

Designing effective AI professional development: A framework grounded in intelligent-TPACK

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ARTICLE INFO

Keywords:

AI professional development
Intelligent-TPACK
AI TPACK
Generative AI
Professional learning
Ethical AI integration

ABSTRACT

The increasing presence of artificial intelligence (AI) in education requires teachers to develop not only technological proficiency but also pedagogical and ethical fluency in AI use. Responding to this need, this study employs a Conceptual Framework Development model to develop the Intelligent-Technological Pedagogical Content Knowledge-based Professional Development (i-TPACK-based PD) Framework, a research-informed, integrated model that aligns the five knowledge domains of i-TPACK (i.e., i-TK, i-TCK, i-TPK, i-TPACK, and AI Ethics) with four evidence-based AI PD pathways: active learning, use of models and examples, coaching and expert support, and feedback and reflection. Drawing from 40 systematic reviews and empirical studies, the framework interweaves these five i-TPACK domains and four AI PD pathways to create a cohesive structure that fosters teachers' AI-specific pedagogical reasoning, technological fluency, content-based applications, and ethical decision-making. The paper provides a detailed mapping of i-TPACK domains to AI PD pathways, a sample scenario that illustrates the practical implementation across the phases of teacher learning, and design principles to support PD developers. Additionally, it outlines recommendations for research and practice while critically addressing limitations related to program duration, delivery format, outcome evaluation, and ethical integration. This model offers actionable guidance for designing, implementing, and evaluating AI PD that is pedagogically grounded, ethically responsive, and adaptable across educational contexts.

1. Introduction

The rapid expansion of AI in education has sparked not only excitement but also uncertainty among teachers across the globe. Many educators are eager to integrate AI tools into their practice, yet feel underprepared, pressured, or unsupported in doing so [1]. At the same time, governments and organizations are calling for large-scale AI upskilling initiatives for educators [2,3], urging teachers to move beyond tool awareness to critical, pedagogically grounded use. Recent reviews and empirical studies caution that while digital competence frameworks such as DigCompEdu provide high-level goals [2,4], they often lack clear guidance on how those competencies should be developed through professional learning [5]. Without well-structured, ethically informed, and context-sensitive professional development (PD), efforts to integrate AI may remain superficial or even harmful [5,6]. Teachers need support not only to learn the technology but to critically reflect, adapt, and thrive in AI-enhanced classrooms [7,8].

Despite growing demand, many current AI PD offerings fall short of meeting teachers' actual learning needs [4,9]. Current AI PD* initiatives

are typically structured around AI platform demonstrations or superficial tool use [10], offering little room for pedagogical reasoning or ethical reflection [11]. While some programs introduce AI tools or AI content (machine learning etc.) and highlight potential classroom uses, they often lack grounding in how teachers learn best [12], relying on one-shot sessions, minimal feedback, and generic content. As noted by Dogan et al. [5], the design of most AI PD does not systematically incorporate effective professional learning practices, such as sustained engagement, reflective feedback, or modeling; and critical elements like ethical reasoning and real-world classroom application are frequently absent. In light of these limitations, researchers and educators are revisiting established frameworks like, Technological Pedagogical Content Knowledge (TPACK) [13] to guide more structured, pedagogically grounded AI PD [14] and re-branded the model to meet the challenges and opportunities of AI in education [15], such as the Intelligent-TPACK (i-TPACK) framework by Celik [16]. Early work on i-TPACK [17] suggests that i-TPACK offers a more nuanced lens for understanding how teachers conceptualize and apply AI in classroom practice, from practical integration to ethical reasoning.

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<https://doi.org/10.1016/j.caeo.2026.100337>

Received 30 June 2025; Received in revised form 13 January 2026; Accepted 8 February 2026

Available online 9 February 2026

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However, what remains underdeveloped is an integrated approach that explicitly connects the evolving discourse on AI PD with the affordances of TPACK. There is a need for conceptual clarity, design alignment, and shared language to guide the development of PD programs that not only teach AI as content or tool, but also foster ethical, critical, and pedagogically rich implementation. This study addresses that gap by focusing on the following research questions:

1. How are the findings from existing AI PD studies synthesized to inform the i-TPACK-based PD framework?
2. How are i-TPACK-based PD programs designed considering i-TPACK domains and evidence from previous AI PD studies?
3. How does the i-TPACK-based PD framework theoretically afford the conceptualization of teacher growth in the era of AI-based tools?

This Conceptual Framework Development (CFD) study responds to the growing call for structured, pedagogically grounded, and ethically informed AI PD. While numerous initiatives introduce teachers to AI tools or technical content (e.g., machine learning, neural networks), many fail to integrate what we know from decades of PD research, namely, that effective learning is active, supported by experts, and reflective [18–20]. Meanwhile, the newly proposed i-TPACK framework [16] offers an updated structure that brings AI-specific concerns, especially ethics, into the existing TPACK models, aligning closely with the needs of today's classrooms. Ultimately, the study proposes guiding principles that operationalize i-TPACK for AI PD planning, implementation, and evaluation.

This study is organized into five main sections. Following this introduction, Section 2 reviews the i-TPACK framework and its application in teacher learning research. Section 3 presents the Integrated Pathways for Teacher Growth effective AI PD model by Dogan et al. [5] that synthesizes current and foundational research on AI PD, coupled with guiding principles of the model. Section 4 introduces the methodology of the literature search performed and the CFD process. Section 5 introduces the i-TPACK-based PD framework that connects i-TPACK with AI PD activities, offering design elements (i.e., pathways) and a sample AI PD plan. Finally, limitations and anticipated challenges, along with potential research directions, conclude this study.

2. Intelligent-TPACK: a knowledge framework for AI integration

2.1. Overview of the i-TPACK framework

The integration of AI into education demands a rethinking of the traditional pedagogical content knowledge (PCK) [21] and TPACK framework [13]. In response to this need, the i-TPACK framework extends TPACK by infusing it with AI-specific knowledge, particularly around intelligent technologies that exhibit autonomous, adaptive, or generative behavior [16]. While classical TPACK has guided the integration of general digital tools into pedagogy, it falls short in addressing the complexities AI introduces, such as ethical transparency, data-driven feedback systems, and adaptive content delivery [22,23]. By expanding TPACK into i-TPACK, educators are better equipped to design instruction that thoughtfully incorporates both AI tools and generative AI tools not only to enhance learning outcomes but also to ensure that their use aligns with broader pedagogical and ethical goals [16,17,23,24].

