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ORIGINAL ARTICLE

A systematic review of TPACK research in primary mathematics education

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Abstract

This study is a systematic review of Technological Pedagogical and Content Knowledge (TPACK) studies concerning primary mathematics education published between 2005 and 2022. The aim of the systematic review was to identify the common features of previous TPACK research on primary mathematics education and identify the research gaps based on their contexts. The study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedure to investigate TPACK-related studies published during the last 17 years in the primary mathematics education domain and to evaluate the characteristics of TPACK instruments used in primary mathematics education. We identified five foci of these studies of TPACK in primary mathematics education research: designing lessons, evaluating mathematics teachers' knowledge of integrating digital technologies, designing the assessment, evaluating training programs, and informing professional development program designs. Findings from this systematic review of the literature can assist educators in better designing professional development programs to help primary mathematics teachers improve their ability to integrate digital technology into classroom teaching. Also, the findings can assist researchers in locating TPACK instruments that are appropriate and relevant for their research. Finally, we argue that there is a research gap concerning how to measure primary mathematics teachers' TPACK, how to design a TPACK instrument that includes contextual factors, and how to develop TPACK-oriented teacher training programs for primary mathematics teachers.

Keywords Primary mathematics education · TPACK · Digital technology integration · Preservice teachers · In-service teachers

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Introduction

In the twenty-first century, the landscape of mathematics education has undergone a profound transformation, primarily driven by the pervasive influence of digital technology. This transformation has not only provided mathematics teachers with dynamic, graphical, and interactive tools for classroom teaching (Hoyles, 2018) but has also posed unprecedented challenges to their knowledge and pedagogical skills (Loong & Herbert, 2018). The advent of the Internet, mathematics software, interactive whiteboards, and the recent surge in online learning due to COVID-19 (Johns & Mills, 2021) has underscored the pressing need for mathematics educators to acquire advanced knowledge and skills in utilizing these digital technologies effectively (Polly & Rock, 2016). In recent years, the integration of artificial intelligence (AI) has continued to revolutionize mathematics education (Wardat et al., 2023). Amidst these advancements, the Technological Pedagogical and Content Knowledge (TPACK) framework has been recognized for its comprehensive approach to investigating mathematics teachers' capabilities to integrate digital technologies into teaching and learning effectively (Kartal & Çınar, 2022; Orlando & Attard, 2015). While other models like the substitution, augmentation, modification, and redefinition provide valuable insights into the integration of technology, the TPACK framework is chosen for this review due to its specific focus on the intersection of technology, pedagogy, and content knowledge, offering a more granular lens through which to examine teachers' competencies. This distinction is crucial, as TPACK addresses the synergy between technology, pedagogy, and content, which is essential for effective teaching in mathematics, a nuance that is particularly relevant given the subject's unique characteristics and the role of technology in enhancing its teaching and learning (Bonafini & Lee, 2021; Scott, 2021). Consequently, this systematic literature review aims to critically evaluate the general characteristics and findings of studies associated with TPACK and primary mathematics education between 2005 and 2022, providing valuable insights to empower researchers and practitioners to integrate TPACK effectively in primary mathematics education.

The TPACK framework, which is derived from the notion of pedagogical content knowledge (PCK) (Shulman, 1986), has been acknowledged as the knowledge base of the twenty-first century's teachers (Voogt et al., 2013). In 2005, the term technological pedagogical content knowledge (TPCK) was initially used by Koehler and Mishra (2005) to describe the types of knowledge teachers need when using digital technology in the classroom. Subsequently, TPCK was renamed TPACK in 2007 because TPACK more accurately depicted the interdependence of the three primary knowledge domains: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK) (Thompson & Mishra, 2007). The TPACK framework has been widely used in educational research over the past decade to evaluate teachers' knowledge of using digital technology in the classroom (Schmid et al., 2020). The fields of TPACK research are diversified, relating to different subjects, such as preservice science teachers (Kadıoğlu-Akbulut et al., 2020), English teachers in secondary education (Greene & Jones, 2020), and TPACK instrument designs (Wang et al., 2018). In primary mathematics education, the TPACK studies focused on teacher training programs designed to facilitate the integration of digital technology into classroom teaching. For example, Polly (2011b) used the TPACK framework to evaluate a learner-centered professional development project designed to support primary and secondary mathematics teachers' technology integration in classroom teaching. Polly (2011b) found that the TPACK framework could be used to assess the outcome of the learner-centered professional development project effectively because TPACK provided a conceptual framework for understanding the knowledge related to the effective use of digital technology based on empirical evidence. In another study, Niess et al. (2014) used the TPACK framework to assess an online graduate course designed to improve the ability of primary and secondary school teachers to integrate spreadsheets into their mathematics and science lessons. Like Polly (2011b), Niess et al. (2014) argued that the TPACK framework details the knowledge mathematics teachers need to integrate technology, making it suitable for evaluating technology-related professional development programs. Despite the established presence of TPACK theory in primary mathematics education, the continued growth of TPACK research in this specific domain has attracted the attention of a burgeoning community of researchers. This recognition underscores the need for a systematic literature review to synthesize and consolidate the existing body of knowledge. To achieve this goal, we formulated two research questions as follows:

1. What specific characteristics and emerging trends can be identified in research related to TPACK and primary mathematics education between 2005 and 2022, and how do these trends contribute to advancing primary mathematics education?
2. In what ways has the TPACK framework been employed to critically assess primary mathematics teachers' TPACK, and what insights and challenges have arisen from its application in different studies?

Theoretical framework

Since 2006, the TPACK framework has been widely used in educational research to comprehend teachers' knowledge of using digital technology in classroom teaching (Schmid et al., 2020). There are three basic knowledge domains in the TPACK framework: CK, PK, and TK; based on a specific context, they interact and form four additional complex components (see Fig. 1) (Mishra, 2019; Mishra & Koehler, 2006). Despite the growing popularity of the TPACK framework, the debate surrounding the TPACK framework continues. For example, Graham (2011) argued that the TPACK framework lacks a clear definition of its constructs in the overlap areas (see Fig. 1): technological pedagogical knowledge (TPK), technological content knowledge (TCK), PCK, and TPACK, particularly the contextual knowledge (Porras-Hernández & Salinas-Amescua, 2013; Rosenberg & Koehler, 2015). Porras-Hernández and Salinas-Amescua (2013) identified three contextual levels to redefine the contextual knowledge in order to expand upon this theoretical framework. These levels were designed to provide a more detailed and nuanced understanding of the contextual factors that influence technology integration in teaching and learning.

- Micro: the contextual factors related to classroom teaching and learning (e.g., teachers' knowledge of the classroom norms and available digital technologies in the classroom).
- Meso: the contextual factors related to the support from schools and communities, such as the school's culture and system, support from leadership, educational infrastructure, and communities.
- Macro: the contextual factors include national and international policies, culture, economy, and educational background (e.g., national curriculum standards and national education policy).

