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PAPER

# Developing Teacher Digital Competence through Mobile and Interactive Technologies: A Systematic Review Using the TPACK Framework

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## ABSTRACT

The systematic review uses the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to explore the development of teacher digital competence (TDC) through various digital technologies. With an emphasis on the technological pedagogical content knowledge (TPACK) framework, the study synthesizes findings from recent peer-reviewed articles to evaluate the integration of technologies such as massive open online courses (MOOCs), serious games, Internet of Things (IoT), and immersive virtual reality (VR) into educational practices. The review highlights the transformative potential of these technologies for enhancing teachers' pedagogical strategies, fostering digital competence, and addressing gaps in educator training programs. Findings indicate that digital technologies improve immediate teacher competencies and pave the way for more interactive and inclusive learning environments. However, the small number of included studies (n = 10) and other limitations such as short-term study designs and English language only publications highlight the need for future research. The findings offer actionable insights for curriculum design, policy development, and professional training programs to equip educators with the digital competence necessary to thrive in modern educational landscapes.

## KEYWORDS

teacher digital competence (TDC), mobile learning, interactive technologies, massive open online courses (MOOCs), Internet of Things (IoT), professional development (PD), systematic review

## 1 INTRODUCTION

Digital competencies are crucial for future educators. They encompass a wide range of skills and knowledge necessary to integrate digital technologies into

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educational environments effectively. These competencies extend beyond mastery of specific technologies. Digital competence involves a deeper understanding and application of digital technologies for creating inclusive and adaptive learning environments. [1] defines digital competence as "a personal formation that integrates relevant motives, values, attitudes, knowledge about various digital resources, means, tools, technologies, and the ability to apply them in practical pedagogical activities based on critical analysis and evaluation." Digital literacy and competence are interconnected. Digital literacy constitutes the foundation of digital competence and encompasses the skills necessary to use digital technologies and resources effectively. Meanwhile, digital competence refers to a higher-order construct involving the integration of technological, pedagogical, and content knowledge (TPACK). This study examines digital competence as a higher-order construct that includes both technical and pedagogical applications of digital literacy, aiming to enhance content knowledge (CK) and improve student outcomes.

The demands of the modern educational landscape have made digital competence more critical than ever. Teachers must proficiently use virtual learning platforms, digital content creation tools, and online assessment methods to enhance learning outcomes and promote equity and accessibility in education [2]. However, many teacher education programs face challenges in providing sufficient digital training, resulting in gaps in teacher preparedness. As noted by [3], *studies of the use of digital resources show that educators' digital competence is low. Our educators are generally technologically literate but not competent*. This gap underscores the urgent need for comprehensive teacher training programs that effectively integrate digital technologies into pedagogical practices.

### 1.1 Developing teacher's digital competence (TDC)

Developing teacher digital competence (TDC) requires a holistic approach. The TPACK framework provides the relevant model for cultivating TDC. Teacher education programs equip educators with essential digital competence. Realistic assessments allow teachers-in-training to demonstrate their digital competence in real-world scenarios, strengthen the acquisition of digital competence, and build confidence. As highlighted by [2], *teachers' self-perceived technical and pedagogical ICT competence are positive, significant predictors for teachers' ICT adoption in their teaching practice.* Teaching simulations enable technology integration in instructional practices and foster digital competence. Training prepares teachers for the challenges of a digitally interconnected world.

The TPACK model ensures the integration of technical, pedagogical, and content knowledge to enhance learning outcomes [4]. This comprehensive approach helps educators develop the necessary skills to manage the complexities of modern classrooms. Aligning digital technologies with the TPACK framework is critical for maximizing their effectiveness. Recent research by [5] demonstrated that lesson scheduling and grade management platforms designed within the TPACK framework significantly improved content delivery and teacher confidence in integrating technology. Continuous professional development (PD) is essential for enhancing teachers' digital competencies, enabling them to stay updated with evolving technologies and apply them innovatively in their classrooms.

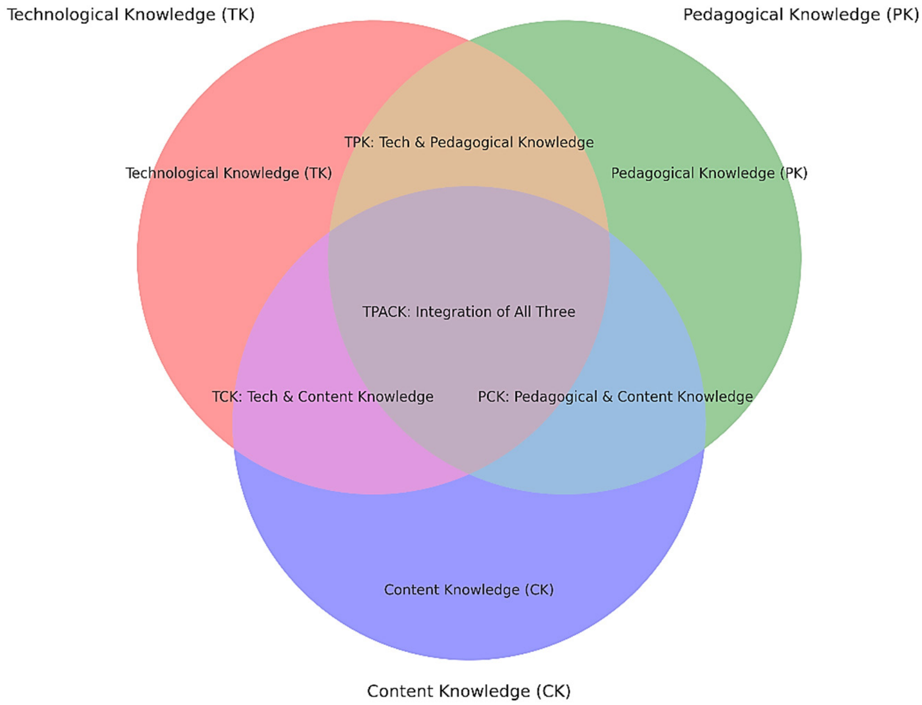


**Fig. 1.** TPACK framework: Integration of knowledge for effective teaching

Professional development programs equip teachers with technical knowledge and foster critical thinking. Teachers regularly engaging in such activities are better prepared to create innovative learning environments that support student engagement, collaboration, and digital competence [6]. Future educators need a blend of digital competence, subject-specific technological skills, and a commitment to lifelong learning to integrate technology into their classrooms effectively [7], [8], [9].

Practical strategies for enhancing TDC include implementing inductive teaching methods [10], utilizing digital measuring tools such as Einstein and Lab Disc [11], and focusing on enhancing student motivation [12]. Tailored digital models for educational environments [13] and targeted training workshops further help educators enhance their digital competence [14]. A holistic approach to digital competence encompasses broader knowledge and skills beyond technical proficiency [4]. Universities play a critical role in this process by using assessments to identify skill gaps and boost teachers' confidence in technology integration [4]. Courses designed by teacher educators should enable future teachers to acquire sufficient digital competence, facilitating the effective integration of digital media into various learning processes while promoting self-directed learning [15].

As digital technologies continue to evolve, teachers must remain engaged in ongoing learning to stay abreast of innovations and effectively incorporate them into their practices. This adaptability ensures that teachers meet current educational demands and prepare their students to thrive in a rapidly changing digital landscape.

## 1.2 Purpose of the present study

The primary objective of this study is to investigate the enhancement of digital competencies among future educators through digital technologies. This systematic review examines the effectiveness of various tools, including the Internet of

Things (IoT), augmented reality (AR), serious games, and massive open online courses (MOOCs), in equipping educators with the digital competence required for modern teaching. It also evaluates the challenges and opportunities these technologies present in teacher training programs and their overall impact in line with the TPACK framework.

The digitalization of teacher education is vital for preparing future educators to navigate an increasingly digital society. As noted by [16], *the digitalization of modern teacher education should ensure the preparation of highly qualified staff, who will be able to apply modern and advanced information technologies with a high level of digital skills and competencies that correspond to social needs and the requirements of the digital economy.* Teacher training programs must evolve and equip educators with the competencies to thrive in digital learning landscapes [16].