The i-TPACK model shown in Fig. 1 presented by [16] consists of five core domains: Intelligent Technological Knowledge (i-TK), Intelligent Technological Content Knowledge (i-TCK), Intelligent Technological Pedagogical Knowledge (i-TPK), Intelligent TPACK (i-TPACK), and AI Ethics. Together, these domains capture teachers' readiness to select, implement, and evaluate AI-based tools within their subject areas [17]. Unlike traditional technology, AI tools require teachers to navigate opaque decision-making processes, adjust to rapidly evolving capabilities, and maintain critical oversight of fairness and accuracy. The i-TPACK framework provides a structured lens through which educators

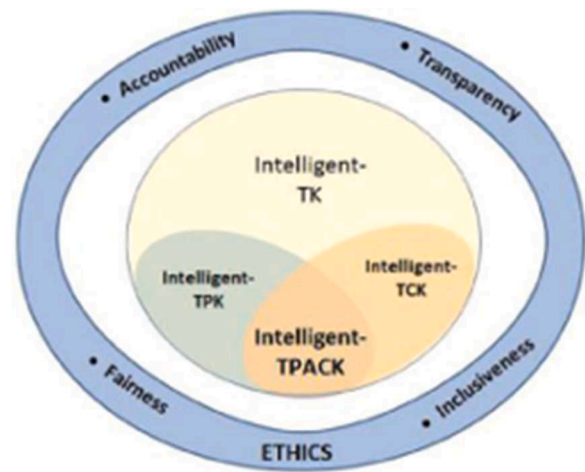


Fig. 1. Intelligent-TPACK sub-domains.

can develop not only technical fluency but also pedagogical intentionality and ethical sensitivity. This framework serves both as a conceptual model for researchers and a practical tool for designing effective AI PD [17].

2.2. i-TPACK sub-domains

2.2.1. Intelligent technological knowledge (i-TK)

It refers to teachers' foundational knowledge of how to interact with and operate AI-based tools [16]. This includes understanding the basic technical functionalities of AI systems and being able to use them effectively in both instructional and non-instructional contexts [17].

According to Celik [16], this component covers a range of competencies, including the ability to interact with AI tools in daily life (i-TK1), execute tasks using these tools (i-TK2), and initiate AI-supported actions through text or speech (i-TK3). It also includes having sufficient general knowledge for using AI-based technologies (i-TK4), and being familiar with their technical capacities (i-TK5). These competencies together define the core technological fluency required for AI integration in education. Teachers with strong i-TK can navigate AI-powered interfaces, understand how to prompt systems effectively, and recognize the affordances and limitations of various AI tools.

In practice, a teacher with developed i-TK might use a generative AI chatbot to schedule parent-teacher meetings through voice or text commands, prompt an AI tool to generate quiz questions, or select an appropriate app for grading assistance based on its technical specifications [25]. These routine yet purposeful uses of AI support both classroom efficiency and planning. Such foundational competence enables teachers to take full advantage of AI affordances in education and lays the groundwork for deeper pedagogical integration.

2.2.2. Intelligent technological pedagogical knowledge (i-TPK)

It refers to a teacher's ability to understand and utilize AI tools for instructional purposes, specifically in ways that enhance pedagogical strategies and student learning outcomes [16].

Celik's [16] survey outlines this component through several pedagogically focused competencies. These include understanding the pedagogical value of AI tools (i-TPK1), evaluating the usefulness of AI-generated feedback for learning (i-TPK2), and selecting tools that enable students to apply their knowledge (i-TPK3). Teachers are also expected to know how to monitor student learning through AI (i-TPK4), interpret messages from AI systems to deliver real-time feedback (i-TPK5), and scaffold student learning based on AI-generated alerts (i-TPK6). Additionally, this component includes selecting AI tools that sustain student motivation (i-TPK7). Together, these competencies support the strategic use of AI for responsive, student-centered

instruction.

In practical terms, a teacher with strong i-TPK might use an AI platform to monitor student progress during a writing assignment, respond to automated feedback alerts, and offer differentiated support based on students' needs [17]. For instance, in a science class, the teacher might implement an AI-based simulation that allows students to test hypotheses in real time, then use the system's dashboard to analyze patterns in student engagement and tailor follow-up questions accordingly. These pedagogical decisions are informed by the teacher's understanding of both what the AI tool can do and how it can support learning goals.

2.2.3. *Intelligent technological content knowledge (i-TCK)*

It refers to the ability of teachers to meaningfully connect AI-based tools with the specific content knowledge of their teaching domain [16]. It emphasizes the integration of content expertise with an awareness of how AI technologies can enhance, enrich, or transform disciplinary understanding [17].

In Celik's [16] framework, i-TCK includes competencies such as using AI tools to locate educational resources related to one's subject area (i-TCK1), being aware of field-specific AI applications used by professionals (i-TCK2), and utilizing AI to deepen personal understanding of subject content (i-TCK3). It also includes the ability to operate specialized AI tools that align with domain-specific practices, such as using an intelligent math tutor or AI-based simulations in science instruction (i-TCK4). These competencies collectively support a more robust disciplinary fluency, where teachers can draw on AI to both teach and continue learning their subject matter.

In practical terms, a language arts teacher with strong i-TCK might use AI tools to find authentic reading materials tailored to specific literacy goals, such as news summaries generated at different reading levels [17]. A science teacher could use AI-assisted virtual labs to illustrate complex phenomena that are otherwise difficult to demonstrate in real-life classrooms. When teachers understand the relevance and capabilities of AI tools specific to their subject areas, they can design more meaningful learning experiences that connect students to how knowledge is created, applied, and expanded within that discipline.

2.2.4. *Intelligent TPACK (i-TPACK)*

It represents the intersection and dynamic integration of pedagogical, content, and technological knowledge through the use of AI tools. It reflects the teacher's ability to design and implement effective, AI-enhanced instruction that is pedagogically sound, content-appropriate, and technologically feasible [16], also known as implementation knowledge [17].

Based on Celik's [16] survey, i-TPACK includes several key competencies: knowing how to use AI-based tools for adaptive feedback (i-TPACK1), personalized learning (i-TPACK2), and real-time responses during instruction (i-TPACK3). It also covers designing lessons that integrate content, pedagogy, and AI technology through diverse teaching strategies (i-TPACK4, i-TPACK5), taking leadership roles in supporting AI integration among peers (i-TPACK6), and selecting AI tools to monitor students effectively (i-TPACK7). These competencies define a comprehensive capacity to synthesize multiple forms of teacher knowledge in real-world AI-integrated classrooms.

In practice, a teacher with strong i-TPACK might co-design a unit on environmental science where students use AI to analyze satellite data on deforestation. The teacher selects appropriate AI tools, scaffolds inquiry-based learning, and adapts feedback based on the students' progress. They also collaborate with colleagues to refine the design and share best practices. This example illustrates how i-TPACK involves orchestrating all domains of knowledge to foster meaningful and ethical uses of AI in education.

2.2.5. *AI ethics*

It represents a teacher's capacity to critically evaluate and apply AI

tools in ways that are transparent, fair, inclusive, and accountable [16, 26]. These principles form the foundation of ethical decision-making in AI-supported teaching, requiring educators to consider not only how AI works but also its potential impact on diverse learners [23]. More broadly, it's important to distinguish between taking actions that are considered ethical and approaching all actions with an ethical mindset [27].

