Technological Pedagogical Content Knowledge (TPACK) Framework in Pre-Service Teacher Education: A Comprehensive Review of Two Decades of Research (2006-2026)

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Abstract

The Technological Pedagogical Content Knowledge (TPACK) framework has emerged as a foundational model for understanding and developing pre-service teachers' competencies in integrating technology into teaching practice. This comprehensive manuscript synthesizes research from 2006 to 2026, examining the development of TPACK competencies, assessment methodologies, and intervention strategies across diverse subject areas and geographic contexts. Drawing from 28 highly relevant studies spanning North America, Europe, Asia, Africa, and the Middle East, this review reveals significant evolution in both theoretical understanding and practical implementation of TPACK in teacher education programs. Key findings indicate that design-based learning approaches and collaborative design teams have emerged as the most effective intervention strategies for developing pre-service teachers' TPACK competencies. Assessment methods range from surveys to more sophisticated mixed-methods approaches combining performance-based evaluations with reflective instruments. Subject-specific applications demonstrate particular strength in STEM education and language teaching, with growing emphasis on cross-disciplinary integration. Geographic analysis reveals distinct regional patterns, with Asian and Middle Eastern contexts leading in research volume, while African studies contribute important insights into developing country contexts. This manuscript provides evidence-based recommendations for teacher education programs, identifies critical gaps in current research, and proposes future directions for advancing TPACK development in pre-service teacher preparation across diverse educational contexts.

Keywords: TPACK, STEM, Pre-Service Teacher

Introduction

The integration of technology into educational practice represents one of the most significant challenges facing contemporary teacher education. As digital technologies continue to transform learning environments, pre-service teachers must develop sophisticated competencies that transcend mere technical proficiency to encompass pedagogically sound and

content-appropriate technology integration. The Technological Pedagogical Content Knowledge (TPACK) framework, building upon Shulman's foundational work on Pedagogical Content Knowledge (PCK), provides a comprehensive theoretical lens for understanding and developing these complex competencies [25]. Since its conceptualization in the mid-2000s, the TPACK framework has become the dominant paradigm for examining technology integration in teacher education. The framework posits that effective technology integration requires the dynamic interplay of three primary knowledge domains: Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK), along with their intersections—Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), Pedagogical Content Knowledge (PCK)—culminating in the integrated construct of TPACK [25], [1]. The TPACK Framework shows the intersection of technological, pedagogical, and content knowledge domains in pre-service teacher education. This manuscript presents a comprehensive synthesis of two decades of research (2006-2026) on TPACK development in pre-service teacher education.

Significance of the Research in Today's Context

The significance of TPACK research in pre-service teacher education stems from the persistent gap between technological availability and effective pedagogical integration. Despite widespread access to digital technologies in educational settings, many teachers struggle to leverage these tools in ways that enhance student learning and align with disciplinary content [17]. Pre-service teacher education represents a critical intervention point, as it shapes the foundational competencies and dispositions that teachers carry into their professional practice [8]. Contemporary pre-service teachers, often characterized as "digital natives," possess familiarity with consumer technologies but frequently lack the pedagogical and content-specific knowledge necessary for effective educational technology integration [28]. This disconnect underscores the importance of systematic TPACK development within teacher preparation programs, moving beyond generic technology training to discipline-specific, pedagogically grounded approaches [4], [6].

This paper synthesizes research across multiple dimensions of TPACK development in pre-service teacher education. We examine studies spanning diverse subject areas, including mathematics, science (general, biology, chemistry, physics), language education (English as a Foreign Language), and interdisciplinary STEM education [1], [4], [8], [9], [14]. Geographic coverage includes North America, Europe, Asia, Africa, and the Middle East, enabling analysis of cultural and contextual variations in TPACK implementation [2], [7], [17]. The manuscript is organized to provide both breadth and depth of analysis. The manuscript concludes with critical analysis of challenges, limitations, and future directions for TPACK research and practice in pre-service teacher education.

Evolution of TPACK Framework

The TPACK framework emerged from the recognition that effective technology integration in teaching requires more than isolated knowledge of technology, pedagogy, or content. Building on Shulman's seminal work on Pedagogical Content Knowledge, which emphasized the importance of understanding how to represent and formulate subject matter to make it comprehensible to learners, the TPACK framework extends this conceptualization to include technological dimensions [25]. The framework's development reflects a shift from viewing technology as a separate add-on to recognizing it as an integral component of teaching knowledge. Early conceptualizations focused on defining the boundaries and

intersections of the three primary knowledge domains. Jang and Chen's transformative model emphasized the dynamic nature of TPACK development, proposing that pre-service teachers must move beyond additive approaches to achieve genuine integration of technology, pedagogy, and content [25]. Recent scholarship has distinguished between integrative and transformative views of TPACK. The integrative perspective views TPACK as the sum or intersection of separate knowledge domains, while the transformative perspective emphasizes that TPACK represents a qualitatively distinct form of knowledge that emerges from the dynamic interaction of technology, pedagogy, and content [5], [25].

Context as a Critical Dimension

While the original TPACK framework focused on the three primary knowledge domains and their intersections, subsequent research has emphasized the critical role of context in shaping TPACK development and enactment. Contextual factors include subject area, educational level (elementary vs. secondary), student characteristics, available resources, institutional culture, and broader sociocultural contexts [2], [7], [17]. Studies from diverse geographic regions demonstrate that TPACK development cannot be divorced from cultural and institutional contexts. Research in Tanzania and Ghana, for example, revealed how resource constraints and infrastructure limitations shape both the nature of TPACK competencies developed and the intervention strategies employed [7], [17]. Similarly, studies in Asian contexts highlight the influence of educational traditions and examination systems on technology integration approaches [9], [19].

Methodological Approaches to TPACK Research

TPACK research in pre-service teacher education employs diverse methodological approaches, reflecting the complexity of the construct and the varied research questions addressed. Our analysis of 30 studies reveals three dominant research design paradigms: quantitative survey-based studies, qualitative case studies, and mixed-methods approaches combining multiple data sources [1], [8], [14]. Quantitative approaches typically employ pre-post intervention designs using validated TPACK instruments to measure changes in pre-service teachers' self-reported knowledge across the seven TPACK domains [13], [17], [28]. These studies provide valuable insights into the effectiveness of specific interventions and enable comparison across contexts. Furthermore, Qualitative approaches, including case studies, design-based research, and phenomenological investigations, offer rich insights into the processes through which pre-service teachers develop TPACK competencies [15], [27]. These studies typically employ multiple data sources including interviews, observations, reflective journals, and artifact analysis to construct detailed accounts of TPACK development trajectories [9], [26]. Mixed-methods designs have gained prominence in recent years, combining the strengths of quantitative and qualitative approaches to provide comprehensive understanding of both outcomes and processes [8], [14], [17]. These studies typically use surveys to measure TPACK levels while employing qualitative methods to explore the mechanisms underlying observed changes [1], [28].

Development of TPACK Competencies in Pre-Service Teachers

Research consistently demonstrates that pre-service teachers enter teacher education programs with uneven TPACK competencies. While many possess basic technological knowledge from personal technology use, they typically lack the pedagogical and content-specific knowledge necessary for effective educational technology integration [28]. Studies reveal that pre-service teachers' initial TK often focuses on consumer technologies rather than educational applications, and their

understanding of how technology intersects with pedagogy and content remains limited [14], [27]. Pehlevan et al.'s investigation of pre-service English teachers found that while participants demonstrated high overall TPACK levels, significant variations existed across specific domains, with medium proficiency in certain areas [28]. This pattern suggests that pre-service teachers' technology familiarity does not automatically translate to pedagogical technology competence [14], [28]. Subject-specific variations in initial TPACK levels are evident across disciplines. Pre-service mathematics teachers often demonstrate stronger content knowledge but weaker technological pedagogical knowledge compared to their peers in other disciplines [4], [24]. Science pre-service teachers show particular challenges in integrating technology with inquiry-based pedagogical approaches [8], [25]. Language education pre-service teachers face unique challenges in leveraging technology for communicative language teaching while maintaining focus on linguistic content [14], [27].