Subsequently, in 2019, Mishra added an eighth factor to the TPACK framework: contextual knowledge (XK), to better explain teachers' knowledge to integrate technologies in teaching and learning (see Fig. 1). XK addresses the intricate interplay between contextual levels (Micro, Meso, and Macro) and the traditional TPACK components, where micro is the classroom level, meso refers to the school level,

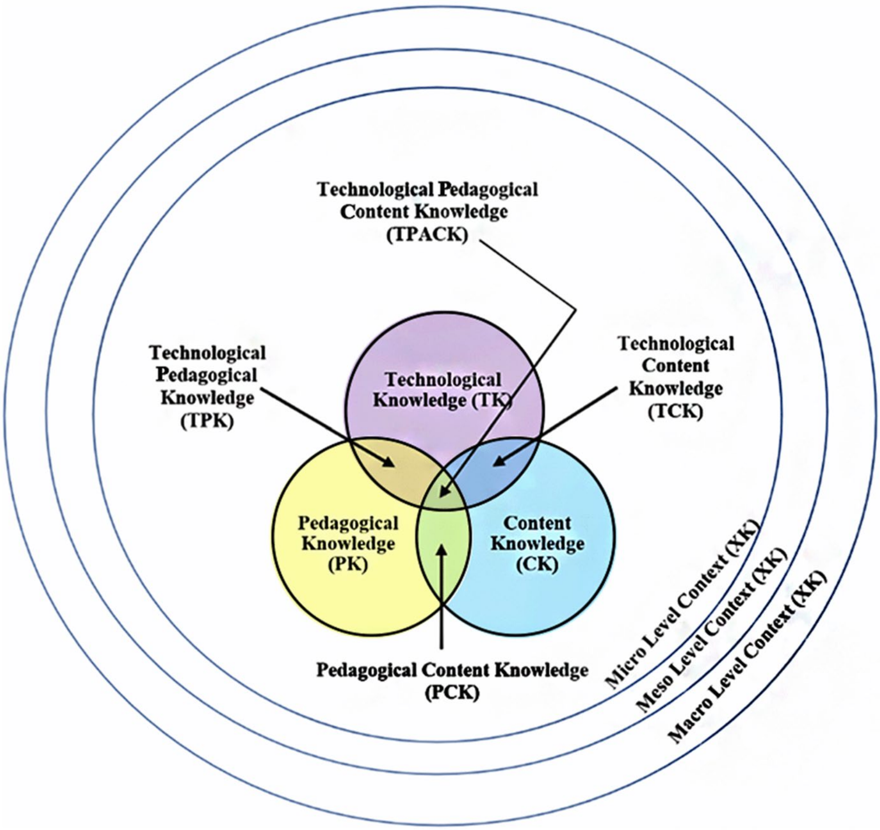

Fig. 1 The components of the TPACK framework (Mishra & Koehler, 2006; Porras-Hernández & Salinas-Amescua, 2013)

and macro is the national level, emphasizing the significance of comprehending how these contextual factors intersect and contribute to teachers' decision-making processes when integrating technology into their pedagogical practices (Mishra, 2019). Consequently, by enriching the TPACK framework with XK's introduction, a comprehensive lens is provided for exploring the multifaceted nature of teachers' knowledge in the digital age. XK illuminates the impact of contextual factors on the traditional TPACK model while highlighting the dynamic interplay among technology, pedagogy, content, and context within educational settings.

In the updated TPACK theoretical framework, the eight factors are described below. CK is teachers' knowledge of a subject matter to be taught or learned. It encompasses theories, concepts, models, frameworks, existing practices, and methods for developing CK (Shulman, 1986). TK is difficult to define because technology is in flux. However, there is a consensus that TK can be thought of as the ability to accomplish various tasks using digital technology (Koehler et al., 2013). PK refers to the knowledge regarding the process or approaches in teaching and learning, and it encompasses knowledge in classroom management, student assessment, comprehending how students learn and designing instruction plans (Koehler et al., 2013).

PCK refers to the knowledge that enables teachers to apply different teaching strategies and methods to deliver the curriculum in a specific discipline (e.g., mathematics, science, and language). In addition, PCK is the ability that enables teachers to find ways to motivate and enlighten students to comprehend the content of particular subjects (Shulman, 1986). TCK is the knowledge that enables teachers to understand how different digital technologies and content are mutually influenced and limited in a specific discipline or domain (Koehler et al., 2013). TPK is the knowledge that enables teachers to optimize their teaching strategies and methods through the use of various digital technologies (Mishra & Koehler, 2006). Also, it requires an understanding of the pedagogical limitations and affordances of digital technology in relation to pedagogical designs in a specific subject (Koehler et al., 2013). TPACK is a complicated form of knowledge formed through the interaction of CK, PK, and TK. TPACK enables teachers to effectively integrate digital technologies into their teaching in a specific discipline, such as mathematics and science (Koehler et al., 2013). XK has been defined as the knowledge that enables teachers to understand the factors impacting digital technology use in teaching and learning from the perspective of schools (micro-level context), districts (meso-level context), states, or national policies (macro-level context). In summary, the TPACK framework includes CK, PK, TK, PCK, TPK, TCK, TPACK, and XK, which interact and influence each other to form a teacher's ability to effectively integrate digital technologies into teaching and learning (Mishra, 2019).

While the TPACK framework has grown in popularity, the debate around its applicability and relevance continues. For example, Graham (2011) argued that the TPACK framework lacks a clear definition of its constructs, particularly in the overlap areas (see Fig. 1): TPK, TCK, PCK, and TPACK. Moreover, Angeli and Valanides (2009) proposed that the conceptual clearness of the TPACK framework needs further clarification. Indeed, the debates around TPACK can be categorized into two perspectives: integrative and transformative views (Schmid et al., 2020). The proponents of the integrative view believe that the components of TPACK are highly related and support each other (Graham, 2011). For instance, improving TK can positively impact TPK. In contrast, with regard to the transformative view, researchers argue that the four complex components (PCK, TCK, TPK, and TPACK) have unique bodies of knowledge instead of simply combining the basic three knowledge domains (Angeli & Valanides, 2009). Hence, the centralized knowledge of TPACK cannot be directly improved by merely improving CK, TK, and PK. The two perspectives reflect distinct conceptions on the development of teachers' TPACK. While ongoing debate and discussion exist about the precise definitions and overlap of these knowledge domains (Graham, 2011), the TPACK framework provides a valuable theoretical framework for understanding the complex knowledge and skills required for effective technology integration in education (Schmid et al., 2020; Schmidt et al., 2009; Voogt et al., 2013). While the TPACK framework may not be perfect, it has had a significant impact on the field of educational technology and remains a useful tool for understanding the complex nature of technology integration in education.

Previous systematic literature reviews of TPACK

In this section, we report on previous published systematic reviews of TPACK-related studies. We analyzed eight peer-reviewed literature review articles from 2011 to 2022 to determine the general characteristics of these literature review articles. This analysis helps researchers understand the big picture of previous literature reviews of TPACK-related studies in the educational domain. As recorded in Table 1, these literature reviews of previous TPACK research related the following four aspects of the basic information of previous TPACK research: article information, participants' information, methodology information, and educational background information (see Table 1).

