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A Theoretical Framework for Integrating Artificial Intelligence in Teaching Based on the TPACK Model: A New Approach and Implications for Developing Teacher Competence

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ABSTRACT: The rapid development of artificial intelligence in recent years has brought about significant changes in the field of education, particularly in instructional design, the organization of teaching activities, and assessment. Given the growing need for innovation in teaching methods and the development of teacher competencies in the context of digital education, the establishment of a systematic and scientific theoretical framework for integrating AI into teaching has become increasingly urgent.

This paper aims to analyze the role of artificial intelligence in modern education, clarify the theoretical foundations of the Technological Pedagogical Content Knowledge (TPACK) model, and examine its recent extensions in response to emerging technologies. On this basis, the study proposes a theoretical framework for integrating artificial intelligence into teaching grounded in the TPACK model, emphasizing the interaction among content knowledge, pedagogical knowledge, technological knowledge, and AI-specific competencies.

The proposed framework highlights not only the role of AI as a teaching tool but also its function as a catalyst for pedagogical innovation, personalized learning, and enhanced teaching effectiveness. Furthermore, the paper discusses key implications for teacher competency development, including the cultivation of digital pedagogical thinking; the capacity to design teaching activities supported by AI applications; the ability to assess learning processes in AI-enhanced environments.

The findings contribute to strengthening the theoretical foundation for AI integration in teaching through the TPACK approach, while also offering practical directions for teacher training and professional development in the context of ongoing digital transformation in education.

KEYWORDS: Artificial intelligence in education , TPACK model , AI-TPACK, Teacher competence , Digital transformation in education

INTRODUCTION

The rapid development of artificial intelligence (AI) is bringing about profound changes across multiple fields, with education being among the sectors most directly and rapidly affected. AI tools and platforms have created new opportunities for teaching and learning, ranging from the personalization of learning processes to supporting assessment, instructional design, and learning analytics. In this context, the need to innovate teacher competencies has become increasingly urgent, as the effective application of AI in teaching requires not only technological knowledge but also the ability to integrate technology with content knowledge and pedagogical knowledge in a coherent and scientifically grounded manner.

Although a growing body of research has examined the application of AI in classroom settings, much of this work continues to adopt fragmented and isolated approaches. As a result, the central issue, how to integrate AI into teaching strategies in ways that generate genuine educational value, remains insufficiently addressed. The absence of a robust theoretical framework for AI integration in teaching often leads to inconsistent implementation, an overemphasis on technology, or a disconnect between content knowledge and pedagogical knowledge.

Within this context, the Technological Pedagogical Content Knowledge (TPACK) model, widely regarded as a foundational framework for technology-integrated teaching, offers a useful lens for explaining how AI can be effectively incorporated into educational practice. However, the traditional TPACK model does not fully capture the complexity of AI-driven teaching environments, thereby necessitating the expansion and reconfiguration of its knowledge components to accommodate the distinctive characteristics of artificial intelligence technologies.

Accordingly, this paper aims to develop a theoretical framework for integrating AI into teaching based on the TPACK model, with the goal of clarifying the knowledge structure required of teachers when applying AI in instructional activities. Building on this framework, the paper proposes a novel approach to AI integration in teaching and discusses its implications for teacher competency development in the AI era. It is expected that this study will provide a solid theoretical foundation for pedagogical innovation, as well as for teacher education and professional development, within the context of the ongoing digital transformation of education.

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THEORETICAL FRAMEWORK

Artificial Intelligence in Education

AI is driving significant transformations in education, as evidenced by the wide range of technological applications supporting teaching and educational management. AI has evolved from traditional computer-based technologies to intelligent systems such as robots, online platforms, and chatbots, enabling instructors to perform tasks related to management, grading, and the personalization of learning content more effectively (Chen, Chen, & Lin, 2020). Beyond improving the operation of educational systems, AI also directly influences the learning process through its capacity to enhance student engagement and improve academic performance. Recent studies support the claim that AI can positively affect learning outcomes when it is appropriately integrated into educational practice.

Sasikala and Ravichandran (2024) demonstrate that AI facilitates personalized learning, increases learner interaction, and supports learning progression, while also drawing attention to challenges related to privacy, ethics, and the reliability of algorithms. In the context of adaptive learning, Rekha et al. (2024) describes how AI systems track learning data in real time and dynamically adjust content and difficulty levels to align with individual learner progress, thereby enhancing engagement and learning outcomes.

