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RESEARCH ARTICLE

Improving the Digital-Pedagogical Competencies of Mathematics Teachers on The Basis of The TPACK Model

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PAGE: 38-42

Abstract

This article examines the development of mathematics teachers' digital-pedagogical competencies based on the Technological Pedagogical Content Knowledge (TPACK) framework. It analyzes the key components of TPACK and their application in technology-enhanced mathematics instruction. Based on a systematic review of recent empirical and theoretical studies, the article identifies challenges in integrating technological, pedagogical, and content knowledge and highlights the need to strengthen teachers' technological pedagogical competencies. The study proposes a practice-oriented model that includes competency assessment, collaborative professional development, technology-integrated lesson design, and reflective practice. The findings suggest that sustainable improvement of mathematics teachers' digital-pedagogical competence requires systematic institutional support and continuous professional development within the TPACK framework.

KEYWORDS

TPACK; digital-pedagogical competence; mathematics teacher; technology integration; professional development; DigCompEdu; teacher education.

INTRODUCTION

The digital transformation of education has placed increasing demands on mathematics teachers to integrate technology purposefully into their instructional practice, rather than treating digital tools as auxiliary additions to traditional teaching methods. Mathematics, more than many other school subjects, depends on the ability to represent abstract structures — functions, geometric transformations, statistical distributions — in dynamic, manipulable forms, which digital technologies are uniquely capable of supporting. Yet the presence of technology in a mathematics classroom does not, by itself, guarantee pedagogical improvement; its effectiveness depends on the teacher's capacity to integrate technological tools with sound pedagogical strategy and deep disciplinary content knowledge.

The Technological Pedagogical Content Knowledge (TPACK) framework, introduced by Mishra and Koehler (2006) as an extension of Shulman's (1986) construct of pedagogical content knowledge, offers the most widely adopted theoretical account of this integrated capacity. TPACK conceptualizes effective technology-supported teaching not as the simple addition of a technological skill set to existing pedagogical and content knowledge, but as a qualitatively distinct form of knowledge that emerges at the intersection of all three domains. For mathematics education specifically, Niess (2005, 2013) extended this framework to describe how technological pedagogical content knowledge develops specifically in relation to mathematical topics, arguing that teachers must learn to see particular technologies through the lens of the mathematical concepts they are meant to illuminate.

Despite the framework's wide theoretical acceptance, empirical studies consistently report that mathematics teachers' digital-pedagogical competence remains uneven, with pronounced weaknesses in the technological dimensions of TPACK relative to disciplinary content knowledge. This article addresses three questions: (1) how is the TPACK model structurally suited to describing mathematics teachers' digital-pedagogical competence; (2) what does recent empirical research reveal about the current state and gaps in this competence; and (3) what practice-oriented measures, grounded in the TPACK framework, can most effectively improve it.

TPACK is conventionally represented as three overlapping circles of knowledge — Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK) — whose pairwise intersections produce Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK), with the central intersection of all three constituting TPACK proper (Koehler & Mishra, 2008; Mishra, 2019). For mathematics teachers, CK refers to command of mathematical concepts, structures, and reasoning; PK refers to general instructional strategies such as questioning, scaffolding, and formative assessment; and TK refers to operational familiarity with digital tools ranging from dynamic geometry software to online assessment platforms. The intersections are where the framework's explanatory power becomes most evident for mathematics instruction specifically: TCK captures a teacher's understanding of how a given technology — for example, a graphing calculator or computer algebra system — alters the representation of a mathematical object, while TPK captures the pedagogical strategies suited to technology-mediated instruction independent of specific content, such as managing collaborative problem-solving in a digital environment.

Building on the general TPACK framework, Niess (2005, 2013) proposed a mathematics-specific development model describing how pre-service and in-service teachers progress through recognizable stages — from recognizing technology's relevance to mathematics teaching, through accepting and adapting it for instructional use, to exploring and finally advancing its integration in ways that reshape their instructional practice. A related case study applying and extending this model among pre-service mathematics teachers found that lesson-plan analysis, micro-teaching, and structured interviews were effective means of enriching the descriptors of each developmental stage, providing teacher educators with a more granular basis for diagnosing where individual trainees stand within the model (Education and Information Technologies, cited in the reviewed literature). The CITE Journal's Mathematics Teacher TPACK Standards and Development Model similarly frames TPACK as the cumulative package required for designing instruction that supports mathematical thinking with digital technologies, emphasizing that the framework must remain dynamic as technologies, learners, and classroom contexts continue to evolve.

Recent conceptual work situates TPACK alongside complementary frameworks to describe a more complete professional development pathway for mathematics teachers. One proposed framework integrates TPACK, the Digital Competence Framework for Educators (DigCompEdu, developed by Redecker in 2017), and the concept of Professional Learning Communities (PLC) to describe mathematics teacher development in three interlocking layers: core competencies integrating disciplinary knowledge, pedagogy, and technology; experiential and collaborative learning processes; and supportive institutional conditions shaped by digital transformation and school culture. In this synthesis, TPACK describes the knowledge base mathematics teachers require, DigCompEdu clarifies how digital competence manifests specifically in designing, organizing, and assessing learning activities, and PLC provides the collaborative professional setting in which teachers plan lessons together, examine classroom evidence, and iteratively adjust practice.