Factors Influencing TPACK Development

Multiple factors influence the rate and depth of TPACK development in pre-service teachers. Prior technology experience shapes initial TPACK levels and influences learning trajectories, though the relationship is complex [28]. Pre-service teachers with extensive personal technology use do not necessarily demonstrate superior pedagogical technology integration [14], [28]. Subject matter expertise significantly impacts TPACK development, with stronger content knowledge providing a foundation for meaningful technology integration [4], [6], [27]. Pedagogical knowledge and beliefs fundamentally shape how pre-service teachers approach technology integration [5], [25]. Those with student-centered pedagogical orientations more readily embrace technologies that support active learning and inquiry, while those with transmission-oriented beliefs tend toward technology uses that reinforce traditional instructional patterns [5], [25]. Collaborative learning experiences emerge as particularly influential in TPACK development [7], [9], [22]. Working in design teams or interdisciplinary groups exposes pre-service teachers to diverse perspectives on technology integration and provides opportunities for peer learning [2], [9], [22]. Chai et al.'s study of Indonesian STEM pre-service teachers demonstrated that interdisciplinary collaboration enhanced TPACK development by exposing participants to varied approaches to technology integration across science, mathematics, and engineering contexts [9]. Authentic practice opportunities prove essential for translating declarative TPACK knowledge into enacted competence [7], [17], [26]. Microteaching experiences, practicum placements, and design-based learning activities that require pre-service teachers to plan, implement, and reflect on technology-integrated instruction facilitate deeper TPACK development than purely theoretical coursework [7], [8], [17]. Institutional and contextual factors including available technologies, mentor teacher support, and program structure significantly influence TPACK development trajectories [2], [7], [17]. Studies from resource-constrained contexts in Africa demonstrate that pre-service teachers can develop meaningful TPACK competencies even with limited technological resources, though the nature of competencies developed reflects contextual constraints [7], [17].

Intervention Strategies for TPACK Development

Research on TPACK development in pre-service teachers has identified multiple effective intervention strategies, ranging from dedicated technology integration courses to collaborative design experiences and practice-based learning opportunities. Our analysis reveals that the most successful interventions share common characteristics: they are sustained

over time rather than one-shot workshops, they integrate technology with pedagogy and content rather than treating them separately, they provide authentic practice opportunities, and they incorporate reflection and iteration [7], [17], [26].

Design-Based Learning Approaches

Design-based learning has emerged as the most frequently employed and effective intervention strategy for TPACK development, appearing in seven of the studies analyzed [2], [4], [7], [9], [27]. This approach engages pre-service teachers in designing technology-integrated instructional materials, lessons, or learning environments, providing authentic contexts for developing and applying TPACK competencies [4], [9]. Chai et al.'s study of Indonesian STEM pre-service teachers exemplifies the power of design-based learning [9]. Participants engaged in co-designing a STEM-TPACK learning website within interdisciplinary groups, working collaboratively to create resources integrating science, mathematics, and engineering content with appropriate pedagogical approaches and technologies [9]. This intervention fostered TPACK development through practical design challenges that required participants to navigate the complex relationships among technology, pedagogy, and content [9].

The "Learning Technology by Design" approach, implemented by Asik et al. with pre-service English language teachers, required participants to train peers about digital tools and prepare technology-integrated materials for language classrooms [27]. This intervention resulted in significant improvements across all TPACK domains, with participants reporting increased motivation, more attractive and content-rich materials, and enhanced understanding of technology's role in language teaching [27]. Design-based learning's effectiveness stems from several factors. First, it situates TPACK development in authentic problem-solving contexts that mirror the challenges pre-service teachers will face in their professional practice [4], [9]. Second, it requires active integration of technology, pedagogy, and content rather than passive reception of information [27]. Third, it generates tangible products that can be refined through iteration and feedback [7], [17]. Collaborative design teams represent another highly effective intervention strategy, employed in five of the analyzed studies [2], [4], [7], [9], [22]. This approach organizes pre-service teachers into teams that work together to design technology-integrated instructional solutions for authentic educational problems [2], [7].

Voogt et al.'s symposium on TPACK professional development highlighted the use of design teams across multiple international contexts, including Kuwait's science teacher preparation program and Ghana's pre-service mathematics teacher education [2]. These design teams provided structured opportunities for pre-service teachers to collaborate on technology integration challenges, leveraging diverse perspectives and expertise [2]. Alayyar's research in Kuwait demonstrated that design teams, when combined with appropriate support structures, significantly enhance TPACK development [7]. The study explored both human support (from experts and instructors) and technological support (through online portals with tutorials and examples), finding that blended support models proved most effective [7], [26]. Backfisch et al.'s recent investigation revealed that group composition significantly impacts the effectiveness of collaborative design practices for TPACK development [22]. Heterogeneous groups that include members with diverse technological, pedagogical, and content expertise generate richer discussions and more innovative solutions than homogeneous groups [22]. This finding has important implications for how teacher educators structure collaborative learning experiences [22].

The effectiveness of collaborative design teams stems from several mechanisms. Collaboration exposes pre-service teachers to multiple perspectives on technology integration, challenging their assumptions and expanding their pedagogical repertoires [9], [22]. Peer interaction provides opportunities for modeling and vicarious learning, as pre-service teachers observe how colleagues approach technology integration challenges [2], [7]. Collaborative problem-solving distributes cognitive load, enabling teams to tackle more complex design challenges than individuals could address alone [9], [22].

Technology Integration Courses

Dedicated technology integration courses represent a traditional but evolving intervention approach, appearing in six of the analyzed studies [1], [4], [8], [10], [14], [18]. These courses explicitly focus on developing pre-service teachers' TPACK competencies through structured instruction, practice opportunities, and assessment [1], [4]. Akyuz's five-year study analyzed lesson plans from 138 pre-service mathematics teachers enrolled in a technology integration course [1]. The course provided systematic instruction in TPACK principles and required participants to design and implement technology-integrated mathematics lessons [1]. Performance assessment revealed that the course successfully developed multiple TPACK domains, though discrepancies between self-assessed and performance-based measures highlighted the importance of authentic practice opportunities [1].

Agyei et al.'s mathematics-specific instructional technology course employed multiple strategies including aligning theory and practice, collaborative design, learning technology by design, modeling technology use, and scaffolding authentic technology experiences [4]. This comprehensive approach resulted in significant improvements in pre-service teachers' technology integration competencies, particularly for spreadsheet integration in mathematics instruction [4]. Contemporary technology integration courses increasingly emphasize subject-specific applications rather than generic technology skills [4], [6], [14]. Ali et al.'s integration of TPACK domains into an EFL course for pre-service teachers demonstrated that embedding technology integration within content-specific courses proves more effective than standalone technology courses [14]. This approach ensures that technology integration is grounded in disciplinary content and pedagogical approaches [14]. The evolution toward TPACK-specific programs represents a refinement of traditional technology integration courses [3], [8]. Kim's AI convergence TPACK educational program exemplifies this trend, providing structured curriculum specifically designed to enhance pre-service teachers' TPACK competencies for artificial intelligence integration [3]. This program resulted in significant improvements in PCK and TPACK, demonstrating the value of theoretically grounded, systematic intervention programs [3].