The application of AI in educational measurement and evaluation has likewise attracted considerable scholarly attention. Yaneva and von Davier (2023) highlight the role of natural language processing (NLP) in automated scoring, feedback analysis, and question generation, while emphasizing the importance of ensuring fairness and validity in AI-based assessment practices. From the perspective of teacher professional development, Brandão, Pedro, and Zagalo (2024) argue that teachers need to be equipped with foundational AI knowledge, skills in using generative AI (GenAI), and the capacity to address ethical issues in order to guide students in the safe and responsible use of technology.

In addition, studies by Lampou (2023) and Walter (2024) indicate that AI contributes to pedagogical innovation by supporting lesson design, facilitating instruction for students with special educational needs, and enabling the provision of real-time feedback to improve teaching quality. At the theoretical level, Baker (2000) emphasizes the role of educational models in shaping the design of learning systems and stresses the need for close alignment among technology, curriculum, and educational agents. Empirical research by Grassini (2023), Zhu et al. (2025), and Létourneau et al. (2025) further provides evidence of the impact of AI and generative AI on learning outcomes, although the magnitude of this impact varies depending on learners' skills, implementation strategies, and educational contexts.

Overall, the literature indicates that AI offers substantial opportunities for innovation in teaching and teacher professional development. Artificial intelligence has become a central component of the digital transformation of education, driven by technologies such as machine learning, deep learning, and natural language processing that enable systems to simulate aspects of human cognition. Current applications of AI in teaching range from the design of digital learning materials and the assessment of learner competencies to learning analytics and the personalization of learning experiences. However, the literature consistently emphasizes that for AI to deliver genuine educational value, it must be integrated into pedagogical strategies rather than used merely as a technological add-on. This, in turn, requires teachers to understand not only how AI technology's function but also how to strategically leverage them in lesson design, the organization of learning activities, instructional decision-making, and the evaluation of student learning outcomes.

The TPACK Model and Recent Extensions

The Technological Pedagogical Content Knowledge (TPACK) framework was developed from Shulman's concept of Pedagogical Content Knowledge (PCK) by incorporating a technological dimension to address the demands of educational innovation in the digital era (Mishra & Koehler, 2006; Schmidt et al., 2009). The TPACK model conceptualizes teachers' professional knowledge as the integration of three core components: technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK) (Koehler et al., 2011; Mishra et al., 2010), The intersections among these components give rise to pedagogical content knowledge (PCK), technological content knowledge (TCK), and technological pedagogical knowledge (TPK), which together form the comprehensive TPACK framework representing the knowledge base required for effective technology-integrated teaching.

TPACK emphasizes not only teachers' familiarity with educational technologies but also their ability to meaningfully integrate technology into pedagogical strategies and subject matter instruction. This integration requires an understanding of how technological tools can support the representation of concepts, enhance pedagogical approaches, address learners' difficulties, and align with students' prior knowledge and cognitive processes. Accordingly, TPACK encompasses knowledge of learning theories and the pedagogical use of technology to design instructional activities that are responsive to learners' needs and abilities (Meredit et al., 2017).

A substantial body of empirical research has demonstrated that the development of TPACK can enhance teachers' instructional design skills, promote student interaction, and improve learning effectiveness across various subject areas, including mathematics, science, foreign languages, and early childhood education (Santos & Castro, 2020; Jammeh et al., 2023; Aldalalah et al., 2025). Effective TPACK development is commonly associated with sustained professional development initiatives, hands-on practice in technology-integrated lesson design, collaborative learning communities, and ongoing formative feedback (Tondeur et al., 2019; Anwar et al., 2025).

Despite its strengths, the implementation of TPACK faces persistent challenges, such as limited technological infrastructure, insufficient professional training, time constraints, and linguistic and cultural barriers, particularly in remote or multicultural educational settings (Vijayatheepan, 2025; Priyanda et al., 2025). In response to the rapid advancement of artificial intelligence (AI), recent research has sought to extend the TPACK framework to better reflect the realities of AI-enhanced teaching environments. Models such as AI-TPACK and Intelligent-TPACK explicitly incorporate AI-related technological knowledge and emphasize teachers' competencies in ethical judgment, critical evaluation, and responsible use of AI tools in education (Celik, 2022; Ning et al., 2024; Oved & Alt, 2025).

Longitudinal reviews and bibliometric analyses indicate that since its introduction, TPACK has become one of the most influential theoretical frameworks for technology integration in education, with widespread application across disciplines such as mathematics, language education, health sciences, and the humanities (Schmidt et al., 2009; Irwanto, 2021; Zou et al., 2022). The volume of TPACK-related research has increased steadily, reflecting its continued relevance in an era of digital transformation (Prasetya & Irwanto, 2025). Recent extensions of the model have

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further incorporated contextual knowledge (XK), recognizing the significant influence of institutional, cultural, and curricular contexts on the effectiveness of technology integration, particularly in mathematics education (Li & Li, 2024).