First, with the exception of Abbitt (2011), the remaining seven literature review articles analyzed the information concerning authors' information, published year, and journal information. The evidence suggests that authors' information and publication years are two widely used categories in these literature review studies, and this highlights the importance of identifying the authors and publication years of previous studies in the field when conducting a systematic literature review. Second, four literature review articles (Abbitt, 2011; Scott, 2021; Wang et al., 2018; Willermark, 2018) provided information concerning the research methods used in the TPACK-related articles. For instance, Willermark (2018) used a table to highlight the qualitative, quantitative, and mixed methods research approaches utilized in 107 articles. This strategy helps other researchers easily find methodology information from the table and helps other researchers identify and compare research methods across studies. Third, as shown in Table 1, the early literature review studies preferred to evaluate participants' information based on the population of a single group, such as preservice or in-service teachers. Abbitt (2011) and Young et al. (2012), for instance, focused on preservice teachers, while Voogt et al. (2013) evaluated just in-service teachers. In contrast, in recent years, the systematic literature review articles from Wang et al. (2018), Willermark (2018), and Scott (2021) expanded the scope of their

Table 1 Basic information analyzed by previous systematic literature reviews

	Article information			**Methodology information**			**Participants information**		**Other information**						
Basic information	Authors	Years	Journal	Qualitative	Quantitative	Mixed method	Preservice teacher	In-service teacher	Early childhood/ primary	Secondary school	Tertiary	Mathematics	Other subjects (e.g., science)	Research location	Limitation
Abbitt (2011)	\	\	\	x	x	\	x	\	x	\	\	x	x	\	Methodology participants scope
Young et al. (2012)	x	x	\	\	\	\	x	\	\	\	\	x	x	\	Methodology participants scope
Voogt et al. (2013)	x	x	\	\	\	\	\	x	\	\	\	x	x	\	Methodology participants scope
Rosenberg & Koehler (2015)	x	x	x	\	\	\	\	\	\	\	\	\	\	\	Methodology participants scope
Moore-Adams et al. (2016)	x	x	\	\	\	\	\	\	\	\	\	\	\	\	Methodology participants scope
Wang et al. (2018)	x	x	\	x	x	x	\	\	\	\	\	x	x	\	Participants scope generic

Table 1 (continued)

	Article information			**Methodology information**			**Participants information**		**Other information**						
Basic information	Authors	Years	Journal	Qualitative	Quantitative	Mixed method	Preservice teacher	In-service teacher	Early childhood/ primary	Secondary school	Tertiary	Mathematics	Other subjects (e.g., science)	Research location	Limitation
Willermark (2018)	x	x	x	x	x	x	x	x	\	\	\	x	x	\	Scope generic
Scott (2021)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	Generic

The "x" indicates that the background information for the corresponding column was examined. The "\" means that the article did not provide this information in the corresponding column. Scope: This indicates the extent or range of topics and areas covered within the reviewed articles. Methodology: This pertains to the research methods and approaches used in the reviewed studies. Participants: This refers to the individuals or groups involved in the research, indicating in-service and preservice teachers. Generic: This means that it lacks specificity and focuses on a broad range of teachers, which limits its ability to address the unique challenges and considerations of TPACK in a specific educational context like primary mathematics education reviews to include both preservice and in-service teachers. The scope of participants' information analyzed in the literature reviews has expanded over time, with more recent reviews including both preservice and in-service teachers. This suggests a shift towards more comprehensive evaluations of TPACK research, allowing for comparison within and across participants groups. The curriculum context for the studies included in these literature reviews varied or was not identified, suggesting that, to some extent, the literature review articles for a particular discipline are limited. None of these studies, for instance, focused exclusively on a literature review of primary mathematics instruction. With the increasing number of TPACK studies in primary mathematics education, there is a need for more systematic literature reviews focused specifically on this curriculum context.

Furthermore, the researchers discussed how the TPACK framework was used in previous research. For example, Wang et al. (2018) analyzed 88 peer-reviewed journal articles published from 2006 to 2015 concerning TPACK research, and they argued that during the period, the TPACK framework was used to evaluate preservice teachers' TPACK development in the following five ways: self-report measure, open-ended questionnaire, performance assessments, interviews, and observations. Similarly, Willermark (2018) systematically reviewed 107 peer-reviewed journal articles regarding the utilization of TPACK in empirical research published between 2011 and 2016; Willermark (2018) contended that self-report and performance on a teaching activity were the most frequent approaches used by researchers to evaluate teachers' TPACK. Evidently, while previous literature reviews have provided valuable insights into the use of the TPACK framework in a general sense, there is a lack of specific information regarding how the framework has been used in the context of primary mathematics education.

Additionally, previous literature review studies analyzed the TPACK instruments used to measure preservice and in-service teachers' knowledge of technology integration in classroom teaching (Abbitt, 2011; Scott, 2021). For instance, Abbitt (2011) evaluated 91 documents, including 34 journal articles, 52 papers published in conference proceedings, and 2 book chapters between 2006 and 2010. According to Abbitt (2011), developing self-report and performance-based TPACK measurements were the two primary methods researchers used to assess teachers' knowledge of using technology in the classroom. Regarding the self-reporting measurement, Abbitt (2011) pointed out that TPACK provided researchers with a logical and systematic knowledge base for assessing teachers' technology use. Regarding the performance-based TPACK measurement, Abbitt (2011) suggested that measuring teachers' knowledge in the TPACK domain could be achieved by investigating the process of designing and planning lessons. Similarly, Scott (2021) also conducted a systematic literature review concerning TPACK as a self-assessment instrument from 2006 to 2020. Scott (2021), however, narrowed the research scope and focused on the research methods that previous studies used to design the self-assessment TPACK instruments. Scott (2021) discovered, after analyzing 233 peer-reviewed articles, that the TPACK framework prompted researchers to conduct factor analysis to verify the reliability and validity of the TPACK instruments. These findings imply that it is feasible to use TPACK to evaluate teachers' knowledge of teaching with technology.

The limitations identified across the reviewed literature (see Table 1) collectively point to a research gap in the existing body of knowledge regarding TPACK in the context of primary mathematics education. These limitations primarily revolve around the lack of comprehensive methodological information, a narrow focus on a broad audience of teachers, and a failure to exclusively address primary mathematics education. The absence of in-depth methodological insights hampers our ability to assess the rigor and quality of the reviewed studies. Moreover, concentrating on a wide spectrum of teachers, including both preservice and in-service educators, overlooks the specific requirements and nuances of different levels of experience in primary mathematics instruction. Addressing these limitations through a systematic literature review that thoroughly examines methodological approaches while emphasizing primary mathematics education is crucial. Such a review holds significance for both practical and academic domains, as it can inform educators, researchers, and policymakers about the appropriateness and effectiveness of teachers' TPACK in enhancing mathematical understanding among primary-grade students. Moreover, the systematic literature review reported in this article is aimed to contribute to bridging the existing gap between TPACK studies and the unique challenges posed by primary mathematics education, ultimately advancing evidence-based practices in this specific educational context.

Finally, it is imperative to thoroughly examine the appropriateness of technology utilization in primary grades. The integration of technology into primary education should be approached with meticulous consideration for developmental factors and pedagogical principles that align with the distinctive needs and characteristics of young learners (Ertmer & Ottenbreit-Leftwich, 2010; Koehler & Mishra, 2009). The developmental stage of primary-grade students necessitates a distinct approach to technology integration that considers their cognitive development, attention span, motor skills, and socio-emotional requirements (Prensky, 2001). While the fundamental principles of TPACK remain consistent across educational levels, it is crucial to acknowledge that primary mathematics education may require tailored strategies and considerations. For instance, within the context of primary education, TPACK's interplay could encompass integrating interactive and age-appropriate educational software while fostering a balance between digital and non-digital learning experiences (Shi & Rao, 2022). As primary mathematics education lays the groundwork for subsequent learning endeavors, comprehending the intricacies of technology integration specific to this context becomes paramount (Higgins et al., 2007).

In summary, in this section, we have critically examined the landscape of TPACK-related literature review research within the primary education domain. The analysis of eight peer-reviewed literature review articles from 2011 to 2022 reveals essential trends in the field. While authors' information and publication years have been consistently emphasized, recent reviews have expanded their scope to include both preservice and in-service teachers, indicating a shift towards more comprehensive evaluations of TPACK research. However, there remains a significant gap regarding applying the TPACK framework in the context of primary mathematics education, a domain with distinctive developmental and pedagogical considerations. This gap highlights the necessity of a dedicated systematic literature review that focuses on TPACK within primary mathematics education. Moreover, recognizing the importance of technology integration tailored to the unique needs of young learners, in this review, we acknowledge the critical role of developmental factors and pedagogical principles specific to primary education. Therefore, the systematic literature reported below holds significant implications in both the practical domain of primary mathematics instruction and the academic sphere, where it can provide valuable insights to mathematics educators, researchers, and policymakers regarding the suitability and efficacy of TPACK in promoting mathematical comprehension among primary-grade students while enhancing pedagogical practices of primary mathematics.