Despite progress, significant gaps remain in understanding the effects of digital technologies on teacher competence and their scalability in resource-limited settings. Furthermore, previous studies often lack a focus on integrating foundational frameworks, such as the TPACK framework, into diverse contexts. This review employs the TPACK framework. It is a comprehensive model integrating TPACK. It enables educators to design and deliver content effectively using digital technologies. This study aims to:

1. Analyze relevant studies to identify effective strategies for incorporating digital technologies into teacher training programs.
2. Highlight the challenges associated with deploying these technologies in diverse educational contexts.
3. Bridge existing capacity gaps by integrating TPACK in teacher development.

## 2 METHODOLOGY

### 2.1 Timeframe selection

First, the rapid evolution of digital technologies and their educational applications necessitated focusing on recent studies (2018–2023) to capture contemporary trends. Technological tools and educational strategies have undergone significant transformations in recent years, particularly after the COVID-19 pandemic, which accelerated the adoption of digital technologies in education [17]. The authors in [18] highlighted the significance of research and development of digital competencies among educators after COVID-19. As noted by [19], 'there has been a notable and exponential increase in the number of publications on TDC, especially in recent years.' The systematic review by [19] has shown a growing scholarly focus on digital competencies in higher education from 2017 onwards and reported the highest number of 18 published manuscripts in 2020 [19]. Another systematic review examined the concept of teachers' professional digital competence (TPDC) as represented in educational research literature from 2010 to 2019 [20]. Six of the 18 studies selected for analysis were published in 2018 or later [20]. The analysis shows that the research focus on TPDC has grown in recent years. Therefore, research published before 2018 did not adequately reflect the current landscape of digital competencies in teacher training programs. Second, focusing on this five-year window aligned with our research questions, aiming to evaluate cutting-edge methods relevant to TPACK-based teacher training. Studies before 2018 did not adequately reflect the modern digital competence landscape, particularly mobile and interactive technologies.

## 2.2 Framework

The review employed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework to ensure transparency and replicability in selecting and analyzing articles [21], [22]. The decision to use the PRISMA framework stems from its well-established credibility in organizing comprehensive reviews [23], [24]. PRISMA's emphasis on clearly delineating the inclusion and exclusion criteria, search processes, and inclusion of studies guided this study inquiry to ensure a thorough and unbiased examination of digital technologies in teacher education [22], [25], [26]. Key decision points included identifying relevant articles and subsequent screening of articles based on titles and abstracts to identify relevance. It was followed by a full-text review to confirm inclusion. Figure 2 outlines the stages of Identification, Screening, and Inclusion. We also mapped our findings onto the TPACK framework to assess how each technology (IoT, AR, VR, MOOCs, serious games) addressed technological (TK), pedagogical (PK), and CK components.

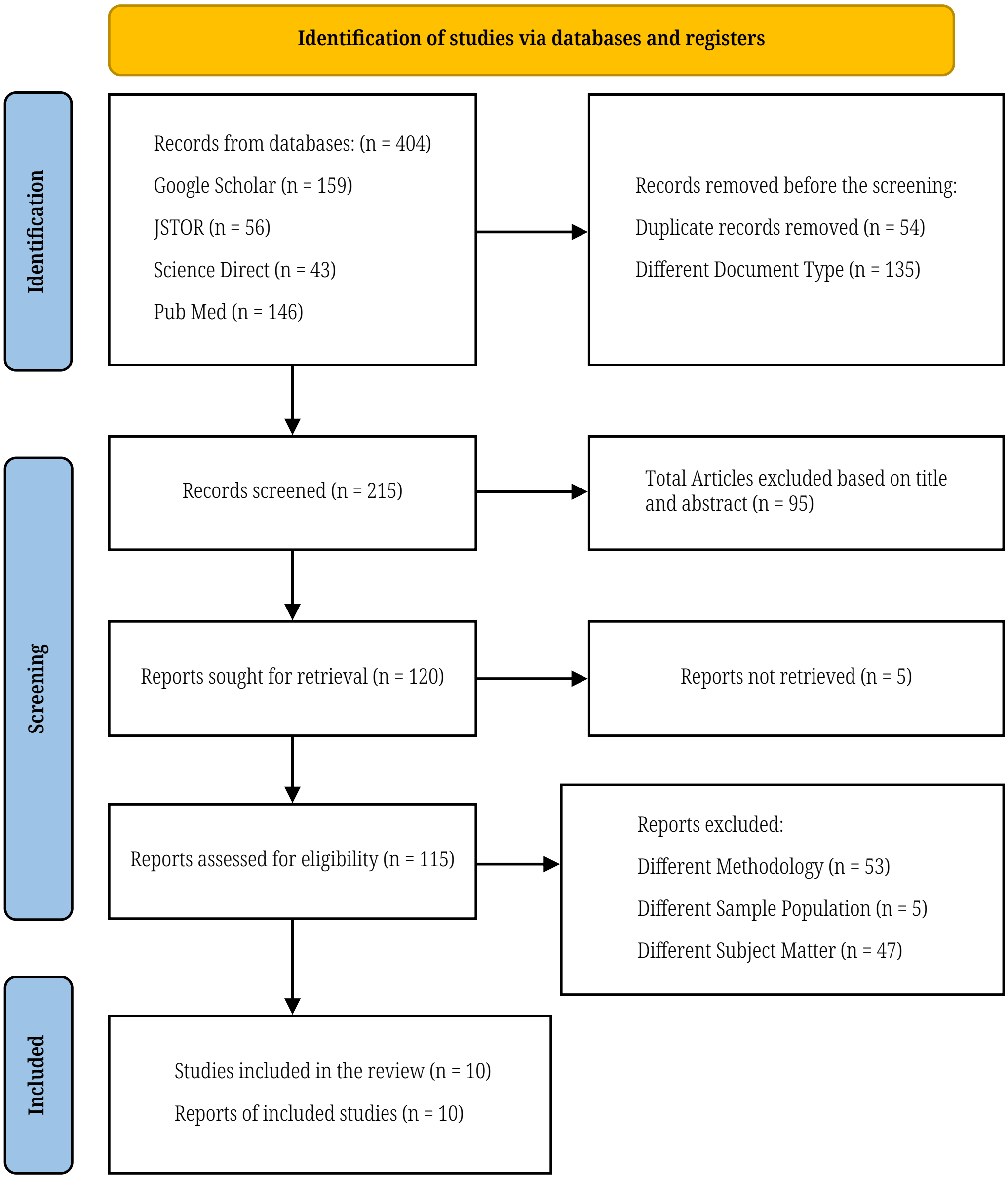


**Fig. 2.** PRISMA guideline flowchart

## 2.3 Search strategy

As illustrated in Table 1, a comprehensive search strategy was employed across multiple academic databases, using a focused set of keywords to identify relevant studies on teacher digital competencies. Zotero was used to manage the 404 identified articles, streamline the citation process, and assist in removing duplicates. After an initial screening of titles and abstracts, the selection was narrowed to 120 articles.

**Table 1.** Database search results for systematic review

| Keywords Used | Database | Date | Articles |
|---|---|---|---|
| ("Teacher Digital Competence") AND ("Teacher Training") AND ("experimental" OR "RCT" OR "Randomized Controlled Trial") AND ("test") AND "Research Articles" AND ("2018" [Date – Publication]: "2023"[Date – Publication]) | Google Scholar | 14/04/2024 | 163 |
| ("Digital technologies" OR "educational technology") AND ("teacher training" OR "digital competencies") | JSTOR | 14/04/2024 | 56 |
| ("Teacher Digital Competence") AND ("Training") AND "Research Articles" AND ("2018" [Date – Publication]: "2023"[Date – Publication]) | Science Direct | 14/04/2024 | 43 |
| ("Teacher Digital Competence") AND ("Training") AND ("2018"[Date – Publication]: "2023" [Date – Publication]) | Pub Med | 14/04/2024 | 146 |

## 2.4 Screening

The screening process followed a dual-review approach to ensure the reliability and accuracy of the paper selection. Both reviewers independently assessed each paper against the predefined inclusion and exclusion criteria (refer Table 2). These criteria were specifically designed to focus on integrating digital technologies in teacher training programs and evaluate their effect on developing digital competencies. We included studies that contained quantitative measures of digital proficiency and excluded studies focusing solely on traditional teaching methods or without comparative analysis to refine the selection process.