In Celik's [16] survey, this component is described through key competencies such as assessing whether AI tools account for student diversity, including factors like race and gender (AI ETHICS1), evaluating whether AI tools operate fairly across different student groups (AI ETHICS2), understanding the reasoning and logic behind AI decisions (AI ETHICS3), and recognizing who is responsible for the design and decision-making processes within AI tools (AI ETHICS4). These indicators help educators determine if AI tools align with the values of equity, responsibility, and openness.

Research suggests that ethical assessment in AI integration requires both technical and pedagogical literacy [28] and it is associated with teachers' use of that specific generative AI tools when they teach [23]. Without foundational understanding, educators may overly trust AI systems or miss critical evaluation opportunities [29]. Teachers equipped with stronger AI knowledge are more likely to recognize potential risks and take proactive steps to safeguard students' learning experiences and data privacy. For example, a teacher informed by AI ethics may choose not to adopt an AI grading platform if it lacks explainability features or has not been tested for bias against multilingual learners. They might also initiate conversations with school leaders about the need for transparency in tool selection and engage students in discussions about how algorithmic decisions are made. Ultimately, this knowledge helps educators advocate for the responsible use of AI while ensuring all learners are treated equitably.

2.3. *i-TPACK in teacher learning: what we know from prior research*

The i-TPACK framework has been increasingly cited and adapted across various educational studies, affirming its value as a conceptual model for examining teacher knowledge in the context of AI integration. Several recent studies have utilized i-TPACK to explore foundational teacher competencies, often focusing on the interaction between technological proficiency and pedagogical understanding. For example, Hava and Babayigit [30] examined the relationship between teachers' digital proficiency and their i-TPACK development. Similarly, Ye et al. [31] investigated Chinese pre-service EFL teachers' readiness and learning needs through the lens of i-TPACK, and Karatas and Atac [32] compared TPACK and i-TPACK skill levels of English pre-service teachers. Other studies explored its relevance in broader professional teaching contexts, such as Celik and Dogan's [17] work on literacy instruction and AI, and Mah et al.'s [33] investigation of future-oriented teaching using AI in higher education. Wu et al. [34] also employed items from the i-TPACK scale to examine multi-level factors influencing behavioral intentions in AI-enabled learning environments.

Another growing trend is the use of i-TPACK to examine the ethical and contextual challenges associated with AI integration. For instance, Belkina et al. [35] focused on describing TPACK domains in the context of generative AI, and Lan et al. [23] adapted the framework to generative AI by emphasizing the importance of AI ethics. Anand [36] employed i-TPACK to support arguments for integrating generative AI in medical education. Furthermore, researchers like Castro et al. [37] applied the framework to understand the pedagogical opportunities and challenges of AI use in rural schools, while Alhiane and Nafidi [38] adopted a SWOT perspective to analyze the implications of AI in K-12 contexts. Sperling et al. [8] also cited i-TPACK in their review of teachers' conceptions about AI.

Despite the growing body of literature applying i-TPACK in diverse settings and contexts, most of these studies remain cross-sectional, correlational, or descriptive. There is currently no published research

that systematically uses the i-TPACK framework to design, implement, and evaluate sustained AI PD programs for teachers. This gap highlights the need for future research to move beyond theoretical exploration and toward the practical application of i-TPACK in AI PD efforts.

3. Integrated pathways for teacher growth model: effective AI PD

This section introduces Dogan et al.'s [5] Integrated Pathways for Teacher Growth model, a design perspective that emphasizes how core elements of AI PD (Active Learning, Use of Models and Examples, Coaching and Expert Support, and Feedback and Reflection) operate as connected learning experiences, not isolated interventions, shown in Fig. 2.

The Integrated Pathways for Teacher Growth model emphasizes that effective teacher learning emerges not from isolated elements, but from their intentional and dynamic interaction. While each pathway offers distinct benefits, their true impact unfolds when they are purposefully combined (like a continuous flow of learning inputs) to support teachers' AI integration and AI-based tool implementation.

The concept of these integrated pathways is grounded in a systematic review conducted by Dogan et al. [5], which synthesized empirical findings from diverse AI PD programs across various contexts over a two-decade period. Their analysis revealed that high-impact AI PD programs rarely relied on single elements in isolation, but instead combined multiple design elements in ways that scaffolded teacher learning over time. Building on this insight, the present model envisions an AI PD process where these elements are intentionally layered and sequenced to form meaningful developmental pathways. The concept is further supported by a growing consensus in the literature on effective PD elements drawn from foundational work on PD design Darling-Hammond et al. and Desimone [19,20], empirical studies on teacher change Timperley et al. [39], and recent systematic reviews, criticisms, and meta-analyses by Cirkony et al. and Sims et al. [18,40]. These elements also appear in studies of diverse PD modalities, online [41], blended [42], and bichronous formats [43,44] and are synthesized across review studies [45] and meta-analyses [46]. Recognizing that high-quality design elements directly impact teacher growth and ultimately student learning, these studies helped inform the analytical framing.

3.1. Active learning

It involves teachers engaging with the content, other teachers, and/or experts, rather than simply absorbing the content through passive

learning. Active learning involves sustained, interactive experiences that position teachers as active participants in constructing, testing, and applying new pedagogical knowledge [5,20]. Rather than receiving information passively, teachers engage in activities that closely simulate or reflect classroom practice, such as lesson co-design, analysis of student work, or collaborative inquiry [19]. These types of experiences are especially critical in the field of AI, where tools and ethical considerations evolve rapidly. Active learning creates space for teachers to experiment with AI tools, confront uncertainties, and develop pedagogical fluency through iterative, hands-on engagement.

The dynamic nature of AI requires a shift from traditional, information-heavy PD to formats that prioritize exploration, iteration, and collaborative sense-making (e.g., [47]). Teachers must not only learn about AI tools but also learn with and through them. This entails engaging in inquiry-based tasks such as experimenting with prompts, simulating student use, and analyzing AI outputs to evaluate their pedagogical appropriateness and ethical implications [48]. Active learning enables teachers to critically evaluate the use of AI in their context and prepares them to make informed instructional decisions (Ning et al.) [49]. Based on the systematic review [5], some AI PD programs incorporated active learning as practical tasks like building chatbots or robots, while others focused on lesson planning, peer teaching, or analyzing AI-generated student work. Despite differences in approach, there is an emphasis on the value of experiential learning to deepen understanding and build confidence in using AI tools effectively. This is evident in empirical studies like Sun et al. [9], which involved classroom visits and lesson planning with AI, and Nazaretsky et al. [50] emphasised group discussions and practice grading with AI tools. Moreover, Ding et al.'s [47] study used active learning through a case-based AI PD program where teachers collaboratively discussed real-world AI integration scenarios. They analyzed challenges, shared experiences, and solved problems related to AI tools, promoting critical thinking and reflection. Hands-on activities and group discussions encouraged active engagement, enabling teachers to apply concepts directly to their practice.

