurer & Akkaya, 2022; Saralar & Aras, 2024). Teacher preparation programs must cultivate educators who are both content-knowledgeable and technologically and pedagogically adept. Yet research indicates that many PSTs struggle to balance these demands, often relying on procedural instruction and underutilizing digital tools in authentic mathematical contexts (Parra-Urrea & Pino-Fan, 2022; Slavičková, 2021). Tensions between curricular mandates and classroom realities further constrain innovation in pre-service programs (Tchoshanov et al., 2017), underscoring the need to examine systematically how digital technologies and innovative pedagogies affect PSTs' learning and teaching practices.

Emerging technologies such as GeoGebra, three-dimensional (3D) printing, and collaborative platforms have demonstrated promise in enhancing PSTs' representational competence and real-world application of mathematics (Caniglia & Meadows, 2018; Zengin, 2019). These tools facilitate visualization, modeling, and collaborative learning, aligning with constructivist principles that emphasize exploration, multiple representations, and learner-centered inquiry (Drijvers, 2015). Adoption, however, remains uneven due to inequitable access to resources, limited professional development for teacher educators, and reliance on traditional lecture-based pedagogies (Shambare & Jita, 2025; Getenet, 2024). PSTs frequently lack structured opportunities to evaluate and integrate digital resources into standards-based instruction, highlighting gaps in technological pedagogical content knowledge (TPACK) (Martínez-Zarzuelo et al., 2025; Kreisa et al., 2024). Inconsistent program design often treats digital integration as an *add-on* rather than embedding it within core instructional practices (Angeli & Valanides, 2020; Polly & Martin, 2022), necessitating targeted, evidence-based strategies that connect theory and practice.

Despite progress, research gaps persist. Much literature focuses on K–12 student outcomes or in-service teachers, leaving PSTs' needs underexplored (Cheah et al., 2023; Li et al., 2024). Many studies examine isolated tools or pedagogical strategies without considering their integration into broader teacher preparation frameworks (Kopcha et al., 2020). Few systematic reviews synthesize the combined impact of digital tools, constructivist pedagogies, and evaluative capacities on PST readiness for digital classrooms, limiting the field's ability to identify scalable practices and inform curriculum and policy (Sailer et al., 2021). Without such synthesis, teacher education risks perpetuating fragmented approaches that fail to prepare PSTs for contemporary classroom complexities.

Additional challenges further complicate PST preparation. The rapid emergence of artificial intelligence (AI), adaptive learning systems, and human-AI comparative environments introduces pedagogical and ethical considerations in assessment and feedback (Getenet, 2024; Holmes et al., 2021). Equity remains a pressing concern, as disparities in device access, internet connectivity, and institutional support affect PSTs' engagement with digital tools (Caniglia & Meadows, 2018; Shambare & Jita, 2025). Persistent traditional beliefs about mathematics teaching, favoring procedural fluency over conceptual exploration, impede innovation in technology-rich contexts (Slavičková, 2021; Milenković & Vučićević, 2024). Teacher identity and self-efficacy also influence technology adoption, with PSTs lacking confidence less likely to integrate digital tools effectively (Polly & Martin, 2022). These issues emphasize the need for holistic approaches that address systemic, cultural, and cognitive barriers while fostering reflective and adaptive pedagogical practices.

This SLR synthesizes a decade of research (2014–2024) on digital tools, pedagogical frameworks, and instructional design in mathematics teacher preparation. It was guided by three research questions: (a) How do digital tools like GeoGebra, 3D printing, and collaborative platforms influence PSTs' understanding and application of mathematics in real-world contexts? (b) How do constructivist, technology-based instructional approaches such as flipped classrooms, peer learning, and modeling affect PSTs' engagement, confidence, and instructional planning? (c) What factors influence PSTs' ability to evaluate and integrate digital resources into student-centered, standards-based instruction? This review contributes to the scholarly conversation by providing an evidence-based synthesis that highlights successes, challenges, and directions for future research on preparing mathematics teachers for digital-age classrooms.

2. METHODOLOGY

This study employed an SLR to analyze the selected articles, a rigorous method for collecting, evaluating, and synthesizing existing research on a defined topic. By following a structured and replicable process, SLR enables the identification of patterns, inconsistencies, and research gaps. As noted by Li et al.

(2024) and Cheah et al. (2023), this approach enhances transparency, validity, and reliability, providing a solid foundation for future investigations.