During the dual review process, disagreements between the two reviewers on whether certain studies met the inclusion criteria were addressed through structured deliberation. The two reviewers first discussed any conflicting decisions to identify the root of the disagreement. These discussions typically revolved around the interpretation of the inclusion criteria. A third neutral reviewer was consulted when consensus could not be reached. This third reviewer had no prior involvement in the review process, thus providing an unbiased resolution. The third reviewer assessed the articles independently and provided input, and the final decision was reached through a majority agreement. This process maintained the integrity and rigor of the systematic review while ensuring that all perspectives were considered fairly.

**Table 2.** Inclusion and exclusion criteria for article selection

| Criteria Category | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| **Document Type** | Peer-reviewed journal articles | Conference papers, unpublished theses, or grey literature |
| **Dependent Variable** | Integration of digital technologies with explicit pedagogical applications | Traditional teaching methods without digital technology integration |
| **Educational Context** | Studies within teacher training programs targeting pre-service or in-service educators | Studies focused solely on primary, secondary, or unrelated educational levels |
| **Study Results** | Quantitative measures of digital proficiency (e.g., pre/post-tests, competency assessments) | Studies without measurable outcomes or subjective anecdotal results |
| **Research Approach** | Randomized Controlled Trials, Quasi-Experimental Designs, Mixed-Methods Studies | Descriptive, inferential, or observational studies lacking experimental elements |
| **Publication Period** | Studies published between 2018 and 2023 | Studies published before 2018 or after 2023 |
| **Technological Scope** | Use of advanced digital technologies (e.g., IoT, MOOCs, VR, Serious Games) | General ICT or traditional non-digital tools without a focus on innovative pedagogical integration |
| **Linguistic Scope** | Publications in English | Non-English publications |
| **Comparative Analysis** | Studies with clear comparative analysis of digital competencies | Studies lacking comparative frameworks or baselines |

## 2.5 Final study selection

Although our initial search yielded 120 articles meeting the preliminary criteria, we ultimately included ten that met our stringent requirements for methodological rigor, explicit focus on digital competence within a TPACK framework, and use of advanced digital tools (IoT, AR, VR, MOOCs, serious games). These ten studies offered robust quantitative or mixed-methods data critical for examining TDC in depth. We acknowledge that this narrow selection may limit the overall generalizability of our findings but ensures a concentrated exploration of cutting-edge research relevant to our study questions.

## 2.6 Data extraction and synthesis

We created an Excel template to record each study's title, year, sample size, methodology, digital tools used, and key outcomes (e.g., pre or post-test gains in TDC, TPACK self-assessments). This structured approach facilitated a comparative analysis of findings across studies, ensuring consistency and reproducibility. The extracted data were synthesized using thematic analysis to identify common trends in the effectiveness of digital technologies. This method allowed for a nuanced exploration of how different technologies impact TDC across various educational contexts.

**a)** Coding scheme: We aligned findings with TPACK sub-domains:
- TK: Tools teachers learned or mastered

- PK: Instructional approaches or methods
- CK: Subject-specific competencies

**b)** Narrative synthesis: Because of the heterogeneity in instruments and effect size reporting, we pursued a systematic review without meta-analysis, highlighting thematic overlaps (e.g., teacher readiness, institutional support, resource constraints).

**c)** Thematic analysis: We grouped recurring themes such as the development of TDC, the category of the digital tools used in the study, and the impact.

**Table 3.** Summary of studies included in the review

| Source | Sample Size & Population | Objective | Methodology | Technology Used | Outcome |
|---|---|---|---|---|---|
| **[27]** | 30 students in the Master's in Teacher Training program | To explore the usability and educational impact of immersive virtual learning environments. | Case study analysis of virtual environments implemented in real classrooms. | Virtual classroom tools (Google Sites, Kahoot, Socrative) | Digital Content Creation: r = 0.74 (Knowledge), r = 0.73 (Use) in post-tests |
| **[15]** | 56 academics | To analyze the acceptance of serious games for developing digital competencies in higher education academics. | Mixed-methods approach using TAM framework and serious game trials with academics. | Serious Games (Astro Código) | Attitudinal competencies score: Pre-test 51.23, Post-test 51.75 |
| **[28]** | Ten students from the Faculty of Educational Sciences | To study the role of digital storytelling in fostering creativity and critical thinking. | Action research with iterative feedback on digital storytelling workshops. | Immersive Virtual Reality and other technologies | Attitude towards technology: Pre-test d = 1.127, Post-test significant improvement |
| **[29]** | 297 university professors | To determine the relationship between technology integration and student performance in hybrid learning setups. | A longitudinal study tracking performance metrics across technology-integrated classrooms. | Nano-MOOCs | Digital content creation improvement in 75.75% of participants |
| **[30]** | 269 university teachers | To assess the potential of e-learning platforms in enhancing cognitive and practical skills. | Survey-based research evaluating user perceptions of e-learning platforms. | Academic management system, virtual learning system | Training effectiveness: Pre-test 51.5, Post-test 74.4 (22.88% improvement) |
| **[31]** | 61 in-service science teachers from 92 secondary schools | To examine the impact of gamified learning tools on learner engagement and educational outcomes. | Quantitative analysis with pre and post-test design focusing on gamified modules. | Personalized ubiquitous learning system (KKU Smart TPACK) | TK score: Pre-test 0.90, Post-test 1.43; TCK score: Pre-test 0.38, Post-test 0.64; TPK score: Pre-test 0.44, Post-test 0.57 |
| **[32]** | 147 third-year education students | To investigate the effectiveness of digital tools in promoting collaborative learning and knowledge retention. | A qualitative study with focus groups and content analysis on digital tools usage. | Massive Open Online Courses (MOOCs) | Z-scores for the motivational, technological, cognitive, and ethical components (–2.314, –3.264, –5.882, –4.073, respectively) indicate significant improvements |
| **[33]** | 56 pre-service teachers | To measure the effect of AI-driven educational tools on individualized learning paths. | Data-driven analysis using AI models to predict educational outcomes. | Digital resources and devices for teaching languages | High competence: Pre-test 14.3%, Post-test 39.3% |

*(Continued)*

**Table 3.** Summary of studies included in the review *(Continued)*

| Source | Sample Size & Population | Objective | Methodology | Technology Used | Outcome |
|---|---|---|---|---|---|
| **[34]** | 32 student teachers | To assess teacher attitudes toward digital pedagogy and its influence on instructional practices. | Survey and interviews assessing teacher training and attitudes toward technology. | Webcast applications | Internet browser usage rating: Mean 4.72, SD 0.656 |
| **[35]** | 908 Educational degree students | To evaluate adaptive learning technologies in improving student comprehension and satisfaction. | Experimental design with control and treatment groups utilizing adaptive technologies. | Various digital technologies (e.g., Loom, Kahoot, Twitter) | Final course scores: Users of > 2 tools 357.13, non-users 190.05 |

## 3 RESULTS

The systematic review critically evaluated the impact of digital tools on enhancing TDC through a rigorously selected array of studies. Table 3 provides a concise summary of each included study. We mapped the reported outcomes onto the TPACK domains. For instance, serious games and IoT systems contributed primarily to TK and partially to PK, while immersive VR or AR frequently enhanced CK. By synthesizing findings across these domains, we illustrated each digital tool's specific alignment with teacher digital competence.