For AI PD to be effective, active learning must be at its core [5]. It not only empowers teachers to explore AI tools meaningfully but also aligns AI PD processes with the complex demands of i-TPACK development. Without active engagement, teacher learning risks becoming superficial, focused on tool exposure rather than pedagogical transformation [51]. Embedding active learning across the AI PD design has the potential to ensure sustained professional growth.

3.2. Use of models and examples

Use of models and examples² in PD refers to providing teachers with specific demonstrations, sample practices, and real-life instructional artifacts and best examples that illustrate how knowledge can be applied in classroom settings [18,19]. In AI PD, these might include annotated lesson plans, video demonstrations, curated AI prompts, or simulations of AI-assisted instruction. Particularly, video-based modeling of effective instructional practices has been shown to significantly enhance teachers' ability to apply new strategies across subjects, making abstract concepts more concrete and transferable to classroom practice [52]. When teachers observe and analyze examples, models of samples (e.g., lesson plans, student work analysis etc.), they gain clarity not only about how a particular instructional strategy works but also about how it could be adapted to their own context [5].

In the context of AI PD, the use of models and examples becomes crucial given the abstract and technical nature of many AI tools. Teachers benefit from seeing authentic classroom applications of AI, such as examples of practical exercises in the study by Kandlhofer et al. [53], and previously prepared mobile robots, scripts, tutorials, or slides, and various types of cases/scenarios for teachers to reflect critically on in Ding et al.'s [47] study. These models and examples illuminate both pedagogical strategies and ethical considerations. These cases helped

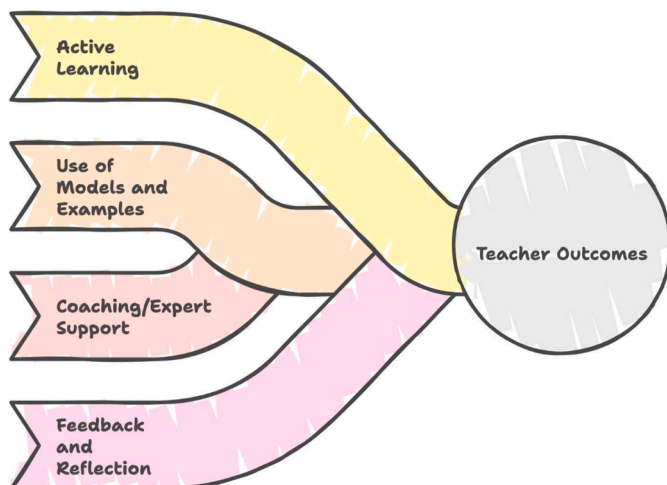


Fig. 2. Integrated pathways for teacher growth model.

teachers anticipate challenges and generate adaptations for their own settings. Dogan et al. [5] reported that AI PD sessions that included curated AI use cases, sample student work with AI feedback, or teacher-led demonstrations were more effective in building pedagogical confidence. In one empirical study, teachers reported a deeper, practical understanding of AI tools after engaging with modeled activities and classroom use cases [54]. In the study by Tang et al. [14], the examples of machine learning (ML) integration include the SmileyDiscovery system, which incorporates ML components to facilitate scientific discovery activities in science classrooms. Teachers observe tutorial videos demonstrating these activities to understand how ML can support inquiry-based learning. Additionally, the researchers provided ML-empowered scientific discovery activities that include phases like tactile exploration of ML concepts, reflection on their application, and discussion of strengths and limitations, all aimed at helping teachers see the practical and meaningful use of ML in their STEM teaching contexts.

Across effective AI PD, models and examples are seen as must-haves and thoughtfully embedded throughout teachers' learning process. They serve as bridges between theory and practice, enabling teachers to visualize complex concepts, adapt strategies to their contexts, and anticipate ethical challenges that AI integration may present [5]. Without concrete, practice-based illustrations, teachers risk superficial engagement with AI tools, focusing on their novelty rather than their pedagogical impact.

3.3. Coaching and expert support

Coaching and expert support² refer to the personalized, sustained guidance provided by experienced professionals who help teachers apply new learning in their specific contexts [19]. This support often includes modeling, observation, feedback, or co-reflection and is crucial for helping teachers navigate the complexities of integrating new technologies like AI. Kraft et al. [55] emphasize that such support must be embedded throughout the PD lifecycle—from introduction to classroom enactment—and be responsive to teacher needs as they evolve. Cirkony et al. [18] further underscore the importance of pairing coaching with collaborative reflection spaces, where educators can jointly make sense of pedagogy and grapple with dilemmas that emerge from its real use. Unlike traditional PD that may offer one-time exposure to new ideas, external (also referred to as outside) expertise and support enable iterative, context-specific growth through ongoing dialogue and shared problem-solving [5,56].

In AI PD, a support mechanism plays a vital role in helping teachers move from technical familiarity to pedagogical fluency. Dogan et al. [5] reported that coaching in AI PD typically manifests as external support focused on AI content expertise or assistance with designing and implementing AI-infused instruction. This may include experienced AI users, peers, or researchers who provide insight, examples, and constructive feedback grounded in practice. For example, some programs involve experts in co-developing lessons, reviewing ethical implications of AI use, or refining tools for context-specific needs. For example, Lutticken et al. [57] illustrated how ongoing coaching supported teachers in integrating AI and other technologies into their inquiry-based lesson plans. Teachers received consistent guidance as they designed, implemented, and reflected on AI-enhanced classroom practices.

Studies have shown a range of approaches to expert support in AI PD. For example, Yang et al. [11] involved engineers and higher education faculty who provided both technical and pedagogical guidance. Sun et al. [9] integrated K-12 coaches into their AI PD design, offering structured facilitation throughout the lesson design and implementation process, although the nature of synchronous and asynchronous support varied. These examples illustrate how expert involvement helps tailor AI use to disciplinary contexts and classroom realities, supporting teachers through ongoing instructional decision-making and ethical reflections. Notably, Ding et al. [47] showed how expert facilitators guided teachers

through case-based analysis of AI tools, providing tailored insights and feedback that shaped teachers' confidence and implementation skills. Such support created a space for dialogic inquiry and mitigated common fears or misconceptions about AI use in education.

Rather than treating coaching and mentoring as separate categories, AI PD emphasizes their shared function: to serve as responsive, context-aware supports that guide teachers through the iterative process of integrating AI in the classroom while fostering confidence and competence in their instructional decisions [5]. For AI PD to be effective, coaching and expert support must be intentionally designed and sustained across the learning process. When teachers have access to knowledgeable guides who provide ongoing feedback, contextual insight, and opportunities for reflection, their confidence in using AI tools grows. Rather than one-time advice or generic technical help, these support structures serve as scaffolds that allow teachers to take risks, refine their practice, and troubleshoot challenges as they arise.