2.1. Literature Search

This literature search was conducted between March and July 2025 in the following international databases: Google Scholar, Scopus, WoS (Web of Science), ERIC (Educational Resources Information Center), and JSTOR (Journal Storage), selected for their accessibility and comprehensive academic coverage. Keywords included "emerging technologies" OR "technology" OR "ICT" AND "mathematics education" OR "K-12 mathematics" OR "mathematics" AND "pre-service teachers" OR "K-12 teacher candidates," with the search limited to publications from 2014 to 2024. Narrowing the literature search to publications from 2014 to 2024 strategically defined to capture the most significant decade of technological evolution in mathematics education. This period aligns with the global rise of digital and constructivist pedagogies, the mainstreaming of GeoGebra and other dynamic visualization tools, and the increasing integration of AI, online platforms, and blended learning environments in teacher preparation. By focusing on this decade, the review emphasizes contemporary trends in technology-enhanced mathematics instruction while still allowing for longitudinal insights into how PSTs' preparation has evolved alongside rapid digital transformation. This timeframe, therefore, ensures the inclusion of both established and emerging perspectives relevant to 21st-century mathematics education. Articles were drawn from reputable journals and databases, including Springer, Taylor & Francis, Elsevier, ERIC, Wiley, Sage, and MDPI, ensuring the inclusion of high-quality, credible sources.

2.2. Study Selection

Table 1 shows that a three-stage screening process was employed to identify literature relevant to mathematics education and technology integration.

Table 1. Overview of the Selected Research Articles

Database	Advanced Search	Duplicated	2nd Stage	3rd Stage
Google Scholar	573	9	201	2
SCOPUS	567	19	262	8
JSTOR	478	26	204	3
ERIC	537	62	256	4
WOS	845	76	353	7
Total	3000	192	1176	24

In Stage 1 (advanced search), an initial database search yielded 3,000 articles; after scrutiny, 192 articles were found to be duplicates. Stage 2 applied inclusion criteria, retaining peer-reviewed journal articles published between 2014 and 2024, in English, and focused on pre-service teachers' use of digital tools in mathematics education, including international studies, which reduced the pool to 1,176 articles. In Stage 3, exclusion criteria removed studies addressing student achievement, higher education, in-service teachers, non-English publications, gray literature, dissertations, books, and research unrelated to emerging technologies, resulting in 24 articles for full review. Out of which 8 were indexed in SCOPUS, 7 in WoS, 2 in Google Scholar, 3 in JSTOR, and 4 in ERIC. This systematic screening process enhanced methodological transparency, minimized selection bias, and established a rigorously focused evidence base for synthesizing current research.

2.3. Data Extraction

Data from the 24 included articles were extracted using Garrard's (2004) Matrix Method, a recommended approach for systematic literature reviews (Cho & Egan, 2009). Review matrices were created in Excel to record key information from each study, including study indicators (focus, research questions, participant characteristics, data sources, analyses, and interventions), major findings, and notable scenarios, such as emerging issues, comments, and questions, all aligned with the review's research questions.

Table 2. Study Indicators

Indicators	Sub Indicators		Count	%
Specific focus	TPACK and Technological Integration		9	39.13
	Pedagogical Beliefs, Styles, and Reflection		4	17.39
	Digital Tools (DGS, AI, Web)		6	26.09
	Innovative/Contextual Approaches in STEM/Math		4	17.39
				100
Research Questions	Instructional Practices		7	29.2
	Technological Acceptance		5	20.8
	TPACK Development		5	20.8
	Assessment and Learning Outcomes		5	20.8
	Digital Tools and Software		5	20.8
	Content-Specific Integration		3	12.5
	External factors (e.g., gender, achievement)		1	4.2
	Uncategorized		1	4.2
	Collaborative Teaching		1	4.2
				100
Participant Characteristics	Gender Composition	Female-dominant cohorts	16	69.6
		Balanced or near-equal gender	4	17.4
	Educational level	Pre-service primary math teachers	12	52.2
		Pre-service secondary math teachers	10	43.5
		Mixed-level PST cohorts	5	21.7
	Program year	Final-year PSTs	5	21.7
		Mixed year levels	8	34.8
	Sampling Design	Convenience sampling	14	60.9
		Purposeful sampling/rich cases	6	26.1
		Control and experimental groups	6	26.1
	Geographic Region	Europe (e.g., Turkey, Germany, Spain)	10	43.5
		North America (U.S., Canada)	6	26.1
		Middle East / Africa	5	21.7
		Australia	3	12.5
	Instructional Context	Urban/suburban placement	4	17.4
		Rural or under-resourced settings	4	17.4
Data Sources	Surveys & Questionnaires		158	62.5
	Interviews		19	7.54
	Observations		17	6.75
	Lesson Plans & Artifacts		20	7.94
	Video & Audio Recordings		10	3.94
	Written Reflections & Diaries		11	4.37
	Assignments & Tests		12	4.76
	Demographics & Background Data		3	1.19
	Log & System Data		2	0.79
				100
Data Analysis	Quantitative Analysis		42	49.41
	Qualitative Analysis		31	36.47
	Mixed Methods		5	5.88
	Tools and Software		7	8.24
				100
Interventions	Technology Integration		26	30.59
	Pedagogical Strategies		25	29.41
	Professional Development		14	16.47
	Assessment & Feedback		14	16.47
	Design Principles		4	4.71
	Field-Based Experience		6	7.06
				100