IoT-enabled systems emerged as a key driver of TK development. These tools allow educators to utilize real-time data for personalized instructional strategies and classroom management. For example, [30] reported significant improvements in technological proficiency among university teachers following the use of IoT-enabled academic management systems. Similarly, [31] used a personalized learning system, KKU Smart, to provide science teachers with customized educational content. The results show significant enhancement in their TK (scores: pre-test 0.90, post-test 1.43) [31]. The integration of IoT in educational settings not only enhanced digital competencies but also supported the development of innovative teaching methodologies. IoT applications, such as smart classrooms and real-time performance monitoring tools, demonstrated potential for tailoring instructional strategies based on real-time analytics [31]. These findings suggest that IoT-enabled systems enhance teachers' digital competence and contribute to the development of data-driven, personalized teaching methodologies.

MOOCs and serious games fostered PK by providing opportunities for scalable and interactive PD. For instance, [32] highlighted how MOOCs improved teachers' pedagogical strategies, incorporating collaborative learning and active methodologies. On the other hand, serious games allowed educators to experiment with pedagogical scenarios in risk-free environments, leading to moderate gains in attitudinal competencies (pre-test 51.23, post-test 51.75) [15]. Additionally, [29] observed significant improvements in digital competence among university professors post-nano-MOOC training. [32] and [29] demonstrated the effectiveness of MOOCs and Nano-MOOCs, respectively, offering extensive courses to broadly improve digital competence and providing concentrated experiences to enhance specific skills among educators.

Digital tools such as immersive VR enhance teachers' CK by enabling the creation and delivery of subject-specific content. For example, [28], documented significant improvements in educators' ability to integrate VR into STEM curricula, fostering better conceptual understanding among students. [27] highlighted significant enhancements across various digital competence domains through virtual classroom tools. Further emphasizing the broad applicability of digital technologies [28] documented improved attitudes towards technology and virtual lab usage via immersive virtual reality.

Studies incorporating multiple digital tools demonstrated the most significant gains in TPACK integration. For example, [35] found that educators using more than two tools scored higher in practical activities (335.59) compared to non-users (204.19). [30] suggests that exposure to diverse technologies fosters holistic TPCK development. [33] showed marked improvements in pre-service teachers' digital competence by deploying diverse digital resources. [35] explored a variety of digital technologies such as Lipgrid, Powtoon, and Kahoot, reflecting the dynamic nature of digital education and its practical applications in enhancing digital competencies. Similarly, [30] documented significant improvements in teacher training effectiveness and satisfaction with systems that streamline educational administration. [27] used virtual classroom tools such as Google Sites and Socrative to create interactive learning environments that significantly enhanced knowledge and application domains of digital competence.

Lastly, [34] identified high competency levels in accessing information among students using webcast applications. Digital technologies significantly improved specific dimensions of TDC, such as TK [31], pedagogical application [34], and attitudes toward technology [15], [32]. A consistent pattern across studies indicates that digital tools significantly enhance specific dimensions of TDC. IoT and AR improve technical proficiency and support adaptive teaching strategies. MOOCs and serious games promote interactive and collaborative methodologies. VR tools enable the creation of visually enriched, subject-specific content.

Despite the consistent improvements reported, certain limitations were observed. For example, many studies focused on short-term outcomes without assessing the long-term sustainability of digital competence. Additionally, the effectiveness of digital technologies often depended on factors such as institutional support [31] and prior familiarity with technology among participants [29]. For instance, while IoT and MOOCs demonstrated significant improvements in digital skills, resource-limited settings posed challenges to full adoption [35], [33].

### 3.1 Methodological critique

After reviewing the ten selected studies, it is evident that while each study aims to improve TDC through varied instructional strategies, their methodological decisions differ significantly, influencing both the validity and reliability of their findings. The ten studies predominantly rely on pre–post or single-group quasi-experimental methods, aiming to track short-term changes in teachers' self-reported competence or attitudes. Only one study includes a separate control group. Sample sizes vary from small pilot groups ($n = 10$, $n = 30$) to moderate or large institutional cohorts ($n > 150$). In several cases, convenience sampling and location-specific conditions hamper broader generalizability. While validated or partially validated questionnaires appear frequently, direct observation or performance-based tasks are less common, limiting robust claims about actual skill mastery. Short-term measurement is common, with few studies addressing whether digital competence gains are sustained or transferred into classroom practice. Table 4 summarizes the major strengths and weaknesses of each study, highlighting design features, instrumentation choices, and sampling procedures. Following the table, a brief narrative synthesis discusses the overarching methodological implications.

**Table 4.** Overview of methodological strengths and weaknesses across the 10 studies included

| Reference | Design & Sample | Strengths | Weaknesses |
|---|---|---|---|
| **[27]** | Pre-experimental (n = 30), single-group, master's students in a fully online university context | Validated framework (INTEF/DigCompEdu); detailed active interventions; effect sizes reported | No control group; small convenience sample limits external validity; short-term measurement only |
| **[15]** | Mixed-method (n = 56), acceptance of serious games for digital competence in HE instructors | Mixed data sources (observations, interviews, TAM-based survey); contextual detail for serious games | No long-term follow-up; limited generalizability to other contexts; mostly self-reported measures |
| **[28]** | Design-based research + quasi-experimental (n = 10), integrating VR/3D printing in STEM PD | Hybrid/hands-on approach; multi-method (questionnaire + interviews); design-based iterative improvement | Very small single-group sample; short-term changes only; VR resources differ from typical schools |
| **[29]** | Quasi-experimental, pre–post (n = 297) in Ecuador, focusing on nano-MOOCs for teacher PD | Large sample with random selection; aligned to INTEF five areas; high instrument reliability | Single institution context; no direct performance measure; short-term data, focus on two competence areas |
| **[30]** | Pre-experimental one-group (n = 269) in Peruvian university, "digital technology architecture" | Institutional-level synergy of academic management + VLE; strong reliability (r = 0.82); pre–post design | No control group; self-reported "satisfaction/improvement" vs. measured skill; context-specific architecture |
| **[31]** | Quasi-experimental, one-group pre–post (n = 161) in-service STEM teachers, AI-based personalization | TPACK subdomain test offers granular data; real AI-based personalization; moderate sample size | Single-group only; short workshop timeline; TPACK measure short, possibly minimal coverage of subdomains |
| **[32]** | Pre–post with control (n = 147) focusing on MOOCs, measured motivational/tech/cognitive/ethical | True control group; 4 subcomponents of digital competence; MOOC tasks clarifying connectivist approach | Unclear randomization; short-term self-report measure only; single instrument for digital competence |
| **[33]** | Mixed-method (n = 56), two-group design in FL teacher training (both treatments, varied supports) | Custom two-domain approach to digital resources (technical vs. methodological); multi-method data | Both groups are interventions, not a real control; short-term posttest only; small sample, modest reliability |
| **[34]** | Mixed-method (n = 32), Bloom's Digital Taxonomy as lens to interpret webcast-based teacher PD | Novel taxonomy-driven design; mixed data (survey + interviews, Kappa = 0.87 for coding) | Single context, small sample; no baseline or control; asynchronous environment conflates minimal interaction |
| **[35]** | Pre-experimental one-group (n = 908 across 3 years) in an online university with active learning | Substantial multi-year dataset; multiple outcome measures (tasks, final exam, % completions); iterative approach | No control group; tool usage frequency conflates quantity with quality; no domain-based digital competence framework |

## 3.2 Variability in measuring digital competence

The conceptual and instrumental inconsistencies across these studies pose a substantial challenge for cross-study comparison. Some adopt TPACK rubrics, exploring technological, pedagogical, and content knowledge intersections, while others frame digital competence in line with the Spanish INTEF or European DigCompEdu. A few go beyond typical "Information and Communication" or "Content Creation" domains to incorporate motivational, ethical, or advanced immersive technology angles. Additionally, different studies weigh "acceptance" or "feasibility" more heavily than performance-based mastery, leaving open the question of how teacher participants might truly integrate technology in actual teaching scenarios.