Methodology

In the age of evidence-based education, the systematic literature review is increasingly used as an investigation method, combining different studies to produce evidence for policy-making, teacher professional development planning, and other research (Cohen et al., 2018). Based on the TPACK framework (Mishra, 2019; Mishra & Koehler, 2006), the current systematic literature review reported below used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedure (see Fig. 2) to investigate TPACK-related studies in the primary mathematics education domain published during the last 17 years. The PRISMA approach was selected for its rigorous and transparent methodology, ensuring a comprehensive and reproducible synthesis of the existing literature, which is crucial for the reliability and validity of our review findings. The PRISMA process is a systematic review methodology applied to identify, screen, and evaluate relevant research for inclusion in a review, which is then used to inform evidence-based decision-making. Subsequently, we articulate the research method from the three dimensions: search strategy, selecting articles, and data analysis.

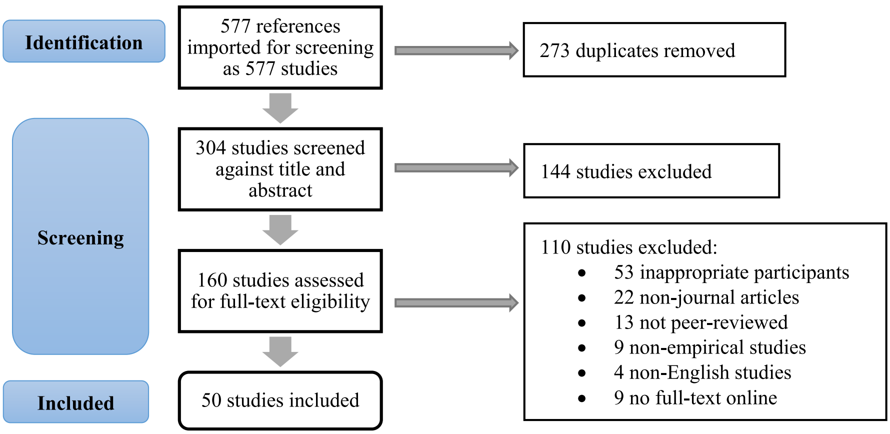

Fig. 2 Procedure of selecting articles PRISMA (Page et al., 2021)

Search strategy

We searched for articles in five scientific databases: Scopus, Web of Science, ProQuest, PsycINFO, and ERIC. The scope of the search was restricted to peer-reviewed journal articles published between (January) 2005 and (May) 2022. Moreover, similar to Voogt et al. (2013), we employed "TPCK," "TPACK," and "Technological Pedagogical Content Knowledge" in the search process. Differently, as this systematic literature review focused on primary mathematics education, we added "Primary," "Elementary," "Math," and "Mathematics" to form various combinations in the search process. For instance, "TPACK and Primary and Mathematics" and "TPCK and Primary and Mathematics" were used during the searching procedure.

Process of selecting articles

Following the PRISMA procedure (see Fig. 2), this systematic literature review employed a three-phase strategy to identify the relevant articles: duplication, screening, and full-text review. Covidence, an online platform for managing systematic review processes, was used to assist researchers in implementing these three processes.

Duplication

The first process was to identify and eliminate repeated articles. Based on the searching strategy, the authors cross-checked the reference lists of the five databases, and 577 articles were selected originally, including information concerning the preservice and in-service primary mathematics teachers. Nevertheless, there were 273 repeated articles. Therefore, after the elimination of the duplications, 304 articles remained.

Screening

The second phase preliminarily identified pertinent articles based on screening articles' abstracts, keywords, and titles. In addition, a keyword screening strategy was employed in this phase (Newman & Gough, 2020). In other words, the authors screened the 304 articles to select articles related to the following keywords: primary (elementary) mathematics teachers, primary (elementary) mathematics education, TPACK, and TPCK. After screening, 144 studies were excluded, including secondary education, tertiary education, and non-mathematics subjects' articles, and 160 were retained for full-text review.

Full-text screening

The full-text screening phase aimed to select relevant articles based on a selection criterion (see Fig. 2) to assess the 160 articles in detail to identify which remaining articles were more likely to be relevant (Newman & Gough, 2020). After the full-text screening, 110 studies were excluded, and the reasons for elimination are the following: 53 studies with participants who were not primary mathematics teachers (e.g., unrelated education levels or subjects), 22 non-journal articles, 13 not peer-reviewed, 9 non-empirical studies, 4 studies published in a non-English language, and 9 no full-text online. The absence of full-text access made it impossible to conduct a comprehensive evaluation of the study's methodology, results, and relevance to our research question. Therefore, articles lacking full-text access were excluded from the final analysis. Eventually, 50 (9%) articles were retained for data analysis.

Data analysis

In this phase, we summarized the selected papers' information in Excel to analyze the 50 studies to extract information concerning the fundamental characteristics of these articles, such as publication years, participants, research questions, research aim, journal information, and countries (Voogt et al., 2013). In addition, the computer software NVivo was utilized to code data and assist researchers in exploring three main issues to answer the study questions: the TPACK instruments, using TPACK in mathematics education, and the findings of these 50 studies. First, we analyzed and summarized the lineage of the instruments, the Likert scale used in these TPACK instruments, and the methods used to design these instruments' items. Additionally, two sub-questions were used to explore the use of TPACK in primary mathematics education. Finally, we examined these articles' main findings from five aspects: designing lessons, evaluating mathematic teachers' knowledge of integrating digital technologies, designing assessments, evaluating teacher training programs, and guiding professional development program design.

Findings and discussion

The aims of this study were to explore the general characteristics of TPACK studies in primary mathematics education and find out how the TPACK framework is used to examine mathematics teachers' knowledge of using digital technologies in their classroom teaching. The findings and discussion are reported in the order of the research questions. First, the previous TPACK instruments used in primary mathematics education were analyzed and compared. Then, this study explored the relationship between the demographic information from these studies and the use of TPACK in primary mathematics education. Finally, the authors discussed what researchers have done with TPACK in primary mathematics education and summarized previous studies' findings.

Characteristics and emerging trends in TPACK research in primary mathematics education

Using TPACK instruments is one of the important characteristics of these investigations. Twenty-one of the 50 articles used TPACK instruments to measure elementary mathematics teachers' knowledge of using digital technology. In order to gain a comprehensive understanding of the influence of these instruments and the way these studies use them, we evaluate them with regard to three respects: the lineage of the TPACK instrument, participants in the survey, and technology-related items design.