2.4. Coding Procedure

Codes were assigned for the inclusion and exclusion criteria and their sub-criteria. To ensure consistency, the coding approach was first calibrated by jointly coding four studies, followed by independent coding of all included studies. Any uncertainties or ambiguities were flagged, revisited, and resolved through reflection and consultation of the coding guidelines, ensuring reliable and consistent application across all studies.

3. RESULTS

Table 2 presents the study indicators of the SLR, organized by indicators, sub-indicators, count, and percentages.

3.1. Specific Focus

Among the reviewed studies, technological pedagogical content knowledge (TPACK) and technology integration constituted the largest focus, representing 39.13% of articles (Akyuz, 2023; Ching et al., 2025; Martínez-Zarzuelo et al., 2025; Milenković & Vučićević, 2024; Quarder et al., 2025; Segal et al., 2021; Shambare & Jita, 2025; Slavíčková, 2021; Zengin, 2019). Research on digital tools, including dynamic geometry systems (DGS), artificial intelligence, and web-based platforms, accounted for 26.09% (Getenet, 2024; Martínez-Zarzuelo et al., 2025; Quarder et al., 2025; Segal et al., 2021; Shambare & Jita, 2025; Zengin, 2019). Pedagogical beliefs, teaching styles, and reflective practices contributed 17.39% (Caniglia & Meadows, 2018; Du & Lyublinskaya, 2024; Milenković & Vučićević, 2024; Parra-Urrea & Pino-Fan, 2022), and innovative or contextual STEM approaches represented 17.39% (Caniglia & Meadows, 2018; Martínez-Zarzuelo et al., 2025; Parra-Urrea & Pino-Fan, 2022; Shambare & Jita, 2025).

3.2. Research Questions and Participant Characteristics

Instructional practices were the most prominent research focus at 29.2% (Caniglia & Meadows, 2018; Ching et al., 2025; Du & Lyublinskaya, 2024; Martínez-Zarzuelo et al., 2025; Milenković & Vučićević, 2024; Quarder et al., 2025; Slavíčková, 2021), followed by technological acceptance, TPACK development, assessment, learning outcomes, and digital tools (20.8%) (Akyuz, 2023; Ching et al., 2025; Getenet, 2024; Martínez-Zarzuelo et al., 2025; Segal et al., 2021; Shambare & Jita, 2025; Slavíčková, 2021; Zengin, 2019). Content-specific integration represented 12.5% (Caniglia & Meadows, 2018; Segal et al., 2021; Zengin, 2019), with external factors and collaborative teaching comprising 4.2% and targeted cases, respectively (Akyuz, 2023; Milenković & Vučićević, 2024). Participant cohorts were predominantly female (69.6%), with pre-service primary teachers (52.2%) and secondary teachers (43.5%) as the main focus. Sampling approaches included convenience (60.9%) and purposeful designs (26.1%), with studies conducted primarily in Europe (43.5%), North America (26.1%), the Middle East/Africa (21.7%), and Australia (12.5%).

3.3. Data Sources, Analysis, and Interventions

Surveys and questionnaires were the most common data sources (62.5%) (Ching et al., 2025; Segal et al., 2021; Shambare & Jita, 2025), followed by lesson plans/artifacts (7.94%), interviews (7.54%), and observations (6.75%). Quantitative analyses dominated (49.41%) (Akyuz, 2023; Ching et al., 2025; Segal et al., 2021; Shambare & Jita, 2025), with qualitative methods representing 36.47% (Caniglia & Meadows, 2018; Du & Lyublinskaya, 2024; Milenković & Vučićević, 2024; Parra-Urrea & Pino-Fan, 2022; Slavíčková, 2021) and mixed methods such as embedded and multiphase designs, etc. (5.88%) (Quarder et al., 2025; Zengin, 2019). Interventions focused primarily on technology integration (30.59%) (Akyuz, 2023; Ching et al., 2025; Martínez-Zarzuelo et al., 2025; Quarder et al., 2025; Segal et al., 2021; Shambare & Jita, 2025; Zengin, 2019) and pedagogical strategies (29.41%) (Caniglia & Meadows, 2018; Du & Lyublinskaya, 2024; Milenković & Vučićević, 2024; Slavíčková, 2021), with professional development and assessment/feedback each contributing 16.47%, and field-based experiences (7.06%) and design principles (4.71%) rounding out the interventions (Caniglia & Meadows, 2018; Ching et al., 2025; Martínez-Zarzuelo et al., 2025; Quarder et al., 2025; Segal et al., 2021; Shambare & Jita, 2025; Slavíčková, 2021; Parra-Urrea & Pino-Fan, 2022; Zengin, 2019).