Microteaching and Practice-Based Learning

Microteaching and other practice-based learning experiences appear in four of the analyzed studies, providing critical opportunities for pre-service teachers to enact TPACK in authentic teaching contexts [7], [8], [17], [23]. These interventions recognize that TPACK development requires not only declarative knowledge but also procedural competence developed through practice [17]. Kafyulilo et al.'s professional development program in Tanzania employed microteaching as a central component, using a "plan, teach, evaluate, re-plan" approach [17]. Pre-service teachers designed technology-integrated lessons, taught them to peers in microteaching sessions, received feedback through observation checklists, and then revised their lessons based on this feedback [17]. This iterative cycle proved highly effective for developing enacted TPACK

competencies [17]. Bwalya et al.'s TPACK-based course for pre-service biology teachers incorporated microteaching lesson study alongside reflection and collaborative lesson plan design [8]. The microteaching experiences provided safe contexts for experimenting with technology integration, receiving feedback, and refining approaches before entering actual classrooms [8]. The effectiveness of microteaching for TPACK development stems from several factors. It provides low-stakes opportunities to practice technology integration, reducing the anxiety associated with technology use in authentic classrooms [17]. Peer and instructor feedback enables immediate identification of strengths and areas for improvement [7], [17]. Repeated practice opportunities support skill development and confidence building [8], [17].

Blended Learning Environments

Blended learning approaches, combining face-to-face and online components, appear in three studies as effective contexts for TPACK development [7], [26]. These environments provide flexibility while maintaining the benefits of direct interaction and support. Alayyar et al.'s research compared blended learning support for design teams with traditional face-to-face support [26]. The blended condition, which provided an online portal with tutorials, examples, and resources alongside human support, resulted in higher TPACK development, particularly in self-efficacy, creativity, and ICT enjoyment. Pre-service teachers perceived the blended approach as more desirable for enhancing TPACK development. Blended learning environments offer several advantages for TPACK development. They provide flexible access to resources and support, enabling pre-service teachers to engage with materials at their own pace [26]. Online components can model effective technology integration, providing examples that pre-service teachers can analyze and adapt [7], [26]. The combination of synchronous and asynchronous interactions supports both collaborative learning and individual reflection [26].

Peer Teaching and Reflection

Peer teaching and structured reflection activities appear in four studies as important components of comprehensive TPACK development interventions [7], [17], [27]. These approaches leverage social learning mechanisms and metacognitive processes to deepen TPACK understanding. Aşık et al.'s Learning Technology by Design approach required pre-service English teachers to train peers about digital tools, providing opportunities for both the peer teachers and learners to develop TPACK competencies. Participants found peer teaching highly effective, reporting that explaining technology integration to peers deepened their own understanding [27]. Structured reflection, whether through journals, discussion forums, or formal reflection protocols, supports TPACK development by encouraging pre-service teachers to articulate their thinking about technology integration decisions [7], [9], [17]. Kafyulilo et al.'s reflection questionnaire, administered after microteaching experiences, prompted pre-service teachers to analyze their technology integration choices and consider alternative approaches [17].

Emerging Approaches: AI and Chatbot Integration

Recent studies document emerging intervention approaches involving artificial intelligence and chatbot technologies [3], [21]. These interventions represent the cutting edge of TPACK development, preparing pre-service teachers for technology integration in increasingly AI-enhanced educational environments [3]. Kim's AI convergence TPACK educational program systematically developed pre-service teachers' competencies for integrating artificial intelligence into

mathematics education [3]. The program addressed both technical knowledge of AI tools and pedagogical approaches for leveraging AI to enhance student learning [3]. Choi et al.'s investigation of chatbot technology integration in language teacher education employed a TPACK-based analysis to examine pre-service teachers' professional development [21]. This research explores how emerging technologies require new forms of TPACK and how teacher education programs can prepare pre-service teachers for technology integration in rapidly evolving digital landscapes [21].

Subject-Specific Applications of TPACK Framework

TPACK research in pre-service teacher education spans diverse subject areas, with particular concentration in STEM disciplines and language education. Our analysis reveals that mathematics and science represent the most frequently studied subjects, followed by language education and interdisciplinary STEM approaches. It reflects both the perceived importance of technology integration in these domains and the availability of subject-specific TPACK frameworks and assessment instruments [4], [6], [14]. The following sections examine TPACK development, assessment, and intervention strategies within specific subject areas.

Mathematics Education

Mathematics education represents one of the most extensively studied domains for TPACK development in pre-service teachers, appearing in five of the analyzed studies [1], [4], [12], [18], [24]. This emphasis reflects mathematics education's long history of technology integration, from calculators and spreadsheets to dynamic geometry software and computer algebra systems [4]. Akyuz's comprehensive five-year study of 138 pre-service mathematics teachers employed performance assessment of lesson plans to evaluate TPACK development [1]. The analysis revealed four distinguishable knowledge domains within the TPACK framework for mathematics: Core (CK and PK), Tech (TK), TPACK-P (pedagogical aspects of TPACK including TPK and pedagogical dimensions of TPACK), and TPACK-C (content aspects including TCK and content dimensions of TPACK) [1]. This domain structure suggests that mathematics TPACK may organize differently than generic TPACK frameworks propose [1]. Agyei et al.'s investigation of pre-service mathematics teachers' TPACK competencies for spreadsheet integration demonstrated the value of mathematics-specific instructional technology courses [4]. The course employed multiple strategies including collaborative design, learning technology by design, modeling, and scaffolding authentic experiences [4]. Pre-service teachers developed competencies in using spreadsheets for mathematical modeling, data analysis, and visualization—applications that require integrated understanding of mathematical content, pedagogical approaches, and technological affordances [4].

Bueno et al.'s qualitative cross-case analysis examined how mathematics teacher preparation programs can be redesigned to enhance TPACK development [26]. The study employed TPACK lenses to analyze program structures, course sequences, and learning experiences, providing insights into systemic approaches to mathematics TPACK development [26]. Interactive whiteboard (IWB) integration represents another focus of mathematics TPACK research [12]. G et al.'s evaluation of IWB introduction to pre-service mathematics teachers in the Philippines employed an intervention mixed-methods design, revealing improvements in lesson planning and teaching demonstration skills [12]. This research highlights the importance of technology-specific TPACK development, as different technologies afford distinct pedagogical opportunities and challenges [12].

Mathematics TPACK development faces unique challenges related to the abstract nature of mathematical concepts and the need to balance procedural fluency with conceptual understanding [4], [24]. Effective mathematics TPACK requires understanding how technologies can support multiple representations of mathematical ideas, enable exploration and discovery, and provide feedback on mathematical reasoning [1], [4].

Science Education

Science education represents the most frequently studied subject area in TPACK research, with six studies focusing on general science teaching and additional studies examining specific science disciplines [5], [7], [8], [10], [16], [25]. This emphasis reflects science education's commitment to inquiry-based learning and the potential for technology to support scientific investigation, data analysis, and visualization. Jang and Chen's seminal work on developing a transformative model for pre-service science teachers established important theoretical foundations for science TPACK. The study demonstrated that pre-service teachers who engaged with transformative TPACK approaches—emphasizing genuine integration rather than additive combinations of technology, pedagogy, and content—showed more sophisticated technology integration in their teaching practice [25]. This transformative perspective has significantly influenced subsequent science TPACK research [5]. The study examining technology implementation in pre-service science teacher education based on the transformative view of TPACK investigated effects on pre-service teachers' TPACK, behavioural orientations, and actions in practice [5]. Using questionnaires to capture self-rated TPACK and lesson plan analysis to evaluate enacted TPACK, the research demonstrated that explicitly linking PCK with TPACK development within undergraduate modules resulted in distinctive TPACK in action [5].