While a few studies mention validated instruments for example, the TPACK-based 13-item tests or the questionnaires aligned with INTEF's five areas, others rely on custom surveys or simplified pre–post scales that measure usage frequency or short-term satisfaction. Self-report remains the dominant approach, often capturing perceptions rather than directly assessing skill-based competence. This phenomenon complicates cross-study metanalysis and suggests a pressing need for standardized frameworks. The reliance on short instruments with minimal subscale coverage (one or two items per domain) further weakens the depth of the measurement, making it difficult to parse subtle differences in skill growth among areas such as "Safety," "Problem Solving," or "Communication and Collaboration." Meanwhile, a subset of studies anchors their metrics in Bloom's Digital Taxonomy or the Technology Acceptance Model, neither of which directly correspond to the official multi-domain digital competence structures. Although that approach can yield insight into cognitive or attitudinal shifts, it remains tangential to the domain-based skills that official frameworks tend to emphasize. In short, although each of the ten studies contributes valuable insights into fostering TDC, the variation in measurement strategies, outcome focuses, and methodological rigor highlights the urgent need for more standardized approaches.

## 4 DISCUSSION

### 4.1 Contextualizing digital competence for teachers

Digital competence has become a cornerstone of modern education, driven by the increasing demand for educators to navigate digital learning environments. Research highlights that integrating digital technologies into teacher training programs improves technical proficiency and fosters creativity, critical thinking, and collaboration. Digital training programs enhance theoretical CK, cultivate linguistic competence, improve cooperative work skills, and foster creativity [36]. Rapid technological advancements necessitate those educators continuously update their digital competence to keep pace with evolving educational demands.

The pedagogical application of digital technologies is crucial. AR tools can bring historical events to life, while IoT devices can monitor student progress in science labs, allowing teachers to tailor instruction based on real-time data. Gamification, incorporating interactive resources and video-game such as activities, further engages students and fosters active learning [37], [38]. The IoT represents one of the transformative technologies enabling interconnected educational environments, enhancing learning experiences and resource management [11]. IoT devices provide a network of tools that automate administrative tasks, monitor student performance, and offer personalized learning experiences. Such systems allow teachers to gather real-time data on student engagement, enabling informed instructional decisions. According to [11], *The use of digital measuring systems and individual tools should be employed in the first years of higher education institutions... and also when conducting career guidance work with high school students.* These technologies support classroom management and transform assessment methods. Real-time feedback allows teachers to tailor their instruction based on student performance.

Integrating IoT into educational settings increases student motivation and cognitive activity [11]. IoT-enabled tools promote a more interactive and practical learning process by fostering *tasks of intellectually directed pedagogy as a means of development and self-development of students in an ICT-saturated environment* [11]. For example, [39] demonstrated how IoT systems enhanced STEM-related competencies among preschool teachers by enabling hands-on learning experiences. Similarly, [40] highlighted that personalized IoT platforms support content-specific learning by linking real-time data with pedagogical decisions.

Digital competence involves various dimensions, including informational, communicative, and creative aspects, which require continuous training [41]. These dimensions encompass subject-specific skills, such as handling digital data acquisition systems in laboratory settings, and broader competencies, such as empowering students for a digital society and fostering digital competence [42]. As [41] observed, *General technological-specific self-efficacy is only moderately related to the highly subject-specific self-efficacy of handling digital data acquisition systems.* Subject-specific digital competence requires targeted training to help teachers fully leverage digital technologies and enhance learning outcomes.

Furthermore, fostering digital competence through PD empowers teachers to integrate digital technologies effectively into their practices and prepare students for a digital society [7]. According to [7], teachers' digital competence is the effective integration of digital technologies into pedagogical practices for improving student learning outcomes. Research also underscores the association between digital competence and individuality. Digital technologies facilitate personalized learning, allowing teachers to adapt instruction to individual needs and shape student personalities [43].

The global shift toward digital education requires teachers to develop 21st-century skills that align with societal demands [44]. As [42] emphasized, *Empowering students for a digital society involves developing learning activities that foster digital literacy, collaboration, and responsible digital engagement.* Teacher education curricula must, therefore, extend beyond traditional technical knowledge to encompass digital competence, critical thinking, and adaptability. As [45] explained, *If we bear in mind the ever-changing digital context, we need to redefine teacher education and decide what competencies we should include in curricula to ensure future teacher preparedness.*

Research highlights significant national differences in digital competence. For instance, [46] compared digital competence levels among pedagogical staff in Italy and Poland, finding notable variations in software use, theoretical knowledge, and ICT application. These findings underscore the need for standardized training across regions to ensure equitable access to high-quality education. Similarly, [47] explored future biology teachers' views on digital competencies in blended learning environments. The authors revealed that although digital technologies were useful, gaps remained in their sufficiency.

The digitalization of teacher education is essential to meet the requirements of the digital economy [16]. Upskilling and training programs are required to develop teachers' digital competence and enhance their ability to use technology creatively [48]. Training programs must advance beyond traditional technical knowledge to include broader digital competence, recognizing the complex knowledge and skills required in digitally mediated environments [49]. Teacher educators (TEDs) are critical in preparing future teachers for these epistemic changes, fostering digital competence and transformative digital agency [50]. As [16] notes, *TEDs are expected to focus on the (pedagogical) use of digital tools.* However, teacher educators must also emphasize digital ethics, privacy, and citizenship to prepare students for misinformation, cyberbullying, and other contemporary issues.

As digital technologies continue to evolve, the role of teachers as facilitators of ethical digital practices becomes even more critical. By equipping teachers with the skills and understanding necessary to navigate these complexities, education systems can foster a generation of responsible digital citizens prepared for a rapidly changing world. However, effective implementation requires enhanced communication and collaboration skills among teachers, mainly when using active ICT-based methodologies [38]. Furthermore, innovation in teaching practices often requires peer collaboration to modernize teaching strategies and improve digital infrastructure [51].

### 4.2 Contextualizing digital technologies for education

Emerging technologies such as the IoT, AR, and serious games are revolutionizing how teachers develop their digital competencies [52]. IoT and AR enable immersive learning environments that traditional methods cannot replicate. For instance, AR brings abstract concepts to life, allowing students to visualize complex processes in history, mathematics, and science [37]. These capabilities transform the learning experience, making it more engaging and interactive. IoT, on the other hand, provides real-time feedback and analytics, facilitating personalized instructional strategies and improving student outcomes [11]. Additionally, [53] demonstrates the viability of advanced mobile interaction systems that integrate location and temporal data for real-time adaptation of teaching content, further personalizing teacher education and bridging the gap between TPACK. Furthermore, [54] emphasizes how AI-based educational tools ranging from cognitive tutors to automated assessments can significantly transform instructional approaches and strengthen teachers' digital competence through context-aware, data-driven methodologies. These studies reinforce the notion that teacher training programs must emphasize real-world application of emerging technologies to fully realize TPACK's integrative potential.

Integrating these technologies demands a high level of digital competence, which many teachers lack, particularly in resource-limited settings [45]. Successful implementation also depends on ongoing PD and institutional support, underscoring the need for systemic capacity-building efforts. Recent research highlights additional benefits of digital technologies in education. For example, [55] demonstrated how motion graphic-based learning media enhanced teacher engagement in digital content creation. Similarly, [56] showcased the effectiveness of Canva-based modules in improving environmental awareness among students, reflecting the dual benefits of technology integration for educators and learners.

Serious games and gamification have also emerged as powerful tools for fostering TDC. As [57] noted, *the digitalization process caused by global trends in the transition to a digital economy and a digital society requires changes in the technologies used by the modern teacher at school and in educational organizations.* Gamification integrates game-like elements into educational activities, boosting student engagement and fostering active learning. According to [46], *the increasing trend in gaming as a popular interactive leisure activity and its capacity to improve skills such as problem-solving, teamwork, and strategic thinking provides opportunities for its application in educational settings.* By incorporating gamification into teacher training programs, educators gain an interactive platform to experiment with new teaching methods and digital technologies in a risk-free environment. Gamification enhances teacher confidence in digital technologies and equips them to implement similar classroom strategies.

Virtual learning environments, such as MOOCs, further revolutionize teacher education by offering flexible, scalable, and accessible PD opportunities. MOOCs enable teachers to enhance their digital competence in areas such as content creation and the integration of digital technologies into pedagogical practices. Studies show that teachers engaging with MOOCs significantly improve their digital competence, content creation abilities, and PK. [27]. Moreover, [27] emphasized that *the implementation of active methodology supported by technological tools in a virtual classroom has enabled an increment in the level of digital competence of future teachers, particularly in digital content creation, problem-solving, and communication and collaboration.* These platforms also allow teachers to connect with global peers, fostering a collaborative community of practice that supports ongoing professional growth.