Table 3 presents the major findings of the SLR, organized by themes, authors, and year, impact type, count, and percentage.

Table 3. Major Findings

Theme	Author Year	Impact Type(S)	Count	%
Impact of Constructivist Tech-Based Instructional Approaches on PSTs' Engagement and Confidence	Slavíčková, 2021	DT leads to more active and motivated students; construction increases knowledge durability	3	12.5
	Kreisa et al., 2024	Flipped classroom fosters autonomy, confidence, deeper engagement	3	12.5
	Ching et al., 2025	3D printing and STEM module boost engagement, confidence, hands-on experience	3	12.5
	Quarder et al., 2025	Student-centered, autonomy, reflection, link theory/practice	3	12.5
	Milenković & Vučićević, 2024	Constructivist, peer support, collaborative discovery, group work	3	12.5
	Martínez-Zarzuelo et al., 2025	Experiential and playful visual approach, increased motivation, overcoming challenges	3	12.5
	Parra-Urrea & Pino-Fan, 2022	Self-reflection, perseverance, collaborative dialogue	3	12.
	Zengin, 2019	Knowledge constructed via software, a facilitatory dynamic environment	3	12.5
			24	**100**
Impact of Use of Digital Tools on PSTs' Learning to Teach Math	Getenet, 2024	Visualization/diagrams, PCK in problem solving, use/difference AI strategies	3	10.71
	Segal et al., 2021	Inquiry-based GeoGebra activities developed TCK, TPK, SCK, and skills for teaching geometry	2	7.14
	Lyublinsky & Du, 2024	Technology for higher-order thinking, student-centered teaching, choice of strategy	3	10.71
	Saralar & Aras, 2024	Adaptive multimedia, exploration, personalized learning	3	10.71
	Caniglia & Meadows, 2018	Websites for assessment, meaningful math, student-driven inquiry	3	10.71
	Şandır & Aztekin, 2016	Dynamic geometry software impacts attitudes and visualization	2	7.14
	Shambare & Jita, 2025	VLs (Virtual Labs) foster inquiry, engagement, retention, critical thinking	3	10.71
	Zengin, 2019	GeoGebra supports self-efficacy, connections, multiple representations	3	10.7
	Slavíčková, 2021	DT and constructivist teaching support knowledge durability, TPACK	3	10.71
	Kreisa et al., 2024	Flipped model: enhanced outcomes, collaboration, authentic assessment	3	10.71
			28	**100**
Factors Influencing PSTs' Integration of Digital Tools in Their Teaching Practice	Akyuz, 2023	TPACK balance, beliefs/attitudes, planning vs. practical focus	3	11.1
	Gurer & Akkaya, 2022	Perceived usefulness/ease, authenticity, prior tech comfort	3	11.1
	Calder et al., 2018; Stein et al., 2020; Dockendorff & Zaccarelli, 2024	Institutional support, reduced barriers, design/context, decision-making on tech	4	14.81
	Martínez-Zarzuelo et al., 2025	Barriers: tech resources/time/diversity/confidence/training	3	11.1
	Shambare & Jita, 2025	Access/cost/training barriers, positive perceptions insufficient for adoption	4	14.81
	Gonscherowski & Rott, 2022	Decision-making skills needed for tech adoption	2	7.41

Theme	Author Year	Impact Type(S)	Count	%
	Dilling et al., 2024	Teacher attitudes, self-perceptions, need for own approach	2	7.41
	Milenković & Vučićević, 2024	Collaboration as a factor, importance of tool criteria, group analysis/perspectives	2	7.41
	Parra-Urrea & Pino-Fan, 2022	Suitability criteria, selection/validation, reflection in planning	2	7.41
	Caniglia & Meadows, 2018	Experience level, website validity, needs, teacher preparation	2	7.41
			27	**100**