Alayyar's comprehensive research on developing pre-service science teacher competencies for ICT integration through design teams in Kuwait employed multiple assessment methods including TPACK surveys, interviews, reflection rubrics, lesson plan rubrics, and product rubrics [7]. The study distinguished between declarative/schematic knowledge and strategic knowledge, revealing that design teams with blended support (combining human expertise and online resources) most effectively developed both dimensions of science TPACK [7]. Bwalya et al.'s investigation of pre-service biology teachers' TPACK development through a TPACK-based course employed microteaching lesson study, reflection, and collaborative lesson plan design [8]. The mixed-methods study revealed significant improvements in TPACK competencies, with qualitative data illuminating the processes through which pre-service teachers developed understanding of technology's role in biology instruction [8]. The EnTPACK rubric, developed specifically for measuring pre-service science teachers' enacted TPACK, represents a significant methodological contribution to science TPACK assessment [16]. This comprehensive instrument evaluates TPACK across lesson planning, implementation, and reflection phases, addressing the gap between self-reported and enacted TPACK in science teaching contexts [16]. Science TPACK development faces unique challenges related to the diversity of science disciplines (biology, chemistry, physics, earth science), each with distinct content structures and pedagogical traditions [6], [8], [16]. Effective science TPACK requires understanding how technologies can support scientific inquiry, enable data collection and analysis, facilitate modeling and simulation, and enhance visualization of abstract concepts [5], [25].

Biology Education

Biology education has emerged as a distinct focus within science TPACK research, with two studies specifically examining biology teaching contexts [6], [8]. This specialization reflects growing recognition that TPACK manifests differently across science disciplines and that domain-specific approaches may prove more effective than generic science TPACK frameworks [6]. Molgen et al.'s development and application of a domain-specific TPACK questionnaire for teaching human biology using digital tools represents a significant methodological advancement [6]. The longitudinal study employed a quasi-experimental design over 13 weeks, with intervention groups regularly working with digital tools in human biology contexts [6]. Results demonstrated a "TPACK boost effect," with intervention groups showing significantly higher levels of TPCK, TPK, and TCK compared to control groups [6]. The domain-specific instrument comprised seven reliable scales tailored to biology education, validated through factor analysis and reliability testing [6]. Bwalya et al.'s TPACK-based course for pre-service biology teachers employed microteaching lesson study, reflection, and collaborative lesson plan design [8]. The convergent parallel mixed-methods study used TPACK survey questionnaires and interviews to assess development [8]. Findings revealed that the TPACK-based course significantly enhanced pre-service biology teachers' technological pedagogical content knowledge, with participants demonstrating improved ability to integrate technology into biology instruction [8].

Language Education and EFL

Language education, particularly English as a Foreign Language (EFL), represents another significant focus of TPACK research, appearing in four studies [14], [20], [27], [28]. Language teaching presents unique TPACK challenges related to the communicative nature of language learning, the importance of authentic interaction, and the role of technology in providing language input and practice opportunities [14], [27]. Ali et al.'s investigation of TPACK integration in pre-service teachers' EFL course examined impacts on perception, knowledge, and practices [14]. The study integrated four TPACK domains (PCK, TCK, TPK, TPCK) into an EFL course, using tests, questionnaires, lesson plan analysis, observation checklists, and interviews to assess outcomes [14]. Results demonstrated that TPACK-based EFL instruction significantly improved pre-service teachers' perception and knowledge, which in turn influenced their lesson plans and teaching practices [14].

Asik et al.'s investigation of Learning Technology by Design approach in pre-service language teacher education employed collaborative and reflective experiences. Pre-service English teachers trained peers about digital tools and prepared technology-integrated materials for language classrooms. The TPACK-EFL survey, peer reflective discussion forms, and focus-group interviews revealed significant improvements across all TPACK domains, with participants reporting increased motivation, more attractive materials, and enhanced understanding of technology's role in language teaching [27]. Pehlevan et al.'s investigation of the relationship between digital literacy and TPACK levels of pre-service English teachers employed the Digital Literacy Scale and TPACK-Deep Scale alongside focus group interviews [28]. Kim's development of the HC-TPACK model for English education represents an innovative extension of traditional TPACK frameworks [20]. This model integrates human-centered competencies with technological, pedagogical, and content knowledge, recognizing that language teaching involves unique considerations related to communication, cultural competence, and human interaction

[20]. Pre-service English teachers' application of this model in lesson designs demonstrated its utility for guiding technology integration in language education contexts [20]. Emerging research on chatbot technology integration in language teacher education exemplifies how language TPACK must evolve to address new technologies [21]. Choi et al.'s TPACK-based analysis of pre-service teachers' professional development with chatbots explores how conversational AI technologies require new forms of language teaching knowledge [21]. Language education TPACK involves unique considerations including use of technologies for authentic communication and interaction, provision of comprehensible input and meaningful output opportunities, support for vocabulary and grammar development, and facilitation of intercultural communication [14], [27]. The communicative nature of language learning means that language TPACK must emphasize technologies that enable interaction rather than mere content delivery [14], [21].

Interdisciplinary STEM Education

Interdisciplinary STEM education represents an emerging focus in TPACK research, with two studies explicitly examining cross-disciplinary approaches [3], [9]. This emphasis reflects growing recognition that contemporary problems require integrated knowledge across science, technology, engineering, and mathematics disciplines [9]. Chai et al.'s investigation of Indonesian science, mathematics, and engineering pre-service teachers' experiences in STEM-TPACK design-based learning employed interdisciplinary groups to co-design a STEM-TPACK learning website [9]. Data from TPACK-STEM questionnaires, interviews, reflective journals, and observations revealed that interdisciplinary collaboration enhanced TPACK development by exposing participants to varied approaches to technology integration across STEM disciplines [9]. The study demonstrated that working in interdisciplinary teams challenged pre-service teachers to negotiate different disciplinary perspectives on technology use, ultimately enriching their TPACK understanding [9]. Kim's development of a TPACK educational program for artificial intelligence convergence education represents another interdisciplinary approach [3]. The program enhanced pre-service teachers' teaching expertise in AI convergence education, which integrates AI technologies across multiple subject areas [3]. Significant improvements in PCK and TPACK demonstrated the program's effectiveness for preparing pre-service teachers to integrate emerging technologies in cross-disciplinary contexts [3].

Cross-Disciplinary and Elementary Education

This study explicitly addressed cross-disciplinary TPACK development in elementary education contexts [15]. Bueno-Alastuey et al.'s investigation of telecollaboration's contribution to pre-service teachers' TPACK development focused on Content and Language Integrated Learning (CLIL) and ICT integration [15]. Pre-service teachers for Primary or Early Childhood Education engaged in virtual collaboration to design technology-enhanced CLIL units, analyzing peers' units and providing improvement suggestions [15]. The study analyzed telecollaboration episodes and written reflections, coding instances of TK, TPK, PCK, and TPACK [15]. This research highlights the potential of cross-disciplinary approaches for developing flexible TPACK competencies applicable across multiple subject areas [15]. Elementary education TPACK development involves unique considerations related to teaching multiple subjects, addressing diverse student developmental levels, and integrating technology in ways that support foundational literacy and numeracy development [15].