IoT-driven approaches, such as IoT-enabled sensors and interactive digital interfaces, further enhance teaching and learning. These technologies enable more personalized, responsive, and effective educational experiences, aligning with modern demands for adaptable, student-centered teaching strategies. By integrating such tools, educators can better address the evolving challenges of digital education, equipping themselves and their students with the skills necessary for success in the 21st-century learning environment.

### 4.3 Findings from the systematic review

The findings of this systematic review demonstrate the transformative potential of digital tools, such as IoT, MOOCs, and AR, in enhancing TDC. These tools significantly contribute to the development of TK, PK, and CK, aligning with the TPACK framework. For example, IoT applications enhance digital competence and facilitate data-driven decision-making, allowing educators to tailor instructional strategies to student needs. Similarly, tools such as MOOCs and serious games provide scalable solutions for PD, particularly in resource-constrained settings.

Variability in the effectiveness of digital technologies was observed across studies, influenced by factors such as institutional support, teacher readiness, and prior exposure to technology. For instance, studies such as [48] demonstrated significant gains in TK through personalized learning systems, while others, such as [50], emphasized the need for multi-tool approaches to achieve broader competence improvements. The systematic review highlights the diverse technological interventions employed across various studies to enhance digital competence among educators, using the TPACK framework as a lens to understand and explain the outcomes. This framework posits that effective teaching with technology involves understanding and integrating technology, pedagogy, and CK [58]. TK evaluates educators' capabilities in employing digital technologies for educational purposes, technological and content knowledge (TCK) gauges the integration of CK with technological resources, and technological and pedagogical knowledge (TPK) measures the effectiveness of teaching strategies via technological means [31]. [31] demonstrated the effectiveness of personalized learning systems in enhancing TK, where teachers experienced a significant increase in TK scores from 0.90 to 1.43, reflecting substantial growth facilitated by the KKU Smart TPACK system. The results indicate that personalized technological interventions can significantly enhance educators' understanding and application of technology in teaching contexts.

In terms of CK and PK, the use of MOOCs was studied by [32], who found significant improvements in digital competence across various components, demonstrating the potential of MOOCs to enhance both CK and PK in an integrated manner [32]. MOOCs incorporated open educational resources, including videos, presentations, texts, quizzes, and discussion topics. These resources were tailored to the MOOC format. Students used Moodle for structured forums. They used Google Groups and Twitter for network discussions [32]. The quantitative analysis of the experimental group revealed significant gains across all assessed components: motivational, technological, cognitive, and ethical (–2.314, –3.264, –5.882, –4.073), respectively.

[27] used virtual classroom tools such as Google Sites, Kahoot, and Socrative, noting large effect sizes in the domains of Digital Content Creation (Knowledge: $r = 0.74$, Use: $r = 0.73$) and Problem-Solving (Knowledge: $r = 0.71$, Use: $r = 0.81$), which shows a robust enhancement in the integration of CK and PK through interactive and engaging platforms [27].

The study by [35] highlighted the utility of a range of digital technologies to support TPCK by showing that students utilizing more than two tools scored significantly higher in practical activities (335.59) compared to those who did not use any tools (204.19) [35]. [50] suggests that exposure to multiple technologies can foster a more holistic development of TPCK. It also prepares students to integrate these tools into their future teaching practices effectively. [15] explored the use of serious games, noting a marginal improvement in attitudinal competencies and technological acceptance (pre-test 51.23, post-test 51.75), which suggests that while serious games can engage and educate, their impact on comprehensive TPCK development may require additional pedagogical integration [15].

Conversely, [28] examined the impact of immersive virtual reality (VR), documenting significant improvements in attitudes towards technology (Cohen's $d = 1.127$), indicating a strong potential for VR in enhancing technological and pedagogical integration [28]. The application of the TPCK framework in analyzing these technological interventions reveals that while each technology has its strengths, the optimal enhancement of digital competencies occurs when interventions are aligned with TPCK components, integrating technology, pedagogy, and CK. The inclusion of IoT in educational practices aligns with the TPCK framework by offering advanced technological capabilities that support content delivery and pedagogical strategies. IoT-enabled environments can provide educators with real-time data and analytics, enhancing their ability to deliver personalized and practical instruction.

While most studies indicate a positive impact of digital technologies on teacher competence, it is essential to acknowledge that not all results are uniformly favorable. In the study by [34], 80.2% of student teachers demonstrated high competency in accessing general information using internet browsers. However, the study highlighted a significant gap in using specialized academic resources such as digital repositories. Only 3.2% of students frequently accessed these resources, suggesting limited digital competence in more advanced academic tools. The results show that digital competence has improved. However, the adoption and effective use of specialized digital technologies for enhancing deep educational competence remained low.

Similarly, [33] found that despite improvements in digital competence, the first experimental group showed only modest gains in the proportion of participants rated as highly competent (14.3% to 39.3%). Additionally, nearly 10.7% still showed low competence post-intervention. The results reflect challenges in achieving comprehensive digital proficiency among all participants. They highlight that those digital technologies alone may not fully address more profound pedagogical skill gaps.

Although [28] demonstrated improvements in attitudes toward technology, they also reported varied feasibility in using immersive virtual environments, with some aspects still presenting significant challenges to full adoption. The analysis suggests that digital technologies such as VR, while promising, may only sometimes be fully practical or easily integrated into current educational practices, especially in resource-limited environments. These examples underscore the importance of considering digital technologies' contextual and practical limitations in teacher training programs. Addressing the successes and shortcomings of such technologies will provide a more nuanced perspective on how digital technologies impact teacher competence.

### 4.4 Mapping discussion components using TPACK framework terms

The TPACK framework diagram visually represents how the discussion components align with the three core knowledge areas essential for effective teaching with technology: TK, PK, and CK. The framework emphasizes integrating these domains to enhance teaching and learning. Each diagram section maps specific tools and methodologies to their relevant domains and intersections.

Technological knowledge encompasses tools such as the IoT, AR, and MOOCs. These technologies provide innovative ways to enhance teaching practices by offering real-time analytics, immersive learning environments, and scalable PD opportunities. PK focuses on the strategies and methods of teaching, represented by tools like Serious Games, which engage teachers in interactive and experiential learning, fostering better pedagogical outcomes. CK addresses subject-specific knowledge, utilizing tools such as VR to deliver visually enriched and immersive content tailored to specific subjects.

The intersections between these domains further illustrate how digital technologies can synergistically support teaching. TPK highlights the integration of AR and serious games to implement engaging and interactive teaching methodologies. The TCK shows how tools such as IoT and MOOCs facilitate personalized and scalable learning experiences tied directly to subject content. Pedagogical and content knowledge (PCK) demonstrates how tools such as VR align teaching strategies with specific learning goals, enhancing subject delivery.