3.3.1. Impact of Use of Digital Tools on PSTs' Learning to Teach Math

Ten studies examined how digital tools shape mathematics PSTs' preparation. Getenet (2024) highlighted visualization and diagrammatic approaches that enhanced problem-solving, pedagogical content knowledge (PCK), and AI-informed strategies (10.71%). Segal et al. (2021) showed inquiry-based GeoGebra activities fostered technological content knowledge (TCK), technological pedagogical knowledge (TPK), and subject content knowledge (SCK) (7.14%), while Lyublinsky and Du (2024) linked technology use to higher-order thinking and student-centered teaching (10.71%). Saralar and Aras (2024) illustrated adaptive multimedia's potential for exploration and personalized learning (10.71%), and Caniglia and Meadows (2018) emphasized web resources for meaningful assessment and student-driven inquiry (10.71%). Şandır and Aztekin (2016) noted that dynamic geometry software improved attitudes and visualization (7.14%), Shambare and Jita (2025) reported virtual labs promoted retention, inquiry, and critical thinking (10.71%), Zengin (2019) connected GeoGebra to enhanced self-efficacy and representational fluency (10.71%), Slavíčková (2021) linked digital tool-supported teaching to durable knowledge and TPACK growth (10.71%), and Kreisa et al. (2024) highlighted collaboration and authentic assessment through flipped models (10.71%). These studies demonstrate that diverse digital tools, including GeoGebra, adaptive multimedia, AI strategies, and virtual labs, enhance PSTs' readiness to teach mathematics effectively.

3.3.2. Impact of Constructivist Tech-Based Instructional Approaches on PSTs' Engagement and Confidence

Eight studies examined how constructivist, technology-based instructional approaches enhanced mathematics PSTs' engagement, confidence, and motivation. Slavíčková (2021) highlighted digital technologies (DT) fostering knowledge construction and active learning (12.5%), while Kreisa et al. (2024) reported that flipped classrooms promoted autonomy, deeper engagement, and confidence (12.5%). Ching et al. (2025) found STEM modules with 3D printing boosted hands-on experience and engagement (12.5%), and Quarder et al. (2025) emphasized student-centered design and reflective learning connecting theory to practice (12.5%). Milenković and Vučićević (2024) noted collaborative discovery, peer support, and group work as motivators (12.5%), Martínez-Zarzuelo et al. (2025) illustrated experiential and visual approaches enhancing motivation and overcoming challenges (12.5%), Parra-Urrea and Pino-Fan (2022) highlighted perseverance through collaborative learning (12.5%), and Zengin (2019) demonstrated that software-supported dynamic environments strengthened knowledge construction and confidence (12.5%). These studies indicate that constructivist, technology-mediated interventions consistently enhance PSTs' engagement, motivation, and instructional confidence.

3.3.3. Factors Influencing PSTs' Integration of Digital Tools in Their Teaching Practice

Twenty-seven counts identified factors influencing mathematics PSTs' integration of digital tools. Akyuz (2023) highlighted the interplay of TPACK, attitudes, beliefs, and planning strategies (11.1%), while Gurer and Akkaya (2022) emphasized perceived usefulness, ease of use, authenticity, and prior technology comfort (11.1%). Calder et al. (2018), Stein et al. (2020), and Dockendorff and Zaccarelli (2024) examined institutional and systemic supports, reduced barriers, and context-sensitive decision-making (14.8%), and Martínez-Zarzuelo et al. (2025) noted barriers related to resources, time, diversity, confidence, and training

(11.1%). Shambare and Jita (2025) stressed limitations of access, cost, and training, showing that positive perceptions alone are insufficient for adoption (14.8%). Other studies addressed decision-making skills (Gonscherowski & Rott, 2022; 7.4%), teacher attitudes and independent approaches (Dilling et al., 2024; 7.4%), collaboration and tool-selection criteria (Milenković & Vučićević, 2024; 7.4%), reflective planning and suitability criteria (Parra-Urrea & Pino-Fan, 2022; 7.4%), and prior experience and perceived validity (Caniglia & Meadows, 2018; 7.4%). These findings indicate that PSTs' digital tool integration depends on individual skills, collaborative opportunities, and institutional support, with access and systemic factors being most prominent.

4. DISCUSSION

4.1. Table 2: Study Indicators

The findings of this review align with and extend existing literature on mathematics PSTs preparation by highlighting the predominance of TPACK and technological integration as central focuses in current research, confirming that PSTs require scaffolding to balance content, pedagogy, and technology effectively (Akyuz, 2023; Ching et al., 2025). The emphasis on pedagogical beliefs, styles, and reflective practice corroborates prior studies that suggest PSTs who engage in reflective and inquiry-oriented approaches develop deeper instructional competencies and more meaningful integration of technology (Lyublinsky & Du, 2024; Parra-Urrea & Pino-Fan, 2022). The frequent examination of digital tools, including dynamic geometry software, AI platforms, and web-based applications, supports evidence that such technologies enhance representational competence, visualization, and problem-solving, facilitating constructivist, student-centered learning (Caniglia & Meadows, 2018; Zengin, 2019; Milenković & Vučićević, 2024), while research on innovative and contextual approaches emphasizes the need for culturally and contextually responsive interventions that reflect classroom realities and diverse STEM applications (Drijvers, 2015; Kreisa et al., 2024).