At the same time, systematic reviews have identified several theoretical and methodological limitations of the TPACK framework, including challenges in measuring its components, conceptual overlap among knowledge domains, and a lack of long-term empirical studies examining its direct impact on student learning outcomes (Willermark, 2018; Karaduman & Akman, 2024). Nevertheless, TPACK continues to serve as a valuable foundation for the design of teacher education and professional development programs, especially when combined with collaborative models such as Lesson Study (Jiménez Sierra et al., 2023).

Overall, the integration of technology into teaching necessitates the intersection of three fundamental knowledge domains technology, pedagogy, and content. Despite ongoing debates and extensions, the TPACK framework remains a robust and widely adopted theoretical platform for supporting effective, context-sensitive, and innovative teaching practices in contemporary education.

Research Gaps on AI Integration in Teaching According to the TPACK Model

The integration of artificial intelligence into education presents substantial theoretical and practical challenges for the TPACK framework. Although recent studies have proposed extended models such as AI-TPACK, several critical research gaps remain unresolved.

First, existing theoretical frameworks tend to enumerate the required knowledge components such as AI-related technological knowledge, pedagogical knowledge, content knowledge, and ethical competence without adequately explicating the intrinsic relationships among these components or the mechanisms through which they interact in teaching practice. In addition, the measurement and evaluation of teachers' AI-TPACK competencies lack standardized instruments and widely accepted indicators, and the reliability and practical applicability of existing tools have yet to be sufficiently validated (Ning et al., 2024).

Second, most empirical studies have concentrated on teachers' cognitive, attitudinal, or technological competencies, while comparatively little attention has been paid to pedagogical integration, content-related decision-making, and, in particular, ethical competence in the use of AI. Many teachers continue to face difficulties in distinguishing between productive pedagogical support provided by AI and the risks of over-reliance on technology. Moreover, limited awareness of issues such as algorithmic bias, data security, and privacy remains a persistent concern (Celik, 2022; Feldman-Maggor et al., 2024).

Third, research on teacher professional development within the AI-TPACK framework remains limited in terms of scale, duration, and contextual diversity. Existing training programs often focus primarily on introducing AI tools rather than fostering teachers' capacities to integrate AI into lesson design, instructional decision-making, and student assessment. Furthermore, there is a notable lack of longitudinal studies examining the sustained impact of AI-TPACK-based professional development on teaching practices and student learning outcomes (Sun et al., 2022; Zulianti et al., 2024).

Finally, contextual factors including regional disparities, infrastructural conditions, policy support, and teachers' readiness to adopt AI have not been sufficiently addressed in current AI-TPACK research. This omission contributes to a persistent gap between theoretical models and classroom implementation, particularly in under-resourced or rural educational settings (Castro et al., 2025; Liu et al., 2025).

Overall, while research on AI in education is expanding rapidly, much of the existing literature continues to emphasize tool-based applications rather than elucidating the pedagogical mechanisms through which AI is integrated into teaching. Studies employing the TPACK framework frequently retain the traditional CK–PK–TK structure without clearly explaining how AI reshapes the nature and interaction of these knowledge domains. Moreover, although many studies highlight the potential benefits of AI for teaching, they often fail to articulate a coherent developmental pathway for enhancing teachers' professional competencies in AI-supported instruction. The most significant gap, therefore, lies in the absence of a comprehensive theoretical framework that systematically connects AI with the core components of TPACK and clarifies the implications of this integration for teacher professional competence. Addressing this gap necessitates the development and articulation of an AI-integrated theoretical framework grounded in TPACK, capable of clearly defining the knowledge structure required of teachers when applying AI in educational practice.

Theoretical Framework for Integrating AI into Teaching Based on the TPACK Model

Artificial Intelligence–Technological Pedagogical Content Knowledge (AI–TPACK) Framework

The theoretical framework proposed in this study aims to clarify the knowledge structure required of teachers when integrating artificial intelligence (AI) into teaching, building upon the foundational principles of the TPACK model. While TPACK emphasizes the intersection of content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK), the emergence of AI necessitates the expansion and reconceptualization of each knowledge component to reflect the distinctive characteristics of intelligent technologies capable of data analysis, learner interaction, and participation in the knowledge construction process. Consequently, restructuring TPACK toward AI integration is essential for strengthening teachers' instructional capacity in the era of artificial intelligence.