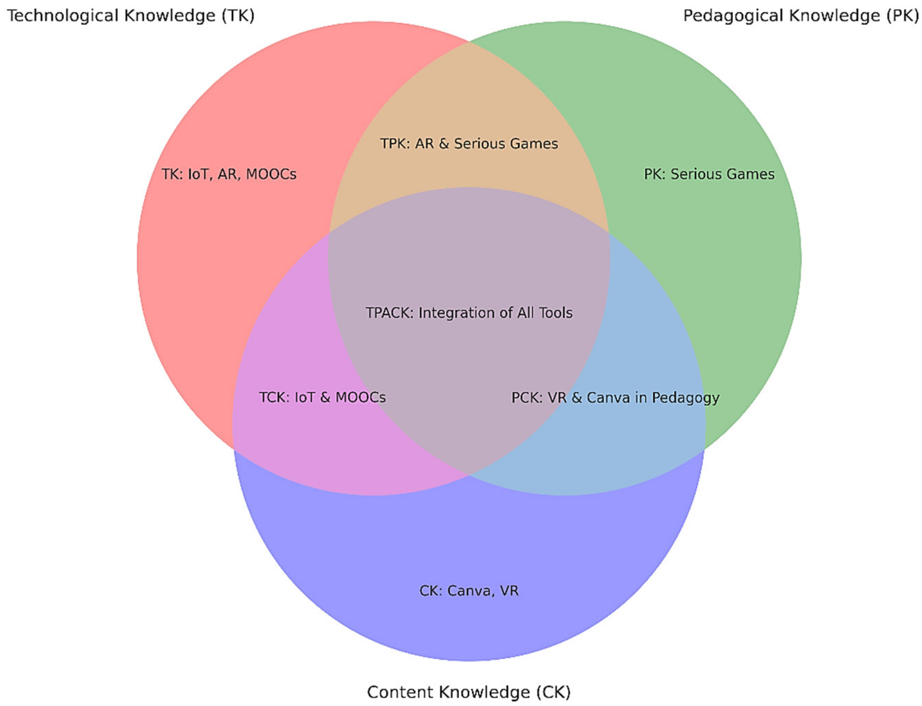


**Fig. 3.** Mapping discussion components onto the TPACK framework: A visual representation of the integration of technological, pedagogical, and content knowledge in teacher education

At the framework's core lies TPACK, the full integration of all three domains. This synergy represents the ideal outcome of teacher education programs, where technology, pedagogy, and CK are cohesively combined to create innovative, effective, and inclusive teaching practices. The diagram provides a structured visualization of how the discussion components relate to the TPACK framework, illustrating the role of digital technologies in each domain and their intersections. This visualization enhances the understanding of how integrating these tools prepares teachers to navigate modern educational challenges effectively, emphasizing the transformative potential of aligning technology with pedagogy and content in teacher training programs.

Our TPACK-focused narrative synthesis revealed that digital tools such as IoT and AR heightened teachers' TK by fostering real-time data use and interactive simulations [31]. MOOCs and Serious Games, in turn, advanced PK through scalable or gamified PD modules. Teachers' CK deepened when VR-based lessons addressed subject-specific content in more immersive ways.

### 4.5 Long-term perspectives on teacher development

A salient gap identified across the ten included studies is the limited evidence regarding long-term sustainability of TDC beyond the immediate post-intervention phase. While short-term gains are consistently positive whether measured by improved attitudes [15], heightened self-reported skill levels [27], [32], or modest increments in TPACK subdomains [31]. Most studies do not verify whether teachers maintain or further develop these competences once the formal training concludes. This limitation poses an open question: How do we ensure that newly acquired digital knowledge and skills do not atrophy but rather translate into sustained classroom integration and pedagogical innovation?

Several authors suggest that PD programs could include iterative follow-up cycles or extended coaching [28], [33]. For instance, repeated refresher courses or in-situ mentorship might provide continuous momentum, vital for teachers navigating new technologies. Similarly, more robust tracking of teacher performance over multiple semesters might reveal whether short-term proficiency actually anchors a deeper shift in teaching practices [30]. Without such multi-phase or longitudinal research, the stability of digital competence gains remains uncertain.

In particular, the two studies that adopt a design-based or iterative approach [28], [34] demonstrate that frequent feedback loops and reflective sessions hold promise for reinforcing teacher skill sets. Extending that logic beyond a single academic term could enhance the internalization of advanced digital literacies. Finally, institutional-level support or professional learning communities might be pivotal in preventing competence decay [30], [35], helping teachers adapt to technological evolutions, and fostering a culture of continuous digital upskilling. Thus, the long-term outlook calls for methodologically rigorous follow-ups, including year-long or multi-year observational data, to solidify the fleeting successes indicated in these short-term interventions.

### 4.6 Variability in digital tool effectiveness

An equally critical area of discussion concerns the diverse range of digital tools employed across studies—some focusing on advanced emerging tech [28], e.g., VR, AR, 3D printing, and others implementing short MOOCs or nano-MOOCs [29], [32]. Variation is also seen in the integrated use of artificial intelligence [31] or game-based learning approaches [15]. This heterogeneity in tools introduces distinct considerations for teacher training design, subject specificity, and institutional feasibility.

Studies highlighting robotics, VR, or 3D printing [28] point out that specialized hardware and robust infrastructure are prerequisites for effective implementation. For instance, VR-based modules can greatly enhance STEM or content-specific tasks, but only if the university or school can finance VR headsets and provide training in the pedagogical integration of immersive simulations [27]. Without such resources, teacher readiness or enthusiasm may not suffice to sustain usage.

By contrast, MOOCs [32] and nano-MOOCs [29] offer broader scalability, addressing large or diverse groups with minimal in-person coordination. However, they may afford less personalization if not paired with adaptive systems or if follow-up is insufficient. In some contexts, short modules or "bite-sized" courses effectively spur incremental skill gains in content creation or security [29], but the question remains how thoroughly these "micro-credentials" shape a teacher's day-to-day classroom behaviors or advanced TPACK uses.

Meanwhile, the personalized AI approach from [31] underscores how teacher PD can be more fine-tuned diagnosing each teacher's TPACK gap, then assigning targeted tasks or resources. Although this fosters strong short-term improvement, it depends on specialized technical architecture, adult-learning design, and consistent instructor oversight.

Variations in tool efficacy also reflect subject-specific or institutional factors. Studies involving prospective foreign language teachers often highlight synchronous and asynchronous language-related tasks or deeper textual-linguistic tools [33], [34]. In these contexts, simpler communication apps or skill-based modules can be more beneficial than advanced maker technologies. Similarly, teacher familiarity with technology, device availability, and robust institutional support can heavily mediate whether a certain approach thrives [30], [35].

Finally, some authors [15], [32] emphasize that widely accessible solutions such as open platforms or Serious Games are more feasible in resource-limited universities. In contrast, complex VR setups might hamper user uptake without intense training or dedicated funding. Aligning each digital resource with the actual skill level, readiness, and infrastructural capacity is thus imperative for long-term teacher adoption. Hence, the choice of tool should be predicated on both the advanced potential of the technology and the local feasibility of sustained usage.

## 4.7 Practical applications and policy implications

The findings of this study underscore the transformative potential of digital technologies such as IoT, Serious Games, and MOOCs in enhancing TDC. Digital technologies can reshape curriculum design by fostering interactive and adaptive learning environments. The practical applications are summarized in Table 5.

**Table 5.** Summary of digital technologies, their applications, and expected outcomes in enhancing teacher digital competence

| Digital Tool | Applications | Expected Outcomes |
|---|---|---|
| **IoT** | Real-time analytics and personalized instruction | Improved engagement and tailored learning |
| **Serious Games** | Interactive professional development | Enhanced problem-solving and teaching strategies |
| **MOOCs** | Flexible training for digital competence | Widespread adoption of updated pedagogy |
| **AR** | Immersive visualization for complex concepts | Better understanding of abstract concepts |

IoT-enabled systems can be incorporated into science and mathematics curricula to monitor student performance in real time. Teachers can use this data to identify areas where students struggle and adapt their instructional methods accordingly. For example, IoT sensors in laboratory settings can track experiment outcomes, providing immediate feedback to both students and educators. Such integration enhances learning outcomes and equips teachers with hands-on experience in data-driven instruction.

Professional development programs should leverage Serious Games to provide educators with immersive and engaging training experiences. A scenario-based game simulating classroom challenges, such as managing diverse learning needs or integrating new technologies, could help teachers practice problem-solving and decision-making in a controlled, risk-free environment. This approach would build confidence and competence, enabling educators to implement similar interactive classroom strategies. Policymakers should consider scaling MOOCs as a critical component of continuing education. By offering flexible, cost-effective access to digital training, MOOCs can help teachers stay updated with the latest pedagogical and technological advancements. Governments could incentivize participation in MOOCs through PD credits or subsidies, ensuring widespread adoption across urban and rural areas.