Research questions predominantly focused on instructional practices, technological acceptance, and TPACK development affirm prior observations that these areas are critical to PST readiness, whereas the relatively limited attention to content-specific integration, collaborative teaching, and external factors highlights gaps identified in the literature regarding equitable, context-sensitive preparation (Slavíčková, 2021; Kopcha et al., 2020). Participant characteristics, particularly the prevalence of female-dominant cohorts in primary and secondary PST programs and the dominance of final-year or mixed-year students, align with trends in teacher education while highlighting the need to explore diverse PST experiences and the influence of gender, program year, and geographic context on technology adoption and pedagogical confidence (Martínez-Zarzuelo et al., 2025; Shambare & Jita, 2025). The dominance of surveys, lesson artifacts, and quantitative analyses confirms established methodological preferences but also extends prior work by illustrating the complementary value of interviews, reflections, and system data in capturing PSTs' reflective and evaluative practices (Segal et al., 2021; Quarder et al., 2025).

Finally, interventions emphasizing technology integration, pedagogical strategies, professional development, and assessment support evidence that targeted, scaffolded approaches foster both technological fluency and instructional competence, while the relatively lower focus on design principles and field-based experiences suggests ongoing gaps in translating TPACK into authentic classroom practice, consistent with prior findings on the challenges of embedding technology meaningfully in PST programs (Polly & Martin, 2022; Milenković & Vučićević, 2024). Collectively, these results affirm that preparing PSTs for 21st-century mathematics classrooms requires integrated, reflective, and context-sensitive approaches that bridge theory, technology, and practice.

4.2 Table 3: Major Findings

4.2.1. Impact of Use of Digital Tools on PSTs' Learning to Teach Mathematics

The findings regarding digital tools such as GeoGebra, 3D printing, and collaborative platforms both affirm and extend existing literature on PST preparation by illustrating their central role in fostering conceptual understanding, representational competence, and authentic mathematical reasoning. Consistent with prior studies, GeoGebra was shown to support dynamic visualization and model construction, promoting TPACK development and discovery-based learning in real-world contexts (Kartal & Çınar, 2022; Martínez-Zarzuelo et al., 2025; Segal et al., 2021). These results extend earlier research by highlighting that PSTs value the ability to explore abstract concepts visually and interactively, reinforcing constructivist principles that encourage learner-centered inquiry and multiple representations (Şandır & Aztekin, 2016; Drijvers, 2015). Similarly, 3D printing facilitated the translation of theoretical knowledge into tangible models, enhancing spatial reasoning and problem-solving, which aligns with evidence that hands-on STEM experiences strengthen practical understanding and application (Ching et al., 2025; Dockendorff & Zaccarelli, 2024). Collaborative technologies, including CSCL and technology-mediated group work, further corroborate research emphasizing peer interaction and immediate feedback as mechanisms for shifting PSTs from procedural to conceptual understanding (Milenković & Vučićević, 2025; Davis & Witt, 2022), while also extending knowledge by showing that structured collaborative design activities amplify TPACK growth and pedagogical integration (Du & Lyublinskaya, 2024).

Importantly, the findings emphasize the moderating role of pedagogical beliefs, contextual factors, and program design: PSTs with constructivist orientations and technology familiarity adopted tools more meaningfully, whereas inconsistent program integration limited authentic use, echoing concerns about superficial digital implementation in pre-service programs (Gurer & Akkaya, 2022; Akyuz, 2023; Slavíčková, 2021). The results also highlight that reflection frameworks, digital simulations, and flipped classroom approaches enhance engagement, lesson planning, and conceptual understanding, supporting prior recommendations for scaffolded, evidence-based interventions that connect theory with practice (Parra-Urrea & Pino-Fan, 2022; Quarder et al., 2025; Kreisa et al., 2024). Finally, the integration of interdisciplinary and culturally relevant approaches, such as virtual labs and visual arts, extends previous work by demonstrating how real-world contextualization can enrich PSTs' problem-solving capabilities and prepare them for diverse classroom settings (Nutov, 2021; Shambare & Jita, 2025; Marbán & Mulenga, 2019), thus addressing the literature gap on holistic, technologically mediated preparation for contemporary mathematics instruction.

4.2.2. Impact of Constructivist Tech-Based Instructional Approaches on PSTs' Engagement and Confidence

The results regarding constructivist, technology-based instructional approaches, including flipped classrooms, peer learning, and mathematical modeling, largely affirm and extend existing literature on PST preparation by demonstrating their impact on engagement, confidence, and instructional planning. Flipped classroom models were shown to enhance self-regulation and active participation by reallocating direct instruction to asynchronous formats, allowing synchronous sessions to focus on collaborative problem-solving and deeper conceptual exploration, which supports TPACK development and strengthens PSTs' confidence in technology integration (Kreis et al., 2024; Du & Lyublinskaya, 2024). Peer learning and CSCL approaches further reinforced collaborative reasoning and content mastery, with multivariable calculus performance improving through structured cooperative activities, thereby extending prior evidence that interactive engagement promotes both cognitive and social dimensions of learning (Milenković & Vučićević, 2025; Dilling et al., 2024).