3.4. Feedback and reflection

Feedback and reflection in AI PD involve structured opportunities for teachers to critically assess their experiences, examine their practices, and receive input that informs their growth [5]. Unlike evaluation or assessment, this element emphasizes formative, dialogic processes that support teachers as active participants in their own learning journey. Feedback is a vital component of effective AI PD, enabling teachers to refine their practices through authentic, moderated, and insightful comments on their lessons or instructional materials, often involving experts such as mentors or coaches [19]. Reflection complements feedback by encouraging teachers to critically analyze their teaching, consider new information, and make informed adjustments to improve student outcomes [18,40]. Both feedback and reflection are central elements in active learning, with research indicating that engaging teachers in these processes leads to deeper understanding and more meaningful changes in practice [39].

In AI PD, feedback and reflection allow teachers to make sense of complex tool interactions, reconsider instructional strategies, and refine ethical considerations in real-time. Nazaretsky et al. [50] incorporated collaborative group reflections focused on the use and implications of AI tools in education. Tang et al. [14] included both structured discussions and individual reflection journals to help teachers weigh the pedagogical strengths and limitations of AI. Yang et al. [11] highlighted the value of expert review of teacher-designed lessons, with concrete suggestions for improvement. In Lee and Perrett's [58] study, teachers reflected on their pedagogical approach to AI and evaluated how they might translate their learning into their classrooms. Similarly, Lee et al. [59] prompted reflection on both AI concepts and the application of curriculum activities in practice. Additionally, the teachers in this study shared their reflections on a messaging platform and during discussions, posting thoughts on the readings, the curriculum activities, and their concerns or enthusiasm about AI concepts. These exchanges provided ongoing feedback loops where teachers could see others' perceptions, share resources, and collaboratively problem-solve. Lutticken et al. [57] showed how coaches provided feedback not just on lesson plans but on implementation outcomes and student work, reinforcing continuous improvement.

For AI PD to be effective, feedback and reflection must be intentionally embedded throughout the learning process, but not as afterthoughts, but as integral components of deep professional engagement. Sustained opportunities to reflect and revise support meaningful learning and empower teachers to become confident, critical, and ethical users of AI in their classrooms.

3.5. Interdependence of AI PD pathways

PD models are often described in terms of elements (or features), mechanisms, or components (e.g., [20]). However, the most effective PD

designs are not those that merely include these elements in isolation, but those that treat them as interconnected parts of a larger developmental process. The Integrated Pathways for Teacher Growth model presented is grounded in the principle of integration, where core elements do not operate in silos but act as mutually reinforcing processes. Each has unique affordances, yet the greatest potential lies in their interplay. One premise of the model is that the more extensively these elements are incorporated and intertwined, the more powerful their effect on teacher learning and AI use in classroom transformation becomes.

Building on prior empirical studies (e.g., [47]) and synthesis frameworks (e.g., [40]), the Integrated Pathways for Teacher Growth model serves as a foundation for designing AI PD with a stronger emphasis on effective practices for teacher learning, depth of engagement, and sustainable school improvement. Although many existing AI PD programs implement one or two of the core elements, they often fail to integrate them meaningfully. The model, firstly proposed by Dogan et al.'s [5] review, highlights this gap and underscores the importance of designing interdependent, layered experiences that maximize the transformative potential of professional learning.

To operationalize the idea of integration, the model is grounded in a set of interdependent guiding principles that guide how the four pathways interact, reinforce, and adapt to one another throughout the professional learning process, shown in Fig. 3.

1. **Collective Synergy Over Silos:** Learning pathways are most impactful when intentionally layered—active learning gains depth when tied to feedback, and coaching becomes meaningful when anchored in modeled practice. This idea aligns with Timperley et al. [39], who argued that teacher learning deepens when knowledge is co-constructed and revisited across multiple modalities. Dogan et al. [5] also reported that effective AI PD programs often infused multiple elements within single tasks rather than isolating them.
2. **Cross-Element Responsiveness:** Similar to the idea presented in Sims et al.'s [40] Insight, Goals, Techniques, Practice framework, the model serves as a foundation for designing learning experiences that go beyond surface-level exposure. Rather than associating each mechanism with a single pathway, the model emphasizes that these mechanisms span across the four elements. For example, reflections can inform adjustments to coaching, or modeling activities may emerge from needs revealed during active learning tasks.
3. **Recursive Learning Loops:** Learning is not linear. Teachers cycle through pathways multiple times—e.g., trying a tool, receiving feedback, revising a lesson, modeling it for peers—each round deepening understanding and confidence. As Cirkony et al. [18] note, iterative engagement fosters deeper learning and professional resilience. Similarly, Sun et al. [9] structured their AI PD model

around cyclical interaction between reflection, collaboration, and experimentation, which proved central to teacher confidence and transfer.

4. **Design for Convergence:** Rather than planning AI PD in isolated sessions (e.g., one on feedback, another on AI tools), developers design for convergence, such as embedding modeling within feedback sessions or linking coaching directly to active learning artifacts. Dogan et al. [5] found that successful AI PD examples blended these moves, creating seamless learning arcs rather than fragmented events. Ding et al. [47] also illustrated how reflective cases, active discussion, and expert facilitation worked best when integrated into a coherent case-based learning cycle.
5. **Flexibility within Structure:** While the four pathways define the architecture, their interactions should flex depending on context, teacher needs, or school goals. Shortly, interdependence allows the system to adapt without fragmenting. For example, Martin et al. [43] and Nalbantoglu et al. [44] show how the same elements play out differently in synchronous, asynchronous, or bichronous settings while retaining their function.

4. Methodology

This study employed a Conceptual Framework Development (CFD) [60,61] approach that consists of four phases, outlined in Fig. 4. Phase I involves reviewing existing evidence on AI PD. Phase II and Phase III expand the review by identifying newly published empirical studies on AI PD and integrating research on TPACK-based PD and recent systematic reviews on effective teacher learning. Phase IV is the synthesis and integration phase, where all relevant findings are consolidated to develop the proposed i-TPACK-based PD framework.

The CFD approach aimed at addressing a specific and timely gap in teacher AI PD for AI integration. Given the evolving nature of AI technologies and their pedagogical, ethical, and content-specific implications for educators, a carefully constructed conceptual framework was necessary to organize, synthesize, and align disparate bodies of knowledge [62]. This methodological choice aligns with recommendations from Antonenko [60] and Ravitch and Riggan [61], who emphasize that conceptual frameworks serve as tools for organizing empirical inquiry, ensuring research rigor, and bridging theory with practical application [63].

Rather than generating empirical data, this study focused on synthesizing existing knowledge from multiple disciplines (AI PD and TPACK) to propose an integrated framework that aligns the i-TPACK domains with key elements of effective AI PD. Following Rallis and Rossman's [63] "inquiry-mindedness" approach to examine potential ways of knowing and Thomas's [62] guidance on constructing a conceptual framework in research and inquiry, the process was iterative, reflective, and grounded in both empirical findings and theoretical constructs.