Educational institutions should establish frameworks that support the long-term integration of digital technologies. For example, schools could adopt IoT-enabled smart classrooms where real-time data analytics guide personalized teaching strategies. Additionally, partnerships with edtech companies can ensure access to cutting-edge tools and training resources, bridging the gap between theory and practice. By aligning these applications with the insights from this systematic review, stakeholders can create dynamic, equitable, and innovative learning environments. These efforts will empower educators and prepare students to thrive in a rapidly evolving digital world.

Although our review primarily includes studies from relatively well-resourced environments (e.g., Spain, Thailand), TDC frameworks such as TPACK can still guide PD in resource-constrained contexts. However, systemic factors such as limited infrastructure, restricted funding, and inadequate policy support may hinder large-scale adoption of tools such as VR or IoT. For instance, schools lacking stable internet connectivity or updated hardware may find MOOC-based or low-bandwidth mobile solutions more feasible. Educators in such settings require a nuanced approach to TPACK, emphasizing creative use of locally available devices (e.g., smartphones) and open educational resources. Future research should explore how digital competence training can be effectively localized and scaled under these challenging conditions.

## 5 LIMITATIONS

This systematic review has several limitations that warrant careful consideration. A key limitation lies in our final selection of only ten studies. While this allows for a more detailed analysis of TDC through advanced digital technologies, it may not capture the full diversity of global contexts, educational levels, or alternative frameworks. Future systematic reviews may benefit from broader inclusion criteria to ensure findings are generalizable across varied settings. The reliance on English-language publications and a specific timeframe (2018–2023) may have excluded significant contributions from non-English sources or earlier foundational research, introducing potential language and temporal biases. The geographic concentration of studies in countries such as Spain, Thailand, and Kazakhstan further limits the generalizability of findings, as these regions may not reflect the diversity of educational systems and technological infrastructures globally.

A key limitation across the included studies involves the possibility of publication and language bias. Several of the articles analyzed report positive or improved outcomes in teachers' digital competence or attitudes toward technology, which may be overrepresented in the scholarly record if journals or conference proceedings favor success stories. Although we have endeavored to include a range of sources, negative or neutral findings might remain unpublished or less visible, potentially creating an inflated sense of efficacy for digital competence interventions. In addition, the search strategy for this review primarily covered articles in English; as a result, potentially relevant works written in other languages or published in regional journals might have been excluded. This language bias further restricts the cultural diversity of the evidence base, warranting caution when generalizing the conclusions drawn here.

The scope of digital technologies reviewed is not exhaustive, limiting the findings' applicability across diverse educational contexts. The variability in research methodologies, including a predominance of quasi-experimental and pre-experimental designs and a lack of randomized controlled trials (RCTs) and mixed-methods studies, affects the robustness and reliability of the evidence base. Additionally, most studies focused on immediate or short-term effects without follow-up, limiting insights into the long-term impact of digital technologies on teacher digital competence.

A lack of consistency in measurement methods and instruments used to assess digital competence across studies further complicates the aggregation and comparison of results. This variability highlights the need for more standardized assessment tools in future research. Lastly, publication bias remains a concern, as the review primarily included peer-reviewed studies reporting significant positive outcomes, potentially overlooking unpublished or grey literature. Efforts to address these biases included a comprehensive database search and adherence to the PRISMA framework. Despite these limitations, the review provides valuable insights into the role of digital technologies in enhancing TDC and identifies areas for improvement in future research.

## 6 ETHICAL CONSIDERATIONS

Ethical implications surrounding digital tools in teacher education emerged as a critical concern across the reviewed studies, particularly for sustaining responsible, inclusive, and equitable technology integration. First, data privacy stands out as a widely shared but variably addressed theme. While some articles [29], [33] reference guidelines for secure data collection, others only tangentially mention the protection of teacher and student information when using online platforms. Robust teacher training must acknowledge legislative standards and promote best practices, such as anonymizing participant data, clarifying consent procedures, and implementing secure data-storage protocols, to prevent breaching confidentiality or misusing personal information.

Second, equitable access remains an ethical challenge. Many interventions, including nano-MOOC proposals or AI-powered platforms, assume consistent device availability and reliable internet connectivity. Yet the contexts represented (e.g., rural schools in Thailand in [31]; single-university settings in Ecuador or Peru in [29], [30]) do not highlight hardware or connectivity shortfalls. Future research and policy discussions should factor in bridging such digital divides. Strategies could include device-loan schemes, flexible offline tasks, or structured IT support to ensure technology-based PD does not inadvertently exclude educators with fewer resources.

Lastly, teacher autonomy requires attention. Several articles highlight institutional mandates or top-down reforms prompting sudden transitions to online or emerging technologies. While these can spur innovation, teachers may feel pressured to adopt tools they do not fully comprehend or value pedagogically. Teacher-training programs, therefore, need to incorporate sustained mentorship or continuing education to ensure that adopting technology is a thoughtful, context-aware decision rather than a one-size-fits-all requirement. Autonomy is particularly relevant in contexts such as "emergency remote teaching" or rapid digital transformations, where educators should retain agency in selecting the tools and approaches that best suit their pedagogical philosophy.

Taken together, these ethical considerations, such as data privacy, equitable access, and professional autonomy, underscore the broader responsibility of educators, policymakers, and researchers to cultivate an environment where digital tools enhance rather than complicate the teaching-learning process. As digital competence becomes a cornerstone of teacher education, stakeholders must also embed structured ethical guidelines and robust support to ensure these innovations serve all participants fairly and effectively.

## 7 FUTURE DIRECTIONS

The diversity of tool usage across the ten included studies reveals that no single digital tool or approach emerges as categorically superior. Instead, efficacy depends on how the tool's design meets teacher needs, the local infrastructural context, and the domain-specific integration strategies. Coupled with the previously noted short-term design, the reviewed literature underscores the need for:

1. **Extended follow-up:** Studies that track TDC over multiple semesters to confirm persistent skill application.
2. **Contextual fit:** Recognition that advanced technologies (VR, robotics) may drive deeper domain-specific gains but require advanced resource infrastructure, while MOOCs or short micro-courses scale more easily but may result in more generic skill improvements.
3. **Performance-based or observational measures:** Tools that evaluate actual digital integration in real teaching to surpass the limitations of self-reported usage or short knowledge tests.
4. **Iterative PD cycles:** Mechanisms enabling teachers to refine and deepen their digital competence after initial training, forming a continuous PD ecosystem.

By considering these long-term and tool-variability dimensions in tandem, educational programs can craft more resilient PD initiatives that accommodate local constraints while systematically scaffolding TDC over time and adopting more standardized approaches. Furthermore, by converging on recognized frameworks and balancing self-report with performance-based evaluations, researchers can more effectively validate how teacher-training interventions cultivate genuine, lasting digital competence. To mitigate these inconsistencies, future teacher-training research on digital competence might adopt a shared standard referencing widely recognized instruments and domain structures. The Spanish INTEF or the European DigCompEdu frameworks offer thorough coverage of areas such as "Professional Engagement," "Digital Resources," "Teaching and Learning," "Assessment," "Empowering Learners," and "Facilitating Learners' Digital Competence." Meanwhile, a TPACK-based observational or artifact-based measure could complement self-report data, ensuring more objective verification of teacher skill.

## 8 CONCLUSION

This study underscores the transformative role of digital tools in fostering TDC, aligned with the TPACK framework, which integrates technological, pedagogical, and content knowledge. Technologies such as IoT, MOOCs, AR, and VR have demonstrated significant potential to enhance educators' skills, enabling innovative teaching practices and effective content delivery. However, barriers such as limited access to resources, teacher readiness, and institutional support remain challenges to their widespread adoption.

The findings highlight the need for scalable, contextually relevant teacher training programs that align with the TPACK framework to ensure adaptive and inclusive teaching strategies. Future research should prioritize longitudinal studies and experimental designs, such as RCTs, to explore digital technologies' long-term impact and scalability across diverse educational settings. Emerging technologies such as AI-driven adaptive learning systems and learning analytics offer promising avenues for personalizing teacher PD. By addressing these challenges, stakeholders can leverage digital tools to transform education, creating dynamic, inclusive, and equitable learning environments that meet the demands of a rapidly evolving educational landscape.

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