The TPACK instruments

The findings from the 21 studies in which TPACK instruments were utilized to assess primary mathematics teachers' knowledge of digital technology integration offer valuable insights into the field. These instruments have varied in their design and application, with some studies developing unique tools tailored to the elementary mathematics teaching context (Handal et al., 2016; Jang & Tsai, 2012), and others adapting existing instruments for their specific needs (see Fig. 3). One prominent instrument, developed by Schmidt et al. (2009), stood out as the most frequently employed in the context of elementary mathematics education. It was directly used by five studies and modified for application in three others. This observation aligns with Scott's (2021) findings, indicating the widespread utilization of Schmidt et al.'s (2009) instrument in assessing teachers' digital technology knowledge. This instrument's popularity suggests the significant influence of Schmidt et al. (2009) on TPACK instrument development in the past decade (Ozudogru & Ozudogru, 2019; Scott, 2021; Wen & Shinas, 2020; Willermark, 2018). While the instrument from Schmidt et al. (2009) took the lead, those developed by Graham et al. (2009) and Sahin (2011) also gained traction, particularly in the education context of Turkey, where 6 out of the 21 studies were conducted. Scott (2021) previously noted the higher number of TPACK instrument development studies in Turkey compared with

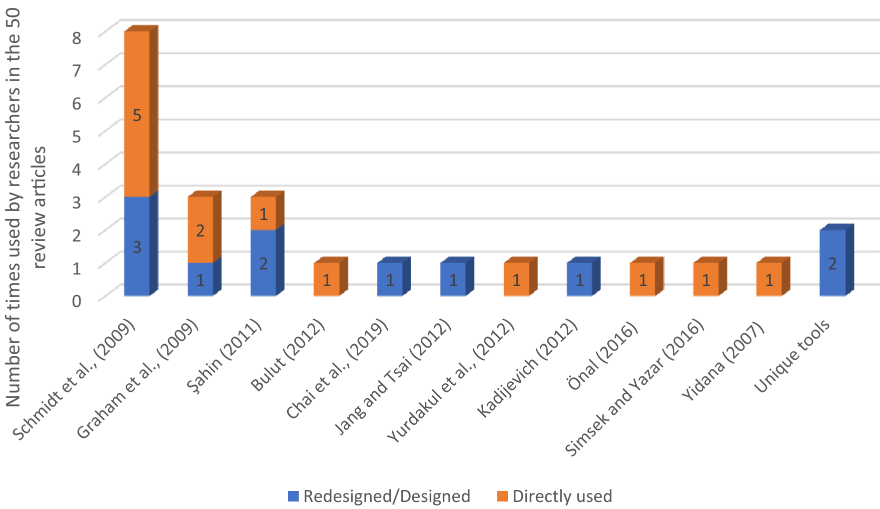

Fig. 3 The TPACK instruments

other countries, which reinforces this finding. The research trend indicates increasing use of TPACK instruments to assess primary mathematics teachers' digital technology knowledge. These tools vary, with some tailored to primary mathematics contexts and others adapted.

Table 2 also includes an overview of the participant characteristics. It is evident that the studies encompassed diverse backgrounds, including preservice and in-service teachers, spanning primary and secondary mathematics education levels, and occasionally extending to other STEM-related disciplines. Notably, only seven studies exclusively focused on preservice primary mathematics teachers. The remaining 14 studies encompassed multiple disciplines, such as science and engineering, and included both primary and secondary mathematics education contexts.

How did these researchers design their instruments for measuring the TPACK of primary mathematics teachers?

When examining how researchers developed instruments to assess primary mathematics teachers' TPACK, it is crucial to explore the data collection strategies employed, particularly regarding survey item design. Analyzing Likert scale information is significant as it ensures the reliability, comparability, and cultural sensitivity of survey data, contributing to the robustness and validity of research findings in this field (Lee et al., 2002). Table 3 provides valuable insights into the types of Likert scales utilized, offering a broader perspective on their application. These Likert scales included four different point variations: 4-point, 5-point, 6-point, and 7-point scales. Notably, despite operating across diverse cultural backgrounds, 81% of studies opted for a five-point scale. This choice highlights the need for careful consideration when interpreting findings since cultural nuances can influence Likert scale results' validity (Lee et al., 2002). Table 4 includes an overview of the item development process, elucidating three distinct item styles: Example Style Item

Table 2 Participants' information

Subjects	Preservice teachers	In-service teachers	Preservice and in-service teachers	Total
Mathematics	**11**			**11**
Primary	7			7
Secondary	4			4
Mathematics and Science	**2**	**3**		**5**
Primary	1	3		4
Secondary	1			1
STEM			**1**	**1**
Secondary			1	1
Mathematics and others	**3**		**1**	**4**
Primary	1			1
Secondary	2		1	3
Total	**16**	**3**	**2**	**21**

Table 3 The Likert scale information

Region	4-Point Likert scale	5-Point Likert scale	6-Point Likert scale	7-Point Likert scale	Total
Australia	1				1
China				1	1
Ethiopia		1			1
Ghana		1			1
Serbia		1			1
Spain		1			1
Taiwan		2			2
Tanzania		1			1
USA		1			1
Turkey	1	9	1		11
Total	**2**	**17**	**1**	**1**	**21**

Design (ESID), Embedded Style Item Design (MSID), and General Term Style Design (GTSD). These approaches to item development possess their own strengths and limitations, providing valuable insights into their applicability and implications for future research. It is noteworthy that nine articles opted for GTSD, utilizing general terms like "computer" and "Information and Communication Technology (ICT)" in their item descriptions, for example, "use digital technologies that allow scientists to observe things that would otherwise be difficult to observe" (Saltan & Arslan, 2017; Tokmak et al., 2013). This approach enhances flexibility and applicability across diverse technological contexts, allowing for adaptability. Conversely, 12 studies employed specific technology names in their items, primarily adopting the ESID method. This approach employs general terms such as "technology" and "computer" to delineate constructs like TK, TPK, TCK, and TPACK. Subsequently, specific technology examples were provided to further illustrate these constructs, for instance, "I can effectively use Dynamic Mathematics/Geometry Software (such as GeoGebra, Sketchpad Desmos, and Cabri)" (Çetin & Erdoğan, 2018) and "I can proficiently utilize basic computer software (e.g., Windows Microsoft Office)" (Bulut & Isiksal-Bostan, 2019). The choice between these approaches depends on the

Table 4 Item development information

	Example Style Item Design (ESID)	Embedded Style Item Design (MSID)	General Term Style Design (GTSD)	Total
Including mathematics technology items	4			4
No mathematics technology items	5	3	9	17
Total	9	3	9	21

specific research context and objectives at hand. While ESID items offer specificity through explicit technology names, GSTD items provide flexibility by employing general terms applicable to various technological contexts.

Moreover, the MSID approach was employed by some studies to embed specific technology names within questions. While this enhances item specificity and participant comprehension, it may limit the generalizability of items to unmentioned technologies, for example, “I use interactive whiteboard (technology) to promote learning and inquiry of lessons” (Jang & Tsai, 2012) and “Using E-books (technology) can improve my teaching approaches to promote students’ learning” (Chen & Jang, 2013). Ultimately, the item development approach should align with the research question, target population, and technologies of interest. Specific technology names offer precision but may limit applicability, while general terms provide flexibility but require careful item interpretation. Researchers are encouraged to consider a range of item development approaches, such as ESID, MSID, and GTSD, to comprehensively capture the complexity of TPACK in various contexts. Employing multiple approaches allows for a more nuanced understanding of TPACK’s multifaceted nature, adapting to different technologies and usage scenarios.

The research trend in the analysis of Likert scales and item development approaches within TPACK research indicates a prevailing preference for 5-point Likert scales, along with a diverse range of item development strategies such as GTSD, ESID, and MSID. This diversity reflects researchers’ adaptability to different research contexts and objectives. However, there are gaps in the comprehensive exploration of how cultural nuances impact Likert scale responses. Furthermore, it is crucial to strike a balance between item specificity and flexibility to effectively assess these emerging complexities, particularly considering the rapid influence of AI on mathematics education in recent years (Wardat et al., 2023). Additionally, there is an opportunity to explore hybrid item development approaches that combine elements from these styles to create more nuanced instruments capable of addressing the ever-evolving landscape of TPACK in various technological contexts. Closing these gaps can contribute towards gaining a deeper understanding of TPACK assessment and its implications for primary mathematics education research in the era of AI-driven education.