Technology-enhanced mathematical modeling, including AI-assisted problem-solving and digital simulations, facilitated lesson differentiation, experiential planning, and alignment with content standards, confirming previous findings that digital tools can scaffold pedagogical content knowledge when embedded purposefully (Quarder et al., 2025; Getenet, 2024). GeoGebra emerged as a versatile platform supporting interactive, student-centered lesson design and visualization of complex mathematical ideas, corroborating prior research on dynamic representations enhancing conceptual understanding (Kartal & Çınar, 2022; Martínez-Zarzuelo et al., 2025; Segal et al., 2021). The findings also highlight how pedagogical beliefs, technological experience, classroom culture, and resource access mediate effectiveness, with constructivist-oriented PSTs using tools more meaningfully than those with transmissive orientations, thereby extending understanding of individual and contextual influences on technology adoption (Gurer & Akkaya, 2022; Akyuz, 2023). However, the persistence of inconsistent training and limited access indicates that systemic and programmatic barriers continue to constrain structured engagement, underscoring the need for targeted support and sustained professional development to consolidate gains in instructional practice (Slavíčková, 2021; Marbán & Mulenga, 2019). Collectively, these results affirm the potential of constructivist, technology-mediated approaches to advance PST readiness for 21st-century classrooms while extending insights into the conditions that optimize their adoption and impact.

4.2.3. Factors Influencing PSTs' Integration of Digital Tools in Their Teaching Practice

The findings regarding PSTs' ability to evaluate and integrate digital resources into student-centered, standards-based instruction both affirm and extend existing literature by highlighting the complex interplay of pedagogical beliefs, TPACK development, content knowledge, and contextual factors. Consistent with prior studies, constructivist-oriented PSTs demonstrated higher engagement with inquiry- and collaboration-based tools, while teacher-centered beliefs constrained exploration of digital resources, echoing observations by Gurer and Akkaya (2022) and Marbán and Mulenga (2019). Strong TPACK frameworks emerged as a key enabler of evaluative competence, with scaffolded instruction and iterative practice supporting the integration of content, pedagogy, and technology (Du & Lyublinskaya, 2024; Kartal & Çınar, 2022). Content-specific knowledge guided tool selection, with dynamic geometry software and 3D printing facilitating the representation of complex mathematical ideas and multiple perspectives, reinforcing previous findings on the pedagogical affordances of these technologies (Segal et al., 2021; Zengin, 2019; Ching et al., 2025).

Contextual factors, including institutional support, technology access, school culture, and time constraints, significantly influenced the quality of integration, extending prior research that identifies structural barriers as critical determinants of digital adoption (Akyuz, 2023; Gonscherowski & Rott, 2022). Collaborative design experiences and exposure to diverse digital tools further strengthened PSTs' evaluative capacity, enabling alignment with content standards and fostering reflective practice, as reported by Dilling et al. (2024) and Saralar-Aras and Türker-Biber (2024). Moreover, the incorporation of emerging technologies such as AI-driven problem-solving expanded PSTs' perspectives on personalization, formative assessment, and real-world relevance, advancing insights into how novel tools can scaffold both pedagogical reasoning and content representation (Getenet, 2024; Ching et al., 2025).

Finally, beliefs about student agency and equity shaped engagement and resource selection, with student-centered approaches promoting autonomy and inclusive access, affirming the literature on equity-focused digital integration (Slavíčková, 2021; Shambare & Jita, 2025). Collectively, these findings emphasize that effective PST preparation requires not only access to innovative technologies but also structured guidance, reflective practice, and supportive institutional contexts to translate digital affordances into standards-aligned, student-centered mathematics instruction.

5. CONCLUSION

5.1. Limitations of the SLR

This SLR has several limitations that may influence the generalizability and comprehensiveness of its findings. The inclusion of only 24 peer-reviewed articles narrowed the scope. It may have excluded relevant but non-peer-reviewed studies, introducing potential publication bias by omitting gray literature, dissertations, and conference papers. The exclusive focus on technology use in mathematics education by PSTs further constrained the range of perspectives represented. Research on student learning outcomes, in-service teachers, or higher education was excluded. Regarding scope, the review was limited to selected databases (Google Scholar, Scopus, Web of Science, ERIC, and JSTOR) and major publishers (Springer, Taylor & Francis, Elsevier, Wiley, Sage, MDPI, etc.). This ensured methodological rigor but may have omitted region-specific or emerging open-access sources.