The "data" for this conceptual inquiry consisted of peer-reviewed literature (including systematic reviews, meta-analyses, empirical studies, and conceptual reports) spanning three primary areas: (1) teacher PD, and (2) TPACK and i-TPACK frameworks. Following Antonenko's [60] suggested method of conceptual framework analysis, literature selection prioritized publications that offered empirical findings of AI PD, or design principles relevant to AI PD, teacher knowledge frameworks (TPACK), and conceptual models of how teachers learn through different modalities (online, blended, etc.). Sources ranged from empirical studies to theoretical papers and systematic reviews.

4.1. Phase I: review of existing evidence on AI PD

The process began with an in-depth review of Dogan et al. [5], a PRISMA-based systematic review that synthesized empirical AI PD studies up to May 10, 2024. This review included 14 AI PD studies examining AI-focused PD. These 15 studies served as the initial evidence

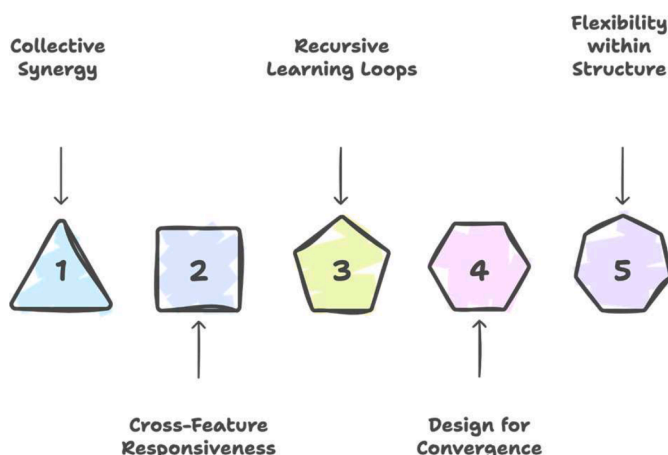


Fig. 3. Guiding principles of the integrated pathways for teacher growth.

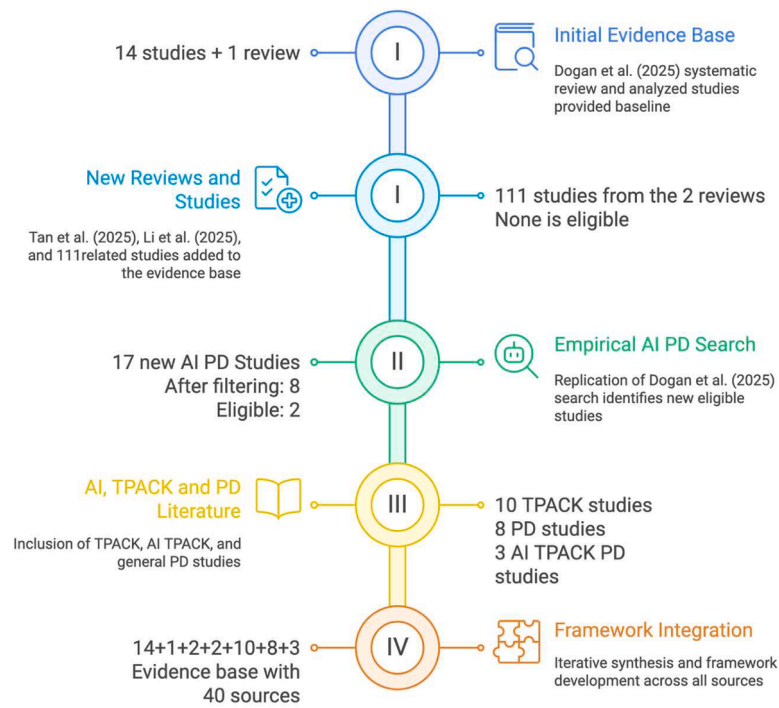


Fig. 4. Conceptual framework development process.

base for this conceptual analysis, informing the identification of effective AI PD features in the existing literature. Publications included in Dogan et al. [5] spanned diverse formats (online, hybrid, and in-person AI PD) and represented multiple educational contexts and subject areas.

In addition, two PRISMA-based systematic reviews on AI PD published after Dogan et al. [5] were located. Tan et al. [64] and Li et al. [65] added diverse perspectives to the initial evidence base. The peer-reviewed studies analyzed in these two systematic reviews were also identified to create a secondary evidence (95+16=111) (Replicates were excluded).

4.2. Phase II: identification of new empirical AI PD studies

In Phase II, to extend the evidence beyond Dogan et al. [5] and other existing studies, we replicated their search strategy, using the same Boolean strings (AI, PD, and teachers) as detailed in Table 1. Searches were conducted in major databases (Scopus, ERIC, and Web of Science), covering the period from May 10, 2024, to May 10, 2025. This process yielded 17 new AI PD studies.

Next, the inclusion and exclusion criteria from Dogan et al. [5] were applied to determine eligibility (see Table 2) of the new 17 studies and the 111 studies analyzed in the two reviews (from Phase I). Beforehand, we filtered out the 128 studies whether or not they had any AI PD

programs. After this filtering, the number of eligible studies went down to 8.

Each study abstract was screened to ensure alignment with the review scope, focusing on empirical AI PD, teacher learning frameworks, and ethics-integrated AI education. This screening process resulted in 2 eligible publications. For example, one newly included study (Brünner et al. [48]) examined an interactive workshop that promoted contextual relevance to introduce AI literacy, genAI, prompting strategies, and ethical considerations. In an example excluded from this study, Mikeska et al. [66] surveyed teachers' AI feedback experience without an AI PD program.

4.3. Phase III: inclusion of empirical and conceptual studies on TPACK and PD

In Phase III, additional TPACK- or AI TPACK-based (different models than i-TPACK) and general PD studies were searched. First, priority was given to highly cited empirical TPACK studies and conceptual PD design papers proposing instructional frameworks [67–75]. A related chapter (Mourlam et al.) [76] from Handbook of Technological Pedagogical Content Knowledge (TPACK) for Educators by Philips et al. [77] was also included in the review. The literature on effective PD elements drawn from foundational work on PD design [19,20], empirical studies on teacher change [39], and recent systematic reviews, criticisms, and meta-analyses [18,40–42,45] were also included. In addition, empirical studies published after May 10, 2024, specifically on AI, TPACK, and PD were also included [22,78,79] (These were not included in Phase I but included in Phase III because of their particular emphasis on PD design with TPACK). Following Antonenko's [60] guidance for conceptual framework analysis, these sources were selected to ensure theoretical rigor, design diversity, and representativeness across contexts. This broader inclusion in Phase III enabled the development of a framework that integrates both AI PD literature and general evidence-based PD and TPACK PD principles.

Table 1

Search string used in Phase II.