Mapping the landscape: TPACK research in primary mathematics education

In examining the landscape of research on TPACK and mathematics education, it is essential to consider the foundational elements of the reviewed articles, including their publication trends and the ways in which the TPACK framework has been applied. Figure 4 reveals a noticeable growth in the number of articles published between 2010 and 2019, with the peak occurring in 2018 and 2019, each having seven published articles. However, the subsequent years, 2020 and 2021, witnessed a slight decline, potentially influenced by the COVID-19 pandemic. While these figures represent articles included in this analysis, it is important to acknowledge that additional relevant research might not have been covered, suggesting that the upward trend is likely to continue. This trend underscores the increasing interest in

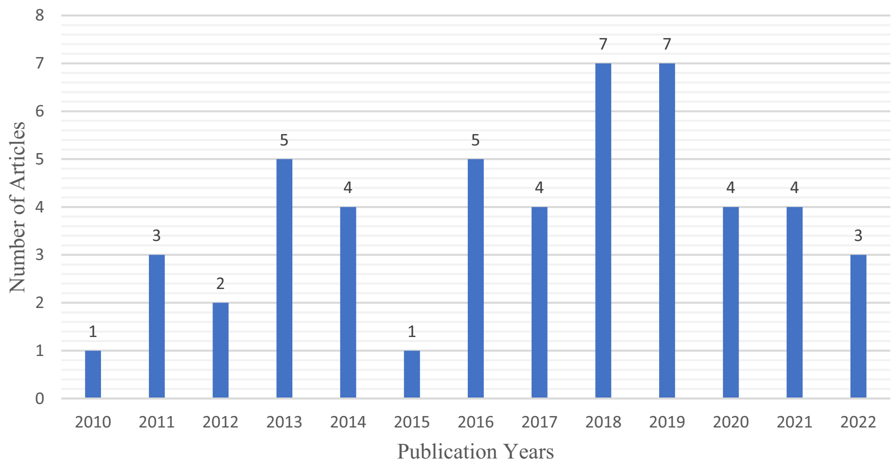

Fig. 4 Number of articles included by publication year (2005–2022) ($N=50$)

exploring the convergence of technology, pedagogy, and content knowledge, especially in primary mathematics education, as technology continues to play a pivotal role in shaping educational practices (Oikarinen et al., 2022; Urbina & Polly, 2017).

Table 5 provides insight into the diverse application of the TPACK framework in educational research, particularly within primary and primary-secondary education settings. Out of the 50 reviewed studies, a majority (76%) utilized TPACK to evaluate teachers' proficiency in integrating digital technology into teaching and learning practices. Within this category, quantitative methods were employed in 52.6% of the studies, while qualitative methods were used in 34.2%, and mixed methods were adopted by only 13.2%. Notably, one study (2.0%) deviated from this trend by employing TPACK to design online summative assessments aimed at engaging learners in mathematics education conducted online. Furthermore, TPACK was applied for designing mathematics lessons (6%), evaluating teacher professional development programs (8%), and guiding the development of professional development initiatives (8%).

Additionally, when narrowing the focus to evaluating mathematics' knowledge of integrating digital technology ($N=38$), which accounts for the highest proportion of the five categories, most studies ($N=20$, 52.6%) used a quantitative method to gauge mathematics teachers' knowledge of integrating digital technology. Also, 13 studies (34.2%) used a qualitative method to measure teachers' TPACK. Only five studies (13.2%) applied a mixed method. Notably, if the angle is narrowed to primary mathematics education, the number of mixed method studies decreased to 3, accounting for about 7.9% of the 38 investigations. It is evident that most previous studies that used TPACK in primary education focused on evaluating teachers' knowledge of integrating digital technology in teaching and learning. This suggests that there is a need for more research on other ways TPACK can be applied in primary mathematics education. Additionally, the data show that there is a higher proportion of quantitative studies than qualitative or mixed-method studies in evaluating mathematics

Table 5 Using TPACK in education research

	Primary	Primary and secondary	Total
Design lesson	**3**		**3**
Qualitative	2		2
Mixed method	1		1
Evaluate mathematics teachers' knowledge of integrating digital technologies	**24**	**14**	**38**
Qualitative	11	2	13
Quantitative	10	10	20
Mixed method	3	2	5
Design online assessment		**1**	**1**
Qualitative		1	1
Evaluate teacher professional development program	**4**		**4**
Qualitative	2		2
Quantitative	1		1
Mixed method	1		1
Guide professional development program design	**3**	**1**	**4**
Qualitative	1	1	2
Mixed method	2		2
Total	**34**	**16**	**50**

teachers' TPACK. This implies that researchers should consider using mixed methods to gain a deeper understanding of teachers' TPACK, which is consistent with previous studies (Wang et al., 2018; Willermark, 2018). More importantly, the lack of mixed-method studies in this area highlights a need for further research including both qualitative and quantitative methods to better understand how TPACK can be effectively applied to enhance the integration of digital technology in primary mathematics education (Ozudogru & Ozudogru, 2019).

Our study reveals a notable research phenomenon indicating a growing interest in the intersection of technology, pedagogy, and content knowledge in primary mathematics education. This trend is evidenced by a steady increase in the number of published articles from 2010 to 2019, with a peak in 2018 and 2019, underscoring the significance of technology's role in shaping educational practices. However, there is a research gap in the limited representation of mixed-method studies, particularly in primary mathematics education, suggesting a need for more comprehensive exploration of diverse applications of the TPACK framework. Furthermore, the higher proportion of quantitative studies compared with qualitative or mixed-method studies points to an opportunity for researchers to employ mixed methods to gain a deeper understanding of teachers' TPACK. Bridging these gaps will contribute to a more comprehensive understanding of how TPACK can effectively enhance the integration of digital technology in primary mathematics education.

Exploring TPACK finding: designing lessons, evaluation of teachers' TPACK, designing assessment, teacher training, and teacher professional development

In this section, the findings of a comprehensive research review in the field of primary mathematics education, with a specific focus on the TPACK framework are presented. The discussion within this section encompasses five key aspects: lesson design, assessment design, evaluation of teachers' knowledge in integrating digital technologies, evaluation of teacher training programs, and guidance for professional development program design.

Designing lessons

Three studies from different countries, Singapore, the USA, and China, employed the TPACK framework to explore how primary mathematics teachers design lessons that integrate digital technologies. These studies, conducted by Bos (2011), Huang et al. (2021), and Koh (2018), shared a common belief that TPACK can illuminate teachers' abilities to incorporate digital tools effectively in mathematics instruction. Notably, despite diverse teacher backgrounds, all three studies converged on the importance of a deliberate choice of digital tools in designing technology-integrated mathematics lessons. Bos (2011) conducted a study involving 30 primary mathematics teachers in the USA and highlighted the positive impact of Web 2.0 tools on student engagement and understanding. By carefully selecting these tools, teachers could facilitate online collaboration among students, enhancing the comprehension of mathematical concepts. Similarly, Huang et al. (2021) conducted an online cross-cultural lesson study between China and Australia. They identified two primary factors influencing online teaching quality: teachers' TPACK and their ability to select appropriate online teaching digital technologies. These findings underscored the necessity for primary mathematics teachers to possess a strong grasp of TPACK and the skill to choose suitable online resources to engage and motivate students effectively. These findings emphasize the pivotal role of TPACK in informing the selection and integration of digital technologies in mathematics lessons. They also have important implications for the professional development of primary mathematics teachers and the design of technology-integrated mathematics curricula to enhance students' learning outcomes.