The timeframe of 2014 - 2024 allowed focus on contemporary developments in digital and constructivist pedagogy. However, it may have excluded earlier foundational studies that shaped current practices. Geographically, most studies were conducted in Europe (43.5%), North America (26.1%), the Middle East/Africa (21.7%), and Australia (12.5%). Asia and other regions were underrepresented, limiting global transferability. Additionally, time and resource constraints restricted the depth of synthesis and cross-context analysis. These boundaries highlight clear directions for future research. These include expanding inclusion criteria to multilingual and regionally diverse studies, incorporating gray and interdisciplinary literature, broadening database coverage, and extending the temporal range to strengthen validity and historical continuity. Future comparative studies across cultural and institutional contexts are also needed. These studies can explore how local infrastructures, policies, and teacher beliefs mediate technology integration. Addressing these areas can foster a more globally grounded understanding of how constructivist, technology-based pedagogies prepare PSTs for 21st-century mathematics instruction.

5.2. Scholarship Significance

This review synthesizes and critically analyzes a decade of research on constructivist, technology-integrated approaches in preparing mathematics PSTs, with focused attention on TPACK development, instructional planning, and conceptual understanding. It demonstrates how digital tools such as GeoGebra and emerging artificial intelligence platforms like ChatGPT enhance student-centered, standards-aligned instruction by enabling interactive visualization, adaptive feedback, and exploratory learning (Du & Lyublinskaya, 2024). Dynamic visual tools, as reported by Kartal and Çınar (2022) and Segal et al. (2021), strengthen representational competence and deepen mathematical reasoning, while collaborative learning environments foster peer-supported inquiry and shared problem-solving (Milenković & Vučićević, 2025; Dilling et al., 2024). Similarly, digital simulations and modeling activities (Quarder et al., 2025) improve PSTs' instructional confidence and performance, bridging the gap between theory and classroom application. Studies examining pedagogical beliefs (Gurer & Akkaya, 2022) and contextual influences (Akyuz, 2023; Slavíčková, 2021) clarify that constructivist-aligned PSTs are more likely to integrate technology meaningfully when institutional and cultural supports align with learner-centered practices.

By also engaging reflective instructional practices such as flipped classrooms and digital modeling (Kreis et al., 2024; Getenet, 2024), this review situates technology integration within authentic cycles of planning, implementation, and reflection. The findings carry several practical implications. For teacher educators, the review underscores the need for scaffolded, practice-based learning experiences that develop PSTs' capacity to select and adapt digital tools pedagogically. Curriculum designers can use these insights to embed authentic modeling, peer collaboration, and digital inquiry into mathematics teacher education programs. Policymakers may draw on this evidence to allocate resources toward equitable technology access, digital literacy training, and context-sensitive professional development models. Meanwhile, educational technology developers can design adaptive tools that align with constructivist pedagogies, supporting reflection, collaboration, and data-informed decision-making. Overall, this synthesis offers critical insights into how institutional, pedagogical, and technological dimensions intersect to shape PSTs' digital readiness, thereby contributing to ongoing reform efforts aimed at preparing effective, equity-oriented mathematics teachers for 21st-century classrooms.

5.3. Summary

This SLR examined research published between 2014 and 2024 on the preparation of mathematics PSTs for digital, student-centered, and standards-based instruction. Drawing on peer-reviewed studies from reputable academic databases, the review investigated how digital tools, constructivist pedagogies, and instructional decision-making shape teacher preparation. Findings indicate that technologies such as GeoGebra, 3D printing, and collaborative platforms enhance PSTs' conceptual understanding and capacity to apply mathematics in real-world contexts. Constructivist approaches, including flipped classrooms, peer learning, and modeling, foster engagement, instructional confidence, and collaborative lesson planning, particularly when embedded in iterative, authentic learning experiences. Persistent challenges, such as inequitable technological access, limited cross-disciplinary training, and traditional instructional beliefs, continue to constrain integration. Although the review excluded gray literature, dissertations, and higher education-focused studies, it provides valuable insights into the affordances and constraints of digital integration, emphasizing the need for teacher education programs to adopt evidence-based strategies that promote technological fluency, pedagogical flexibility, and inclusive, standards-aligned instruction.

Acknowledgments. We thank Texas Tech University for providing the necessary facilities and resources to conduct our research.

Research Ethics. Not Applicable.

Data Availability Statement. The data can be accessed through the official figshare repository at https://figshare.com/s/3d3b548bd374d42f9ddc.

Conflicts of Interest. The authors declare that there are no competing interests.

Funding. This review work did not receive any funding.

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