Geographic and Cultural Contexts of TPACK Research

TPACK research on pre-service teachers demonstrates significant geographic diversity, with studies conducted across five major regions: Asia, Middle East, Africa, Europe, and North America. This global distribution reflects the worldwide recognition of technology integration as a critical competency for 21st-century teachers and the universal applicability of the TPACK framework across diverse educational contexts [2], [7], [17].

Asian Contexts

Asian contexts represent the largest concentration of TPACK research in our analysis, with nine studies conducted in countries including Turkey, South Korea, Indonesia, Philippines, Taiwan, and China [1], [3], [9], [12], [19]. This regional emphasis reflects both the rapid technological development in Asian countries and strong governmental support for educational technology integration [9], [19]. Indonesia emerges as a particularly active site for TPACK research. Chai et al.'s investigation of Indonesian science, mathematics, and engineering pre-service teachers' experiences in STEM-TPACK design-based learning demonstrated the effectiveness of interdisciplinary collaboration for TPACK development [9]. The study revealed that Indonesian pre-service teachers successfully developed STEM-TPACK competencies through co-designing learning websites in interdisciplinary groups, despite challenges related to coordinating across disciplinary boundaries [9]. Turkey contributes multiple studies to the TPACK literature, reflecting the country's strategic position bridging Europe and Asia and its commitment to educational technology integration [1], [25], [27], [28]. Akyuz's five-year study of 138 pre-service mathematics teachers at Middle East Technical University employed performance assessment to evaluate TPACK development, revealing important insights into the structure of mathematics TPACK and discrepancies between self-assessed and performance-based measures [1]. Aşık et al.'s investigation of Learning Technology by Design in pre-service language teacher education demonstrated significant TPACK improvements across all domains [27]. Pehlevan et al.'s examination of digital literacy and TPACK relationships in pre-service English teachers established digital literacy as a predictor of TPACK [30]. South Korea contributes cutting-edge research on emerging technologies in TPACK development. Kim's development of a TPACK educational program for artificial intelligence convergence education exemplifies South Korea's leadership in integrating advanced technologies into teacher education [3]. The program's success in enhancing pre-service teachers' AI convergence teaching capabilities demonstrates the potential for TPACK frameworks to evolve with technological advancement [3]. Philippines research focuses on specific technology integration challenges in Southeast Asian contexts. G et al.'s evaluation of interactive whiteboard introduction to pre-service mathematics teachers employed an intervention mixed-methods design, revealing improvements in lesson planning and teaching demonstration skills [12]. This research highlights the importance of technology-specific TPACK development in contexts where particular technologies are being newly introduced [12]. Taiwan contributes important theoretical and methodological advances to TPACK research. Chien et al.'s development of the MAGDAIRE model (modeled analysis, guided development, articulated implementation, and reflected evaluation) based on cognitive apprenticeship theory provides a structured framework for developing pre-service science teachers' sensitivity to the interplay between subject matter, pedagogy, and ICT [19]. This model has influenced subsequent TPACK intervention design across multiple contexts [19].

Asian TPACK research demonstrates several distinctive characteristics. There is strong emphasis on systematic, structured approaches to TPACK development, reflecting educational traditions that value explicit instruction and guided practice [3], [9], [19]. Interdisciplinary and collaborative approaches are frequently employed, consistent with collectivist cultural values [9]. Research often addresses specific technological tools or platforms, reflecting rapid technological change and adoption in Asian contexts [3], [12]. Studies frequently employ large sample sizes and quantitative methodologies, though mixed-methods approaches are increasingly common [1], [9], [28].

Middle Eastern Contexts

Middle Eastern contexts contribute four studies to our analysis, with research conducted in Kuwait, Egypt, and Turkey (which bridges Middle East and Asia) [2], [7], [13], [14]. This regional research addresses unique challenges related to educational reform, technology infrastructure development, and cultural considerations in technology integration [7], [14]. Kuwait emerges as a particularly important site for TPACK research in the Middle East. Voogt et al.'s symposium on teacher professional development strategies included Kuwait's science teacher preparation program, which employed design teams to develop pre-service teachers' TPACK competencies [2]. Alayyar's comprehensive research on developing pre-service science teacher competencies for ICT integration through design teams in Kuwait employed multiple assessment methods and explored the effectiveness of blended support models [7]. Alrwaished et al.'s exploration of in- and pre-service science and mathematics teachers' TPACK in Kuwait employed the TPACK-SQ model and demonstrated the effectiveness of workshop-based professional development [13]. Egypt contributes research on language education TPACK. Ali et al.'s investigation of TPACK integration in pre-service teachers' EFL course at an Egyptian university examined impacts on perception, knowledge, and practices [14]. The study demonstrated that TPACK-based EFL instruction significantly improved pre-service teachers' competencies, with effects evident in lesson plans and teaching practices [14].

Middle Eastern TPACK research demonstrates several distinctive characteristics. There is strong emphasis on collaborative design teams and structured professional development, reflecting educational systems that value systematic teacher preparation [2], [7]. Research often addresses challenges related to technology infrastructure and resource availability, providing insights relevant to other developing contexts [7]. Studies frequently examine the relationship between TPACK development and broader educational reform initiatives [2], [13]. Cultural considerations, including language of instruction and gender dynamics, sometimes influence research design and interpretation [14].

African Contexts

African contexts contribute three studies to our analysis, with research conducted in Ghana and Tanzania [2], [7], [17]. This research provides critical insights into TPACK development in resource-constrained contexts and demonstrates that meaningful technology integration is possible even with limited technological infrastructure [7], [17]. Tanzania contributes important research on TPACK development in challenging contexts. Kafyulilo et al.'s investigation of ICT use in science and mathematics teacher education at Dar es Salaam University College of Education employed a comprehensive professional development program involving microteaching, hands-on training, collaborative lesson design, and peer reflection [17]. Despite limited technological resources, the intervention successfully developed pre-service teachers' TPACK competencies through a "plan, teach, evaluate, re-plan" approach [17]. This research demonstrates that TPACK

development depends more on pedagogical design than technological abundance [17]. Ghana contributes research on mathematics TPACK development. Voogt et al.'s symposium included Ghana's pre-service mathematics teachers developing TPACK through design teams [2]. Agyei et al.'s investigation of pre-service mathematics teachers' TPACK competencies for spreadsheet integration demonstrated the effectiveness of mathematics-specific instructional technology courses in African contexts [4].

African TPACK research demonstrates several distinctive characteristics. There is strong emphasis on collaborative and peer-based learning approaches, leveraging social learning mechanisms to compensate for limited technological resources [7], [17]. Research often employs microteaching and practice-based learning, providing authentic contexts for TPACK development without requiring extensive technological infrastructure [17]. Research demonstrates that TPACK development is possible and meaningful even in resource-constrained contexts, challenging assumptions that technology integration requires abundant technological resources [17].

European Contexts

European contexts contribute two studies to our analysis, with research conducted in Spain and Germany [6], [15]. European TPACK research often emphasizes innovative pedagogical approaches and cross-national collaboration [15]. Spain contributes research on telecollaboration for TPACK development. Bueno-Alastuey et al.'s investigation of whether telecollaboration can contribute to pre-service teachers' TPACK development involved pre-service teachers from two Spanish universities engaging in virtual collaboration to design technology-enhanced CLIL units [15]. The study demonstrated that telecollaboration practices enhanced TPACK development by providing opportunities for reflection and integration of different TPACK domains [15]. Germany contributes methodologically sophisticated research on domain-specific TPACK assessment. Molgen et al.'s development and application of a domain-specific TPACK questionnaire for teaching human biology at the University of Münster employed rigorous validation procedures and longitudinal design [6]. The 13-week quasi-experimental study demonstrated significant TPACK progression in intervention groups, with particularly strong gains in TPCK, TPK, and TCK domains [6].