Evaluating mathematics teachers' knowledge of integrating digital technologies

In this systematic review, we identified 38 research studies that utilized the TPACK framework to evaluate mathematics teachers' competence in integrating digital technologies into their teaching practices. These studies examined mathematics teachers' TPACK evaluation from three primary perspectives: the influence of prior teaching and learning experiences, the use of digital technologies in classroom instruction, and factors affecting mathematics teachers' TPACK development.

Influence of prior teaching and learning experiences. The first theme in the research studies was the impact of prior teaching and learning experiences on teachers' decisions regarding the integration of digital technology into their classrooms. The studies show that these experiences can be categorized into two significant types that shape teachers' choices in technology integration. The first type relates to teachers' earlier experiences as learners, which significantly shape their decisions regarding the use of digital technology for teaching. For instance, Kartal and Çinar (2018) noted that mathematics teachers who had limited exposure to digital technologies during their own education were less inclined to integrate technology into their classroom teaching. This underscores the importance of providing teachers with successful experiences in real-world contexts when utilizing technology (Kartal & Çinar, 2018). The second type of experience pertains to teachers' hands-on exposure to technology within mathematics classrooms (Açıkgül & Aslaner, 2020; Chen & Jang, 2013; Polly, 2014). Polly (2014) emphasized that increasing teachers' familiarity with technology in these settings enhanced their TPACK competencies, positively influencing technology integration. Polly (2014) recommended enriching teacher education programs with technology-rich activities to offer mathematics teachers genuine experiences in technology integration. This finding suggests that teaching and learning experiences with digital technology significantly influence mathematics teachers' decisions regarding the integration of technology into their classrooms. Consequently, professional development programs should prioritize affording teachers' opportunities to gain hands-on experience with digital technology in authentic settings, ultimately enhancing their TPACK and technology integration skills.

How and why mathematics teachers utilize digital technology. The second theme concerned the how and why mathematics teachers incorporate digital technology into their classroom instruction. Commonly discussed digital technologies in the research studies included GeoGebra, calculators, spreadsheets, interactive whiteboards, and web-based applications. Despite variations in tool usage, the studies reported that teachers commonly cite three aspects motivating their technology integration: visualization, skill practice, and pedagogical enrichment. Numerous researchers have underscored the potential of technology tools to visually represent mathematical concepts, thereby facilitating students' comprehension. For example, Karakus (2018) demonstrated that GeoGebra allowed students to manipulate graphical elements, improving their understanding of rotational processes. The studies reviewed consistently highlight the correlation between teachers' TPACK levels and the quality of classroom learning activities (Açıkgül & Aslaner, 2020; Chen & Jang, 2013; Polly, 2014). Teachers with higher TPACK competencies were better equipped to implement student-centered strategies that support skill development (Niess et al., 2014). For instance, Urbina and Polly (2017) emphasized that teachers lacking TPACK often employed limited strategies for motivating students, resulting in lower-quality activities. Additionally, the relationship between technology and teaching methods in mathematics classrooms emerges as a recurring theme. Digital technologies enable teachers to adopt more student-centered approaches, encouraging collaborative group work and inquiry-based problem-solving (Lyublinskaya & Kaplon-Schilis, 2022; Niess et al., 2014). The finding suggests that mathematics teachers' TPACK levels significantly influence their utilization of technology in mathematics classrooms and, consequently, the quality of classroom activities. This underscores the importance of orienting teacher education programs toward enhancing primary mathematics teachers' TPACK competencies to improve the quality of classroom learning activities.

Factors influencing mathematics teachers' TPACK development. The third theme concerns the factors shaping the development of mathematics teachers' TPACK, encompassing various elements like university course designs, professional teacher training, in-class practice, education policies, and infrastructure. Notably, the impact of teaching and learning experiences on TPACK development has garnered substantial attention within this context. Açıkgül and Aslaner (2020), for instance, stressed the pivotal role of immersive experiences in technologically enriched environments in significantly contributing to the maturation of mathematics teachers' TPACK. They argued that exposure to such dynamic settings becomes paramount for enriching teachers' knowledge and skills, thereby facilitating the seamless integration of digital technologies into their classroom pedagogy. Similarly, Simsek and Yazar (2019) underscored the influential role of university curricula in shaping teachers' formative experiences. Their advocacy for curricula providing extensive opportunities for mathematics educators to actively engage with technology during classroom instruction serves as a cornerstone for strengthening TPACK. Additionally, the significance of collaboration among mathematics teachers emerged as a pivotal factor in TPACK development. DeCoito and Estaiteyeh (2022) recommended that educational institutions should actively foster collaboration by provisioning digital resources, support mechanisms, and collaborative opportunities, effectively bolstering teachers' confidence in technology integration. In a complementary vein, Kafyulilo et al. (2015) highlighted the positive impact of collaborative endeavors, particularly in the co-designing of lessons, as a catalyst for TPACK development. While these studies consistently underscore the importance of digital technology experiences in teaching and learning for the advancement of primary mathematics teachers' TPACK, it is pertinent to acknowledge the need for future research to synthesize these findings and critically evaluate their novelty and contribution to our collective understanding of technology integration in education.

Designing assessment

The study by Galanti et al. (2021), conducted in the USA, delves into the application of the TPACK framework to scrutinize an online assessment tool, particularly the digital interactive notebook. This research underscores the importance of employing TPACK as a reflective framework for crafting both summative and formative assessments tailored for online mathematics teaching. Its significance becomes even more pronounced in light of the prevailing educational landscape, which has undergone a seismic shift towards online and blended learning, largely instigated by the far-reaching impact of the COVID-19 pandemic. Galanti et al.'s (2021) study not only resonates as a call to action for mathematics educators but also highlights the urgent imperative of recognizing online teaching as an opportunity for nurturing TPACK competencies and deepening insights into the effective integration of digital technology. Furthermore, the scarcity of research in this specific domain of online mathematics assessment underscores a notable research gap, underscoring the need for future investigations to delve deeper into TPACK for the development and refinement of summative and formative assessment strategies tailored to the distinctive context of online and blended learning environments. Indeed, research of TPACK and design of assessment is equally relevant and important for face-to-face teaching.

Evaluating teacher training programs

Four distinct studies conducted in the USA, Israel, and Greece (Anat et al., 2020; Doukakis et al., 2010; Havard et al., 2018; Polly, 2011a) utilized the TPACK framework to evaluate the impact of tailored professional training programs for mathematics educators. These studies employed TPACK as a robust benchmark to assess the depth of primary mathematics teachers' proficiency in integrating digital technology into their instructional practices following their participation in these professional development initiatives (Anat et al., 2020; Doukakis et al., 2010; Havard et al., 2018; Polly, 2011a). Notably, their findings highlight the crucial role of TPACK as a guiding framework within teacher training programs. It emerges as a powerful tool capable of effectively evaluating the effectiveness of such programs in equipping mathematics teachers with the necessary competencies to proficiently utilize digital technology in their classroom teaching endeavors. By illuminating this vital connection, this review contributes to the field by emphasizing the pivotal role of TPACK as an evaluation framework. Moreover, it serves as a compass for future directions in teacher training and professional development efforts, providing a clear pathway towards enhancing mathematics educators' ability to effectively harness digital technology in their teaching practices.