A quantitative, cross-sectional study of 71 in-service secondary mathematics teachers, using a validated 21-item TPACK questionnaire, found a moderate overall level of digital teaching competence with a clear asymmetric hierarchy across dimensions: Content Knowledge received the highest mean score, while Technological Content Knowledge received the lowest. The same study identified specific weaknesses in digital assessment practices and in the pedagogically grounded use of artificial intelligence tools, concluding that teachers demonstrate substantially greater confidence in their disciplinary domain than in the pedagogical integration of digital technologies. This asymmetry is consistent with the broader TPACK literature, which repeatedly finds that content and pedagogical knowledge, cultivated over years of subject-specific training, mature well ahead of the more recently emerging technological dimensions of the framework.

A systematic review of mathematics-focused TPACK studies conducted under PRISMA guidelines identified recurring implementation barriers, including limited access to digital resources, wide variation in teachers' baseline TPACK proficiency, and a persistent shortage of professional development specifically tailored to mathematics content rather than generic digital-skills training. The same review noted the absence of standardized TPACK assessment instruments as a further obstacle, complicating efforts to measure teachers' competencies consistently and track their professional growth over time. These findings echo evidence from AI-augmented extensions of TPACK research, which similarly report a gap between the importance teachers assign to technology-related competencies and their self-reported level of actual development, particularly regarding artificial intelligence tools in mathematics instruction.

Where TPACK-based professional development has been implemented, studies report measurable gains in teachers' confidence and instructional competence. Research reviewed in recent mathematics education scholarship indicates that structured TPACK training — including workshops on specific software tools, collaborative lesson-planning sessions, and structured reflection on technology use — improves teachers' confidence and translates into more effective instructional practices, including greater use of dynamic visualizations and interactive simulations to support conceptual understanding. Related classroom-level evidence, for instance concerning interactive whiteboards, shows that technology-related motivational and participation gains are strongest precisely when teachers possess well-developed TPACK and combine game-based, multimedia, and visual features with adequate institutional training and infrastructure support — reinforcing the conclusion that technological provision alone is insufficient without corresponding teacher competence.

Building on the theoretical and empirical synthesis above, this article proposes a four-stage, TPACK-grounded model for improving mathematics teachers' digital-pedagogical competence, intended for implementation within university mathematics methods courses and school-based professional development programs alike.

First, diagnostic assessment. Prior to any intervention, teachers' current TPACK profile should be assessed using validated instruments that separately measure content, pedagogical, and technological knowledge, together with their pairwise intersections, so that professional development can be targeted at the specific dimensions — most commonly TCK and TPK — where the largest gaps are found.

Second, situated collaborative training. Rather than generic digital-literacy workshops, training should be organized around Professional Learning Communities in which mathematics teachers jointly plan technology-integrated lessons for specific curricular topics, examine one another's classroom evidence, and receive structured peer and expert feedback, consistent with the PLC-TPACK-DigCompEdu synthesis described above.

Third, technology-integrated lesson design as applied practice. Teachers should design, teach, and iteratively refine lessons that deliberately target TCK (representing a specific mathematical concept through a specific technology, such as dynamic geometry software for transformations) and TPK (managing collaborative, technology-mediated problem-solving), rather than treating technology use as a generic add-on to an otherwise unchanged lesson plan.

Fourth, reflective evaluation and iteration. Consistent with Niess's staged development model, teachers should periodically revisit their diagnostic profile to assess progression from initial recognition and acceptance of a technology toward its exploratory and advanced integration, allowing professional development to be adjusted as competence matures rather than delivered as a single, undifferentiated intervention.

This model is deliberately cyclical rather than linear: as new technologies — most recently generative artificial intelligence tools — enter mathematics classrooms, the diagnostic-training-practice-reflection cycle must be repeated, since TPACK is, by design, a dynamic rather than a fixed competence.

The evidence reviewed in this article converges on a consistent conclusion: mathematics teachers' digital-pedagogical competence is not limited primarily by access to technology or by disciplinary knowledge, but by the specifically technological dimensions of TPACK — TCK and TPK — that require deliberate, mathematics-specific cultivation. This has direct implications for teacher education policy. Pre-service mathematics teacher education programs should embed TPACK development explicitly within mathematics methods courses rather than delegating digital competence to generic, subject-neutral educational technology courses, since evidence indicates that mathematics-specific technological content knowledge does not transfer automatically from general digital literacy. In-service professional development, correspondingly, should move away from one-off technical training sessions toward sustained, collaborative, PLC-based formats that allow teachers to practice technology integration around real curricular content over time.

A further implication concerns assessment. The absence of standardized TPACK assessment instruments identified in the literature constrains institutions' ability to track competence development systematically. Adopting or adapting validated TPACK questionnaires, of the kind used in the cross-sectional studies reviewed here, would allow teacher education institutions and ministries of education to establish baseline profiles, monitor progress, and target resources toward the dimensions of competence — most often technological content and technological pedagogical knowledge — where mathematics teachers demonstrably need the most support.

This article has examined the TPACK model as a theoretical and practical basis for improving mathematics teachers' digital-pedagogical competencies. The reviewed literature demonstrates that TPACK remains the most robust framework for conceptualizing the integrated knowledge mathematics teachers require to use digital technologies purposefully, but also reveals a persistent and well-documented asymmetry in which technological content and technological pedagogical knowledge lag behind disciplinary content knowledge. Addressing this asymmetry requires more than expanded access to digital tools: it requires diagnostic assessment, mathematics-specific and collaborative professional development structured around Professional Learning Communities, deliberate technology-integrated lesson design, and cyclical reflective evaluation aligned with staged models of TPACK development. Future research should prioritize the development and validation of standardized, mathematics-specific TPACK assessment instruments and longitudinal studies tracing how TPACK-based professional development translates into measurable improvements in classroom practice and student mathematical achievement, including in educational contexts, such as Central Asia, that remain underrepresented in the current empirical literature.

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