AI-Related Technological Knowledge (AI–TK)

Teachers' technological knowledge in AI-enhanced educational environments extends beyond the operational use of digital tools to encompass an understanding of the principles, capabilities, limitations, and ethical implications of AI technologies. AI–TK requires teachers to comprehend how AI supports learning analytics, personalizes instructional activities, provides real-time feedback, automates assessment processes, and facilitates digital classroom management. This component emphasizes teachers' responsibility to critically select, supervise, and regulate AI systems, rather than relying unreflectively on automated technologies.

Pedagogical Knowledge in an AI Environment (AI–PK)

In AI-integrated teaching contexts, pedagogical knowledge must be adapted to semi-automated learning environments. AI–PK reflects teachers' capacity to design and implement learning activities in which AI plays a supportive role in fostering learners' cognitive development, skills, and dispositions, while ensuring ethical and responsible technology use. Beyond organizing AI-supported learning tasks, teachers are expected to guide learners in interacting with AI systems critically, safely, and effectively, thereby enhancing instructional quality and learning outcomes.

AI-Supported Content Knowledge (AI–CK)

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AI-supported content knowledge extends beyond mastery of subject matter to include the ways in which content is modeled, represented, and transformed into meaningful learning tasks through AI technologies. AI–CK highlights teachers' ability to leverage AI to expand content representation, simulate real-world phenomena, and efficiently construct learning scenarios that would otherwise require significant time, resources, or cost. This component also entails teachers' professional judgment in determining which aspects of subject content can be effectively supported by AI and which require direct human mediation.

AI-Integrated Pedagogical Content Knowledge (AI–PCK)

AI–PCK represents the integration of AI–CK and AI–PK, reflecting teachers' ability to select and apply pedagogical strategies that effectively deliver subject content with AI support. This knowledge component underscores teachers' capacity to design AI-enhanced learning activities that promote meaningful knowledge acquisition and application, while ensuring that learners engage with the underlying conceptual foundations rather than merely accepting AI-generated outputs.

AI-Related Technological Content Knowledge (AI–TCK)

AI–TCK refers to teachers' ability to select and apply AI technologies to design, simulate, and organize subject content in ways that surpass the capabilities of conventional digital tools. This includes using AI to model complex phenomena that would be time-consuming, labor-intensive, or costly to reproduce manually; analyze discipline-specific data; and create personalized learning materials aligned with learners' cognitive characteristics and learning pace.

AI-Related Technological Pedagogical Knowledge (AI–TPK)

AI–TPK reflects teachers' capacity to integrate AI into teaching strategies, instructional methods, and organizational forms of teaching. This component requires teachers to evaluate and select appropriate AI platforms in relation to specific pedagogical goals, learning contexts, and instructional scenarios. AI–TPK emphasizes that AI contributes educational value only when embedded within sound pedagogical reasoning, rather than being used as an isolated technological solution for discrete instructional tasks.

Artificial Intelligence–Technological Pedagogical Content Knowledge (AI–TPACK)

AI–TPACK emerges from the dynamic intersection of three core knowledge domains: AI-related technological knowledge (AI–TK), pedagogical knowledge in AI-enhanced environments (AI–PK), and AI-supported content knowledge (AI–CK). This integrated knowledge structure enables teachers not only to understand how AI technology's function but also to apply them meaningfully and responsibly within teaching practice. Unlike the original TPACK framework, which focuses on the general integration of digital technologies, AI–TPACK emphasizes the distinctive affordances of artificial intelligence such as data-driven analysis, adaptive interaction, and generative capabilities that fundamentally reshape how teachers conceptualize and enact technological, pedagogical, and content knowledge. As a result, AI–TPACK constitutes a reconfigured knowledge framework aligned with the demands of AI-driven educational environments.

The Significance of the AI-TPACK Theoretical Framework for Teaching

The proposed AI-TPACK theoretical framework provides a holistic perspective on the role of artificial intelligence in teaching by positioning AI not as an auxiliary or add-on component, but as an integral element of teachers' professional knowledge systems. This framework enables the systematic identification of the competency's teachers need to develop, clarifies how AI can be meaningfully integrated into instructional strategies, and supports the assessment of learners' progress within technology-enhanced learning environments. Consequently, the AI-TPACK framework serves as a robust theoretical foundation for pedagogical innovation and for the advancement of teachers' professional competence in the context of AI-driven education.

Implications for Teacher Competency Development

The AI-TPACK theoretical framework and the proposed approach to integrating artificial intelligence into teaching offer several important implications for the development of teachers' professional competencies in the context of digital transformation. These implications extend beyond the enhancement of technological skills to emphasize the coordinated development of content knowledge and pedagogical knowledge within AI-enhanced learning environments.