Guiding professional development program design

Four additional studies (Bate et al., 2013; Meletiou-Mavrotheris et al., 2019; Niess & Gillow-Wiles, 2014; Tsouccas & Meletiou-Mavrotheris, 2019) stand out for their pioneering approach to the utilization of the TPACK framework to guide the design of professional development programs tailored specifically for primary mathematics teachers. These studies collectively serve as a clarion call, emphasizing the importance of TPACK in shaping effective professional development for teachers in the digital age. The noteworthy consensus emerging from these investigations' centers on the transformative power of TPACK-based training, as mathematics educators who partook in these programs uniformly championed the notion of the thoughtful and strategic application of digital technologies within mathematics classrooms. The teachers in these studies recognized the imperative of discerning not just what technologies to use but also when, how, and why to deploy them, with a clear focus on enhancing students' higher-order thinking skills and problem-solving abilities. Furthermore, these studies underscored the need to provide mathematics teachers with ample opportunities to actively engage with digital technology in classroom teaching settings, effectively addressing a critical research gap in the field. Indeed, these experiences were found to be pivotal, enabling educators to master the art of effectively integrating technology into their pedagogical approaches. This review sheds light on the research gap pertaining to the transformative potential of TPACK in professional learning and teacher training programs. These programs should meticulously prioritize the enrichment of teachers' experiential interactions with digital technology, ultimately enhancing their capacity to employ technology thoughtfully and effectively as a dynamic tool in the realm of mathematics instruction. Thus, this collective body of research not only informs but also paves the way for future developments in mathematics education, significantly contributing to the field by highlighting the central role of TPACK in fostering pedagogical excellence in the digital era.

In summary, this study has explored the prevalent characteristics and emerging trends within TPACK research focused on primary mathematics education from 2005 to 2022. The extensive analysis of TPACK instruments in the reviewed literature underscores their critical role in evaluating and understanding primary mathematics teachers' technological integration competencies. The findings reveal a diverse application of these instruments, reflecting a nuanced approach to assessing teachers' TPACK, vital for effective digital technology integration in mathematics education. Moreover, the study highlights the significance of demographic factors and their correlation with TPACK application in primary mathematics education, offering insights into the broader implications of TPACK framework utilization. The discussion elucidates how the TPACK framework has been employed to critically assess and enhance primary mathematics teachers' knowledge, thereby contributing to advancing primary mathematics education. Through the synthesis of these findings, this study contributes to a deeper understanding of TPACK's role in shaping primary mathematics education, laying a foundation for future research and practice in this vital domain.

Conclusion

In conclusion, this comprehensive review has provided a detailed examination of the landscape of research on TPACK in the context of primary mathematics education. The study aimed to explore the general characteristics of TPACK research and shed light on how the TPACK framework is applied to assess mathematics teachers' knowledge and practice of using digital technologies in their classroom teaching. The analysis and discussion have been structured around key research questions, offering insights into the characteristics and emerging trends in TPACK research; the design of TPACK instruments; the use of Likert scales and item development approaches; the mapping of TPACK research; and the exploration of TPACK applications in lesson design, assessment design, evaluation of teachers' knowledge, teacher training, and professional development program design.

One notable trend that emerged from this analysis is the increasing utilization of TPACK instruments to evaluate primary mathematics teachers' knowledge of integrating digital technologies into their teaching practices. These instruments exhibit variations in their designs, with some specifically tailored to primary mathematics contexts, while others are adaptations of existing instruments. The instrument developed by Schmidt et al. (2009) stands out as the most frequently used, reflecting its significant influence in this field. Additionally, there is a geographic pattern observed, with Turkey conducting a higher number of studies focused on the development of TPACK instruments compared to other countries, highlighting the need for more diverse investigations across different regions. The analysis also explored the use of Likert scales and item development approaches within TPACK research. A prevailing preference for 5-point Likert scales was observed, along with a diverse range of item development strategies such as GTSD, ESID, and MSID. While this diversity reflects researchers' adaptability to different research contexts and objectives, it also underscores the need for future research to examine how cultural nuances impact Likert scale responses. Additionally, researchers should consider striking a balance between item specificity and flexibility to effectively assess the complexities of TPACK.

Furthermore, the study mapped the landscape of TPACK research in primary mathematics education, revealing a growing interest in exploring the convergence of technology, pedagogy, and content knowledge. The analysis identified an upward trend in the number of articles published between 2010 and 2019. However, there is a research gap in the limited representation of mixed-method studies, particularly in primary mathematics education, suggesting a need for more comprehensive exploration of diverse applications of the TPACK framework. The exploration of TPACK applications in lesson design, assessment design, evaluation of teachers' knowledge, teacher training, and professional development program design highlighted the significant role of TPACK in shaping effective teaching practices and teacher training programs. TPACK has been utilized as a guiding framework for designing technology-integrated lessons, assessing teachers' proficiency in technology integration, and evaluating the impact of teacher training initiatives. It has also informed the design of professional development programs, emphasizing the importance of hands-on experiences with digital technology in authentic settings.

Implications

The findings of this review have profound implications for various facets of primary mathematics education, teacher education programs, and future research directions. Primarily, the results underscore the pivotal role of TPACK as an essential framework in amplifying the integration of digital technology within mathematics instruction. Educators and policymakers are encouraged to leverage this insight to formulate and refine teacher education programs, ensuring they emphasize nurturing TPACK competencies. Such programs should equip teachers with advanced technological skills and cultivate their strategic abilities to select and implement digital tools that enhance pedagogical outcomes. Moreover, our review illuminates the need for a balanced and strategic approach to developing TPACK assessment instruments. By utilizing GTSD, ESID, and MSID methods, educators can create comprehensive and adaptable instruments that capture the complexities of TPACK in varied technological environments. These enhanced tools are instrumental for educators, enabling them to conduct thorough self-assessments and continuous improvements in their TPACK, vital for fostering interactive and effective mathematics classrooms.

Considering the transformative impact of technology on education, this systematic review emphasizes the critical importance of cultivating a collaborative culture among primary mathematics teachers. By promoting cooperative endeavors and establishing platforms for sharing experiences and best practices in TPACK integration, the educational community can significantly boost professional development and elevate the standard of mathematics education. Also, the implications extend into the realm of teacher education programs, where there is a pressing need for curricula aligned with the evolving digital landscape, ensuring that educators are well-prepared to navigate and thrive in technology-rich teaching environments. Furthermore, this systematic review catalyzes a call for future research, particularly empirical studies that examine the impact of these enriched teacher education programs on actual classroom practices and student outcomes. Such research is crucial for validating the effectiveness of TPACK-focused training and for identifying areas where further curricular enhancements are needed.

Limitation and future research

While this review provides invaluable insights, it is important to acknowledge its limitations. Firstly, the selection criteria for article inclusion may have inadvertently excluded relevant research, potentially limiting the comprehensiveness of the review. Additionally, focusing primarily on published articles might have overlooked valuable insights from unpublished work or other types of publications, such as conference papers and book chapters. Furthermore, this review's scope was confined to studies published until September 2021, which may not capture recent developments in TPACK research within primary mathematics education. Future research endeavors in this domain should address these limitations by exploring emerging trends and developments in TPACK research, particularly within the context of AI-driven education. Moreover, investigations should delve into the experiences and perspectives of both pre-service and in-service primary mathematics teachers to gain a deeper understanding of the challenges and opportunities associated with TPACK integration. Additionally, there is a need for studies that examine the impact of TPACK-based teacher training programs on student learning outcomes. Evaluating the effectiveness of these programs in terms of enhancing teachers' TPACK and student achievement can provide valuable evidence for educational policymakers and institutions.

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Declarations

Ethical approval As this research involved a systematic literature review and did not involve the collection of primary data or involve human participants, no ethical approval was required. All included studies were conducted in accordance with the relevant ethical guidelines and regulations.

Competing interests The authors declare no competing interests.

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Note: * denotes that the paper is included in the systematic review.

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