Terms	Search Strings
AI	Artificial intelligence' OR 'machine intelligence' OR 'intelligent support' OR 'intelligent virtual reality' OR 'chatbot*' OR 'automated tutor' OR 'personal tutor*' OR 'intelligent agent*' OR 'expert system' OR 'AI-based' OR 'automated grad*' OR 'automated scor*'
PD	'Professional development' OR 'teacher* development' OR 'in-service' OR 'in-service development' OR 'professional learning' OR 'professional learning community*' OR 'teacher leader' OR 'teacher community*' OR 'teacher learning' OR 'training' OR 'workshop' OR 'community* of practice' OR 'coaching'
Teacher	'Teacher' OR 'K-12' OR 'middle school' OR 'primary school' OR 'elementary school' OR 'high school' OR 'school'

Table 2
Inclusion criteria used in Phase II.

Inclusion Criteria
AI as one of the content focuses of PD program and evidence of teacher outcomes
Teachers across all subject areas in the K-12 context
Published in a peer-reviewed journal as an empirical study after May 10, 2024

4.4. Phase IV: integration and framework development - mapping

In the final phase, findings and insights from all 40 reviewed sources were analyzed, interpreted, and mapped through an iterative comparative synthesis process. The synthesis drew from the principles of CFD [60,61] and inquiry-mindedness [63], emphasizing reflection, comparison, and theoretical integration over data aggregation. Consistent with Antonenko’s [60] guidance, this phase sought alignment between the conceptual components, the framing of the problem, and the intended use of the framework to produce a coherent and usable model for AI PD.

A total of 20 cells were constructed in a 4 × 5 mapping matrix, where the four AI PD pathways (active learning, use of models and examples, coaching and expert support, and feedback and reflection) were cross-referenced with the five i-TPACK domains (i-TK, i-TCK, i-TPK, i-TPACK, and AI Ethics). Each cell represents a potential learning activity or professional learning method/technique, synthesized from at least two of the 40 reviewed sources. These activities were not intended to be exhaustive but illustrative and suggestive, reflecting recurring design principles across AI PD, TPACK PD, and broader teacher PD research. By combining evidence from multiple studies, the matrix operationalizes how specific teacher learning mechanisms can support the development of distinct yet interconnected i-TPACK domains.

Because the reviewed studies varied widely in terminology and specificity (particularly in how they named or categorized PD strategies), the integration process required thematic abstraction. Drawing on Antonenko’s [60] conception of conceptual frameworks as “organizing instruments for inquiry,” and Rallis and Rossman’s [63] emphasis on constructive synthesis, activity descriptors were intentionally kept generic but theoretically grounded, ensuring the framework’s adaptability across diverse educational settings. This interpretive mapping may serve both as a heuristic guide for AI PD design and as an inquiry artifact, enabling recursive reflection on how professional learning pathways align with i-TPACK-based teacher growth.

In accordance with the CFD approach [60,61], the framework development process was recursive and reflective, moving iteratively between empirical evidence, theoretical constructs, and conceptual reasoning. The resulting i-TPACK-based PD framework is not a fixed model but a dynamic conceptual map, intended to guide future empirical research, support design-based implementations, and advance theoretical understanding of teacher learning in AI-enhanced environments.

4. Results

The traditional TPACK has served as a foundational framework for designing and evaluating teacher PD for two decades across disciplines and learning environments. For instance, Koh et al. [68] developed a year-long PD program emphasizing collaborative design teams, supported by TPACK rubrics and heuristics. Alemdag et al. [69] implemented a PD program grounded in TPACK, highlighting the value of collaborative, authentic design tasks tailored to the needs of adult educators. Other studies further demonstrate the adaptability of TPACK across in-service, pre-service, and STEM contexts, with consistent findings pointing to improved instructional planning, design fluency, and confidence in technology integration [70–73]. Similarly, Niess et al. [74] emphasized the importance of building teachers’ confidence and adaptive expertise through iterative engagement with TPACK-aligned PD processes. In their TPACK-based PD program, Baran et al. [67]

proposed expanded models that embed discipline-specific pedagogies into TPACK-based PD, reinforcing its ongoing relevance. More recently, Ortiz-Colon et al. [80] further confirm that even in contemporary applications, whether focused on AI or other digital innovations, TPACK is still actively used to inform PD design and teacher preparation. Fabian et al. [81] reaffirm that TPACK continues to serve as a reliable foundation, especially in the face of evolving educational technologies

As TPACK has historically functioned as a flexible and effective framework for guiding teacher PD, the i-TPACK framework similarly holds promise for informing new AI PD designs tailored to AI integration. The framework’s success lies in its adaptability, allowing it to be reshaped for emerging technologies while maintaining its core emphasis on pedagogy, content, and technology. Philipsen et al. [75] have also emphasized that effective PD experiences often align with the types of learning experiences that TPACK-based programs promote, including collaboration, sustained engagement, and reflective practice. Thus, i-TPACK emerges not as a departure from prior frameworks but as a thoughtful extension capable of responding to the needs of AI-enhanced teaching.

Recent AI TPACK-based PD studies have increasingly drawn on general AI TPACK frameworks to support teacher learning, signaling the relevance of the framework for AI integration (e.g., [9]). While not all use the full i-TPACK structure [16], several have adopted similar approaches. For example, Yildirim and Akcan [78] presented a 10-step AI PD model for chemistry teachers, while Amplo and Butler [79] designed a hybrid AI TPACK framework to support higher education faculty. Likewise, Sun et al. [9] and Schleiss et al. [82] applied AI TPACK-informed designs to promote ethical and pedagogical use of AI tools in STEM and flipped learning environments.

Although these studies offer strong empirical insights and align with some AI TPACK principles, they often fall short of systematically integrating effective AI PD elements or sustaining implementation over time. As highlighted by Dogan et al. [5], recent TPACK-based PD studies rarely align fully with best practices in teacher professional learning (i.e., active learning, feedback, coaching, and the use of models), leaving these elements inconsistently embedded. Moreover, one of the most overlooked domains is AI ethics, which is either superficially addressed or entirely absent, despite its growing importance in responsible AI integration. This signals a critical gap that the i-TPACK-based PD framework proposed here aims to address through a more cohesive and research-aligned approach.

4.1. The i-TPACK-based PD framework: mapping i-TPACK domains to integrated pathways

To build a strong and coherent AI PD design for AI integration, it is essential to consider how i-TPACK domains align with core pathways of teacher learning. This section maps the five domains of the i-TPACK framework (i-TK, i-TCK, i-TPK, i-TPACK, and AI Ethics) onto four integrated AI PD pathways: Active Learning, Use of Models & Examples, Coaching & Expert Support, and Feedback & Reflection, shown in Table 3 (See Appendix A for citations integrated into the map)

This mapping is not intended to suggest that each i-TPACK domain should be developed in isolation or exclusively through one specific pathway. On the contrary, a robust AI PD model should incorporate all four pathways to support each i-TPACK domain. For instance, while teachers may gain i-TK through active learning tasks such as prompt experimentation (e.g., [50]), their broader pedagogical integration of AI

Table 3
Mapping i-TPACK domains onto integrated AI PD pathways.