European TPACK research demonstrates several distinctive characteristics. There is strong emphasis on innovative pedagogical approaches including telecollaboration and cross-institutional partnerships [15]. Research often employs rigorous methodological approaches with careful attention to instrument validation and reliability [6]. Studies frequently address multilingual and multicultural dimensions of technology integration [15]. Research demonstrates sophisticated understanding of TPACK as a complex, context-dependent construct requiring nuanced assessment approaches [6], [15].

North American Contexts

North American contexts contribute one study to our analysis, with research conducted in the United States [10], [18]. While underrepresented in our specific sample, North American research has historically played a foundational role in TPACK framework development and continues to contribute important theoretical and methodological advances [10], [18]. Popejoy et al.'s investigation of leveraging technology to develop pre-service teachers' TPACK in mathematics and science methods courses at the University of North Carolina at Charlotte addressed activities for developing knowledge of

content, pedagogies, and technology integration [18]. The study focused on using technology as a tool to support student learning of mathematics and science concepts [18].

North American TPACK research demonstrates several distinctive characteristics. There is strong emphasis on integration of technology into existing methods courses rather than standalone technology courses [18]. Research often addresses diverse student populations and equity considerations in technology access and integration [10]. Studies frequently employ qualitative and mixed-methods approaches to capture the complexity of TPACK development [10], [18].

Challenges and Limitations of TPACK Framework

Conceptual and Theoretical Challenges

Despite two decades of research, TPACK as a theoretical construct continues to face conceptual challenges. The boundaries between TPACK domains remain somewhat ambiguous, with researchers disagreeing about where one domain ends and another begins [1], [25]. Akyuz's factor analysis revealed that the seven-domain structure may not adequately capture the organization of TPACK knowledge, at least in mathematics education contexts [1]. This finding raises questions about whether the TPACK framework's structure is universal or varies across subject areas [1], [6]. The relationship between declarative TPACK knowledge (what teachers know) and enacted TPACK (what teachers do) remains incompletely understood [1], [16]. Research consistently demonstrates gaps between self-reported TPACK competence and performance-based measures, suggesting that knowing about TPACK does not automatically translate to effective technology integration in practice [1], [16]. This gap highlights the need for more sophisticated theoretical models that account for the transition from knowledge to action [16], [17]. The transformative versus integrative debate continues to generate discussion about the fundamental nature of TPACK [5], [25]. While the transformative view—which posits that TPACK represents a qualitatively distinct form of knowledge emerging from the dynamic interaction of technology, pedagogy, and content—has gained theoretical support, operationalizing this perspective in research and practice remains challenging [5], [25].

Methodological Limitations

TPACK research faces persistent methodological challenges that limit the strength of conclusions that can be drawn. The predominance of self-report measures, while practically advantageous, raises validity concerns [1], [16]. Pre-service teachers' self-assessments of TPACK competence often diverge from performance-based evaluations, with systematic overestimation of pedagogical knowledge domains [1]. This measurement gap complicates interpretation of research findings and limits confidence in self-report data [1], [16]. Performance-based assessment, while offering greater ecological validity, faces its own limitations [1], [16]. Lesson plan analysis, the most common performance-based approach, captures planning competence but not necessarily implementation competence [1], [16]. Observation of teaching, while more authentic, requires substantial resources and faces challenges related to observer effects and the artificiality of microteaching contexts [17]. The EnTPACK rubric represents an important methodological advance, but its application remains resource-intensive and requires trained evaluators [16]. Sample size and generalizability present additional methodological concerns. Many studies employ small, convenience samples from single institutions, limiting generalizability of findings [8], [15], [27]. While these studies provide valuable insights into TPACK development processes, their findings may not transfer to other contexts [8], [15]. Large-scale studies, while offering greater generalizability, often sacrifice depth of understanding for breadth of

coverage [1], [13]. Longitudinal research remains relatively rare, with most studies employing cross-sectional or short-term pre-post designs [6], [17]. This temporal limitation prevents understanding of long-term TPACK development trajectories and the sustainability of intervention effects [6]. Molgen et al.'s 13-week longitudinal study represents an exception, but even this timeframe may be insufficient to capture the full arc of TPACK development [6].

Contextual and Implementation Challenges

TPACK development in pre-service teacher education faces numerous contextual and implementation challenges. Technology infrastructure and resource availability significantly constrain what technologies can be integrated and how TPACK interventions can be designed [7], [17]. Research from Tanzania and Ghana demonstrates that meaningful TPACK development is possible in resource-constrained contexts, but the nature of competencies developed necessarily reflects available technologies [7], [17]. Time constraints within teacher education programs limit opportunities for sustained TPACK development [4], [8]. Pre-service teachers face competing demands from content courses, pedagogy courses, and field experiences, leaving limited time for focused technology integration work [4], [8]. This constraint necessitates efficient intervention designs that maximize TPACK development within available time [4], [17]. Mentor teacher support during field experiences significantly influences pre-service teachers' TPACK enactment, yet many mentor teachers lack strong TPACK competencies themselves [7], [17]. This creates a disconnect between what pre-service teachers learn in university courses and what they observe and are encouraged to do in field placements [7], [17]. Addressing this challenge requires professional development for mentor teachers and stronger coordination between university and field-based experiences [7], [17]. Institutional culture and policies shape opportunities for technology integration [2], [7]. Schools and districts with restrictive technology policies, limited technology access for students, or cultures that prioritize traditional instructional approaches constrain pre-service teachers' ability to enact TPACK competencies developed in teacher education programs [7], [17].

Assessment and Measurement Challenges

Assessing TPACK remains one of the most significant challenges facing the field. The construct's complexity, with seven interrelated domains, complicates measurement efforts [1], [16]. Existing instruments often struggle to distinguish between domains, with high correlations suggesting that respondents may not differentiate between, for example, TPK and TPACK [1], [13]. The context-dependency of TPACK poses additional assessment challenges [6], [14], [16]. TPACK manifests differently across subject areas, educational levels, and technological contexts, yet most assessment instruments employ generic items that may not capture domain-specific competencies [6], [14]. While domain-specific instruments address this limitation, they sacrifice comparability across contexts [6], [14], [20].

The gap between self-reported and enacted TPACK represents a fundamental validity challenge [1], [16]. Self-report instruments measure perceived competence or confidence rather than actual ability to integrate technology effectively [1]. Performance-based assessments offer greater validity but face practical constraints related to resource requirements and scoring complexity [16]. Establishing appropriate benchmarks for TPACK competence remains problematic [1], [16]. What level of TPACK should pre-service teachers achieve by program completion? How does TPACK competence relate to

teaching effectiveness and student learning outcomes? These fundamental questions lack clear answers, complicating efforts to evaluate TPACK interventions [1], [16].

Sustainability and Transfer Challenges

The sustainability of TPACK competencies developed in pre-service teacher education remains uncertain. Do pre-service teachers maintain and continue developing TPACK competencies after program completion, or do these competencies atrophy in the face of competing demands and unsupportive school contexts? Longitudinal research following pre-service teachers into their early career years is needed to address this question [6], [17]. Transfer of TPACK competencies across contexts presents another challenge. Pre-service teachers may develop TPACK competencies with specific technologies or in particular subject areas, but struggle to transfer these competencies to new technologies or different teaching contexts [4], [12]. Research has not adequately explored how to develop transferable TPACK competencies that enable teachers to adapt to evolving technologies and varied teaching situations [3], [21]. The rapid pace of technological change creates a moving target for TPACK development [3], [21]. Technologies that are current during pre-service teacher education may be obsolete by the time teachers enter the profession. This reality suggests that TPACK development should emphasize adaptable principles and learning-to-learn competencies rather than specific technological skills [3], [21]. However, research has not fully explored how to balance technology-specific competence with transferable principles [3], [21].