First, the development of teachers' instructional competence should prioritize the cultivation of digital pedagogical thinking. Teachers need to be able to identify the pedagogical value of AI in relation to specific content areas and instructional activities, rather than adopting AI in an ad hoc or trend-driven manner. Digital pedagogical thinking enables teachers to select appropriate instructional strategies and flexibly regulate the role of AI in teaching, thereby ensuring a balance between scientific rigor and humanistic values.

Second, teacher education and professional development programs should focus on building teachers' capacity to design AI-supported teaching and learning activities. The ability to design learning tasks is central to transforming AI from a technological tool into a pedagogical resource that enhances instructional effectiveness. This capacity involves analyzing learning objectives, determining the role of AI within the instructional process, establishing expectations and evaluation criteria, and developing instructional scenarios that anticipate and manage challenges arising during both AI-supported lesson design and AI-mediated student learning activities.

Third, greater attention should be given to strengthening teachers' capacity to assess learning processes in AI-enhanced environments. Beyond evaluating learning outcomes, teachers need to be able to interpret and utilize AI-generated feedback and learning analytics to monitor student progress, identify learning difficulties, address deviations from instructional goals, and adjust teaching strategies accordingly. Such assessment competence contributes to the development of teachers' professional critical thinking and supports more informed and reflective integration of AI into teaching practice.

Fourth, educational institutions and governing bodies play a crucial role in creating professional environments that support the development of AI-TPACK competencies. This includes establishing professional learning communities focused on AI-enhanced teaching, promoting experience sharing through practice-based collaboration, developing robust technical support systems, and implementing policies that encourage pedagogical innovation.

Finally, the innovation of teacher education and professional development programs represents a key implication of the AI-TPACK framework.

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Professional learning initiatives should move beyond a narrow focus on technology use toward the systematic development of integrated AI-related teaching competencies grounded in a coherent theoretical framework. Training content should emphasize the interconnections among AI-related technological knowledge (AI–TK), pedagogical knowledge in AI-enhanced contexts (AI–PK), and AI-supported content knowledge (AI–CK), thereby positioning AI-TPACK as a core component of teachers' professional competence in the artificial intelligence era.

Within this framework, the capacity to apply AI in teaching is understood as the ability to design, organize, and evaluate AI-assisted teaching and learning processes based on clear pedagogical principles. Teachers are expected not only to select appropriate AI tools but also to position AI strategically within the sequence of learning activities. This includes identifying learning objectives that can be effectively supported by AI, selecting task types aligned with specific content components, and designing open-ended learning activities that encourage students to use AI as a tool for inquiry and creativity rather than merely as a source of answers. Such competence also requires teachers to segment tasks appropriately and regulate the level of AI intervention to maintain students' active engagement, while ensuring accuracy, transparency, and ethical use of AI technologies.

Overall, AI-TPACK should be viewed not merely as an extension of the traditional TPACK framework, but as a reconceptualized theoretical model that comprehensively captures teachers' professional competencies in AI-driven teaching environments. The framework integrates pedagogical responsibility, technological expertise, and deep content understanding within a flexible and adaptive approach suited to the rapidly evolving educational landscape.

In summary, the development of teacher competence in the age of artificial intelligence should be approached as a holistic process in which technology does not replace the role of teachers but rather expands their professional capacity. Through the cultivation of digital pedagogical thinking, the design of AI-supported instructional activities, and the assessment of learning in AI-enhanced environments, the AI-TPACK framework provides both practical guidance for current teaching practice and strategic direction for future teacher education and professional development.

CONCLUSION

Based on a theoretical analysis and synthesis of prior research, this study proposes an AI-integrated theoretical framework for teaching grounded in the TPACK model (AI–TPACK), in which technological, pedagogical, and content knowledge are reconceptualized and systematically interconnected to address the demands of AI-supported teaching design and instructional practice. The proposed framework clarifies the role of artificial intelligence within the teaching process and provides a scientifically grounded basis for the development of teachers' professional competence.

The framework highlights digital pedagogical thinking, AI-supported learning task design, and the assessment of learning processes in AI-enhanced environments as core components of AI-integrated teaching competence. The implications derived from this framework extend beyond classroom practice to inform innovation in teacher education and professional development, thereby contributing to the sustainable digital transformation of education.

As a theoretically oriented study, this research inevitably has certain limitations, particularly the absence of large-scale empirical validation. Future research may focus on the development of AI-TPACK-based instruments for assessing teachers' professional competencies or on the design and evaluation of AI-supported teacher training and professional development models. These research directions are expected to further strengthen the theoretical foundation of AI-TPACK and support its more effective implementation in educational practice.

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