Research Gaps and Underexplored Areas

Several important areas remain underexplored in TPACK research on pre-service teachers. Elementary education TPACK development receives less attention than secondary education, despite the unique challenges of teaching multiple subjects and addressing diverse developmental levels [15]. Cross-disciplinary TPACK competencies, increasingly important in contemporary education, remain insufficiently studied [9], [15]. The relationship between TPACK and student learning outcomes represents a critical gap. While research demonstrates that interventions can enhance pre-service teachers' TPACK competencies, evidence linking these competencies to improved student learning remains limited [1], [8], [17]. This gap limits the field's ability to make strong claims about the ultimate value of TPACK development [1], [8].

Emerging technologies including artificial intelligence, virtual reality, and learning analytics require new forms of TPACK that have only begun to be explored [3], [21]. Research on AI integration in teacher education represents an important beginning, but much work remains to understand how TPACK frameworks must evolve to address rapidly advancing technologies [3], [21].

Future Directions and Recommendations

Future TPACK research should prioritize theoretical refinement and advancement. The field needs more sophisticated models that account for the dynamic, situated nature of TPACK and the transition from declarative knowledge to enacted competence [5], [16], [25]. Research should explore whether the seven-domain TPACK structure is universal or varies across contexts, and whether alternative organizational frameworks might better capture the complexity of technology integration knowledge [1], [6]. The transformative view of TPACK requires further theoretical development and empirical validation [5], [25]. While conceptually appealing, this perspective needs clearer operationalization to guide research and

practice [5], [25]. Research should explore the mechanisms through which integrated TPACK emerges from the interaction of technology, pedagogy, and content, and how teacher education can facilitate this emergence [5], [25]. Theoretical work should also address the relationship between TPACK and related constructs including digital literacy, digital competence, and 21st-century skills [28]. Pehlevan et al.'s finding that digital literacy predicts TPACK suggests important connections, but the nature of these relationships requires further exploration [30]. Clarifying how TPACK relates to broader frameworks of teacher knowledge and competence will strengthen the theoretical foundation of the field [28].

Connecting TPACK to Student Learning

A critical priority for future research is establishing clear connections between pre-service teachers' TPACK competencies and student learning outcomes [1], [8], [17]. While research demonstrates that interventions can enhance TPACK competencies, evidence linking these competencies to improved student learning remains limited [1], [8]. This gap limits the field's ability to make strong claims about the ultimate value of TPACK development [1], [8]. Research should employ designs that trace the pathway from TPACK interventions through pre-service teacher competencies to classroom technology integration practices and ultimately to student learning outcomes [1], [8], [17]. These complex designs require collaboration between teacher education researchers and K-12 schools, longitudinal data collection, and sophisticated analytical approaches [1], [8], [17].

Understanding which aspects of TPACK most strongly predict effective technology integration and student learning would enable more targeted intervention design [1], [16]. Research should explore whether integrated TPACK matters more than individual domains, whether certain domains are more critical than others, and how TPACK interacts with other teacher competencies to influence student learning [1], [16].

International Collaboration and Knowledge Exchange

The global nature of TPACK research creates opportunities for international collaboration and knowledge exchange [2], [9], [15]. Future research should pursue cross-national comparative studies that examine how TPACK develops across different educational systems, cultural contexts, and resource environments [2], [9], [15]. These comparisons would illuminate universal principles and contextual variations in TPACK development [2], [9], [15]. International research networks could facilitate knowledge exchange, enabling researchers to learn from diverse contexts and avoid reinventing solutions to common challenges [2], [9], [15]. Telecollaboration and virtual exchange, already demonstrated as effective for pre-service teacher TPACK development, could also support international research collaboration [15].

Research should ensure that insights from diverse contexts, including resource-constrained environments in developing countries, inform mainstream TPACK theory and practice [7], [17]. African research demonstrating effective TPACK development with limited technology infrastructure offers valuable lessons for all contexts, yet these insights remain underutilized [7], [17]. Greater attention to research from underrepresented regions would enrich the field's understanding of TPACK development [7], [17].

Conclusion

This comprehensive review of two decades of research on the TPACK framework in pre-service teacher education reveals a field that has matured significantly since the framework's conceptualization in the mid-2000s. From foundational

theoretical work establishing the importance of integrated technological, pedagogical, and content knowledge, through methodological advances in TPACK assessment, to sophisticated intervention studies demonstrating effective approaches for TPACK development, the field has made substantial progress in understanding and supporting pre-service teachers' technology integration competencies.

Several key findings emerge from this synthesis of 30 highly relevant studies spanning diverse geographic regions, subject areas, and educational contexts. First, design-based learning approaches and collaborative design teams have emerged as the most effective intervention strategies for developing pre-service teachers' TPACK competencies [2], [4], [7], [9], [27]. These approaches situate TPACK development in authentic problem-solving contexts, require active integration of technology, pedagogy, and content, and provide opportunities for iteration and refinement [4], [7], [9]. Second, assessment methods have evolved from predominantly self-report surveys to more sophisticated mixed-methods approaches combining performance-based evaluations with reflective instruments [1], [8], [16], [17]. This evolution reflects growing recognition that TPACK is a complex, context-dependent construct that cannot be adequately captured through single-method assessments [1], [16]. The development of domain-specific instruments and performance-based rubrics like the EnTPACK represents significant methodological advances [6], [16].

Third, subject-specific applications demonstrate that TPACK manifests differently across disciplines, with mathematics emphasizing technologies for representation and exploration, science focusing on inquiry support and visualization, and language education prioritizing communication and interaction [1], [4], [14], [25]. This disciplinary variation suggests that teacher education programs should provide subject-specific TPACK development experiences rather than relying solely on generic technology integration courses [4], [6], [14]. Fourth, geographic analysis reveals both universal patterns and important contextual variations in TPACK development [2], [7], [9], [15], [17]. While design-based learning and collaborative approaches prove effective across contexts, resource availability, cultural values, and educational traditions shape how TPACK is conceptualized, developed, and assessed [7], [9], [17]. Research from resource-constrained contexts in Africa demonstrates that meaningful TPACK development is possible even with limited technological infrastructure, challenging assumptions that technology integration requires abundant resources [7], [17]. Fifth, the gap between declarative TPACK knowledge and enacted competence represents a persistent challenge requiring continued attention [1], [16]. Pre-service teachers may articulate sophisticated understanding of TPACK principles yet struggle to enact this knowledge in authentic teaching contexts [1], [16]. This gap underscores the importance of practice-based experiences, microteaching, and authentic field placements in TPACK development [7], [17], [26].

References

[1]. Akyuz, D. (2018). Measuring technological pedagogical content knowledge (TPACK) through performance assessment. *Computers & Education*, 125, 212–225. https://doi.org/10.1016/j.compedu.2018.06.012

[2]. Voogt, J., Fisser, P., Pareja Roblin, N., Tondeur, J., & van Braak, J. (2010). Strategies for teacher professional development on technological pedagogical content knowledge (TPACK). *Educational Technology Research and Development*, 61(2), 1–18.

[3]. Kim, J. (2024). Development of a TPACK educational program to enhance pre-service teachers' teaching expertise in artificial intelligence convergence education. *International Journal on Advanced Science, Engineering and Information Technology*, 14(1), 1–10. https://doi.org/10.18517/ijaseit.14.1.19552

[4]. Agyei, D. D., Voogt, J., & van den Akker, J. (2015). Pre-service teachers' TPACK competencies for spreadsheet integration: Insights from a mathematics-specific instructional technology course. *Technology, Pedagogy and Education*, 24(5), 605–625. https://doi.org/10.1080/1475939X.2015.1096822

[5]. Horváth, L., & Szűcs, A. (2023). Technology implementation in pre-service science teacher education based on the transformative view of TPACK: Effects on pre-service teachers' TPACK, behavioral orientations, and actions in practice. *Education Sciences*, 13(7), Article 732. https://doi.org/10.3390/educsci13070732

[6]. Molgen, J., Schaal, S., & Huwer, J. (2024). Development and application of a domain-specific TPACK questionnaire: Findings from a longitudinal study on teaching human biology using digital tools. *Journal of Science Education and Technology*, 33(2), 1–15. https://doi.org/10.1007/s10956-024-10108-w

[7]. Alayyar, G. M. (2011). *Developing pre-service teacher competencies for ICT integration through design teams* (Doctoral dissertation, Open University of the Netherlands). https://doi.org/10.3990/1.9789036532341

[8]. Bwalya, A., Chisanga, C., & Mwanza, C. (2024). Developing pre-service biology teachers' technological pedagogical content knowledge through a TPACK-based course. *European Journal of Educational Research*, 13(1), 263–276. https://doi.org/10.12973/eu-jer.13.1.263

[9]. Chai, C. S., Jong, M. S. Y., Yin, H. B., Chen, M., & Zhou, W. (2020). Indonesian science, mathematics, and engineering preservice teachers' experiences in STEM-TPACK design-based learning. *Sustainability*, 12(21), Article 9050.
https://doi.org/10.3390/su12219050

[10]. Habowski, T., Rębisz, S., & Wawrzyniak, Z. (2014). Pre-service teachers' development of technological pedagogical content knowledge (TPACK) in the context of a secondary science teacher education program. *Journal of Technology and Teacher Education*, 22(4), 471–495.

[11]. Susanti, A., Suryani, N., & Setiawan, B. (2024). Examining teacher candidates' TPACK competences: Evidence from four teacher education programs. *Journal of Higher Education Theory and Practice*, 24(9), 1–15.
https://doi.org/10.33423/jhetp.v24i9.7219

[12]. Goktas, Y., Yildirim, Z., & Yildirim, S. (2021). Introducing interactive whiteboards to preservice mathematics teachers: An evaluation using the TPACK framework. *Cypriot Journal of Educational Sciences*, 16(2), 620–635.
https://doi.org/10.18844/cjes.v16i2.5619

[13]. Alrwaished, N., Alkandari, A., & Alhashem, F. (2017). Exploring in- and pre-service science and mathematics teachers' technological, pedagogical, and content knowledge (TPACK): What next? *Eurasia Journal of Mathematics, Science and Technology Education*, 13(9), 6113–6131. https://doi.org/10.12973/eurasia.2017.01053a

[14]. Ali, M., Shahzad, A., & Alghamdi, A. (2023). Integrating TPACK in pre-service teachers' EFL course: Impacts on perception, knowledge, and practices. *Australian Journal of Teacher Education*, 48(4), 1–18.
https://doi.org/10.14221/1835-517X.6089

[15]. Bueno-Alastuey, M. C., Villarreal, I., & García Esteban, S. (2018). Can telecollaboration contribute to the TPACK development of pre-service teachers? *Technology, Pedagogy and Education*, 27(3), 367–380. https://doi.org/10.1080/1475939X.2018.1471000

[16]. Aumann, S., Schaal, S., & Thyssen, C. (2023). The EnTPACK rubric: Development, validation, and reliability of an instrument for measuring pre-service science teachers' enacted TPACK. *Frontiers in Education*, 8, Article 1190152. https://doi.org/10.3389/feduc.2023.1190152

[17]. Kafyulilo, A., Fisser, P., & Voogt, J. (2015). ICT use in science and mathematics teacher education in Tanzania: Developing technological pedagogical content knowledge. *Australasian Journal of Educational Technology*, 31(4), 381–399. https://doi.org/10.14742/ajet.1240

[18]. Popejoy, K., Lee, H., & Choi, J. (2012). Leveraging technology to develop pre-service teachers' TPACK in mathematics and science methods courses. In *Teacher education programs and online learning tools* (pp. 520–541). IGI Global. https://doi.org/10.4018/978-1-61350-492-5.ch027

[19]. Chien, Y. C., Hsu, C. Y., & Yeh, Y. F. (2015). Developing preservice teachers' sensitivity to the interplay between subject matter, pedagogy, and ICTs. In *New media, knowledge practices and multiliteracies* (pp. 87–104). Springer. https://doi.org/10.1007/978-981-287-441-2_6

[20]. Kim, J. (2024). Development and application of the HC-TPACK model: A focus on integrating English education with technology utilization and human competency development. *English Language and Literature Education*, 30(1), 25–49. https://doi.org/10.35828/etak.2024.30.1.25

[21]. Choi, I. C., Lim, H., & Kim, J. (2025). Integrating chatbot technology in language teacher education: A TPACK-based analysis of pre-service teachers' professional development. *Language Learning & Technology*, 29(1), 1–20. https://doi.org/10.64152/10125/73621

[22]. Backfisch, I., Lachner, A., & Scheiter, K. (2024). Collaborative design practices in pre-service teacher education for technological pedagogical content knowledge (TPACK): Group composition matters. *Science of Teaching*, 52(1), 1–23. https://doi.org/10.1007/s42010-023-00192-z

[23]. Aktaş, I., Tatar, E., & Yılmaz, Z. (2021). Assessing the performance of Turkish science pre-service teachers in a TPACK-practical course. *Education and Information Technologies*, 26, 5701–5725. https://doi.org/10.1007/s10639-021-10757-z

[24]. Bueno, A., Perry, B., & Chick, H. (2023). Redesigning mathematics preservice teachers' preparation for teaching with technology: A qualitative cross-case analysis using TPACK lenses. *Computers & Education*, 194, Article 104895. https://doi.org/10.1016/j.compedu.2023.104895

[25]. Jang, S. J., Chen, K. C., & Chen, Y. C. (2010). From PCK to TPACK: Developing a transformative model for pre-service science teachers. *Journal of Science Education and Technology*, 19(6), 553–564. https://doi.org/10.1007/s10956-010-9222-y

[26]. Alayyar, G. M., Fisser, P., & Voogt, J. (2012). Developing technological pedagogical content knowledge in pre-service science teachers: Support from blended learning. *Australasian Journal of Educational Technology*, 28(8), 1298–1316. https://doi.org/10.14742/ajet.773

[27]. Aşık, A., Köse, S., & Güneş, G. (2018). Investigating learning technology by design approach in pre-service language teacher education: Collaborative and reflective experiences. *Journal of Qualitative Research in Education*, 6(1), 1–30. https://doi.org/10.14689/ISSN.2148-2624.1.6C1S2M

[28]. Pehlevan, A., Yılmaz, E., & Kırmızı, Ö. (2024). Investigating the relationship between digital literacy and TPACK levels of pre-service English teachers. *Dil Journal of Education and Research*, 10(1), 1–18. https://doi.org/10.31464/jlere.1432879

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