AI PD Pathways	i-TK	i-TCK	i-TPK	i-TPACK	AI Ethics
Active Learning	Engage teachers in hands-on experimentation with AI-based tools (e.g., prompt tuning, testing tool features) to build technical fluency.	Explore AI applications relevant to content areas (e.g., using science-specific AI simulations) or learning content with AI partners. Share curated use cases or domain-specific tools showing effective AI-based applications.	Evaluate classroom scenarios where teachers apply AI-based tools for formative assessment, monitoring, or personalization in terms of AI-based tool integration.	Design, test, and revise lesson plans or related teaching or student artifacts integrating content, pedagogy, and AI-based tools.	Engage teachers in role-play or case simulations to confront ethical AI dilemmas (e.g., algorithmic bias, data misuse).
Use of Models & Examples	Share annotated walkthroughs, infographics, video tutorials, or screencasts of how teachers use AI-based tools in practice.	Work with subject-matter experts to align AI-based tools with disciplinary practices and content goals.	Examine real-world classroom examples that demonstrate the pedagogical use of AI-based tools (e.g., scaffolding, alerts, formative feedback).	Analyze and discuss sample lessons and implementation videos illustrating full i-TPACK use in classroom settings.	Illustrate ethical AI practices by offering annotated examples or teacher commentaries that foreground fairness, transparency, or accountability.
Coaching & Expert Support	Facilitate guided exploration with mentors or AI experts to deepen understanding of AI capabilities.	Critically reflect on how AI deepens (or limits) content exploration or concept building.	Coach teachers on aligning AI features with pedagogical intentions (e.g., differentiating instruction, motivating students).	Co-design, revise, or evaluate integrated AI-enhanced units with coaches. Utilize AI-based tools during teaching with an expert.	Review ethical AI considerations in lesson planning or analyzing student work with ethicists or AI-literate facilitators.
Feedback & Reflection	Create prompts and use them for journaling and group debriefs on the affordances and challenges of AI tools.		Reflect on how AI supports or challenges their pedagogical goals and instructional equity.	Facilitate structured after-action reflection on full lesson enactment using i-TPACK (what worked, what didn't, what to adapt).	Reflect on inclusiveness, fairness, and transparency in AI use through guided reflection protocols or self-assessment rubrics.

(i-TPACK) will likely require coaching and collaborative planning [11]. Similarly, exploring i-TCK is often best supported through exposure to models and curated examples [5,47]. The goal here is to illuminate possibilities, not prescribe strict boundaries.

The i-TPACK-based PD Framework offers a flexible, research-informed foundation for multiple stakeholders in education. For designers (PD designers, course designers, e-learning developers, and even instructional designers), the framework functions as a strategic planning tool. It outlines evidence-based learning activities mapped to each i-TPACK domain. These activity descriptions are intentionally broad and adaptable, allowing designers to tailor implementation to their specific teacher populations, institutional contexts, and time constraints. When used during the design process, the framework promotes coherence and reduces the cognitive and logistical load of planning. Designers can make informed decisions about sequencing, mode of delivery, and support mechanisms by using the framework as a menu of high-impact practices aligned with both AI PD pathways and AI pedagogical knowledge. This built-in structure ensures that key activities, such as active learning or coaching, are not overlooked or inconsistently applied.

Beyond AI PD design, the framework can serve evaluative purposes. Schools and institutions can use it to retrospectively assess whether an AI PD program aligns with best practices. For example, the matrix could be turned into a checklist, a rubric, or a discussion protocol to guide reflection and feedback after an AI PD program ends. This type of meta-evaluation not only supports continuous improvement but also helps align future AI PD efforts with effective practices.

For teachers, the framework also functions as a professional learning roadmap. Educators who are increasingly asked to choose between various AI workshops, courses, and events can use the i-TPACK-based PD framework and its matrix to screen opportunities. An AI PD program that incorporates modeled examples, expert coaching, and ethical reflection is more likely to yield meaningful and sustained learning. Familiarity with the framework enables teachers to seek experiences that align with their goals and needs.

Although the long-term recommendation is to address all five i-TPACK domains through a balanced AI PD design, the framework can also support more targeted efforts. For instance, a two-day summer institute might prioritize i-TK and i-TPK development for educators new to AI integration. Similarly, school leaders may use the matrix to scaffold a yearlong AI PD progression, focusing on one or two domains each quarter, culminating in integrated classroom practice.

In the next section, how this mapping can inform a dynamic AI PD experience through a practice-based teacher development journey is illustrated. Using a fictional AI tool designed for real-time classroom feedback, we narrate how STEM teachers might engage with each i-TPACK domain across the four pathways, moving from exploration to classroom implementation and reflection. These experiences will also highlight principles such as recursive loops, differentiated entry points, and coherence, emphasizing how the pathways interlock to support meaningful and sustained teacher growth.

4.2. A practical application: bringing i-TPACK and AI PD pathways to life

To illustrate how the i-TPACK framework and integrated AI PD pathways come together in practice, we present a fictional AI PD program⁴ designed for middle school STEM teachers, shown in Table 4. The focus of this AI PD is the integration of a fictional AI-based classroom feedback tool called *ClassEcho*, which uses voice recognition and sensor data to provide real-time formative feedback to teachers about student engagement and misconceptions during instruction.

This fictional AI PD program centers on the integration of *ClassEcho*. Designed as a semester-long experience, the AI PD unfolds over four structured phases: (1) Exploration and Familiarization, (2) Modeling and Co-Design, (3) Classroom Implementation and Coaching, and (4) Reflection and Sharing. Each phase (not sessions, each phase may

Table 4

Fictional scenario: real-time insight with "ClassEcho" in a STEM AI PD program.

Phases	Descriptions	AI PD Pathways	i-TPACK Focus
Exploration and Familiarization	Teachers are introduced to the concept of real-time AI feedback through guided experimentation. Using active learning, participants test how ClassEcho responds to different instructional contexts and explore its functionalities through prompt-based simulations. Experts guide prompt-based simulations and answer questions related to the tool. Teachers analyze ethical AI dilemmas around student data and share their insight on transparency and fairness, aligning with AI ethics.	Active Learning, Feedback & Reflection, Coaching and Expert Support	i-TK, AI Ethics
Modeling and Co-Design	AI PD facilitators showcase model lessons using ClassEcho in a biology and math context. Teachers analyze recorded examples and annotated student data to understand how the tool supports different content areas. Then, in subject-aligned groups, they co-design a mini-lesson that embeds the tool and consider potential ethical AI considerations, receiving coaching and expert support as they build i-TCK and i-TPK fluency.	Use of Models & Examples, Active Learning, Coaching and Expert Support	i-TPK, i-TCK, AI Ethics
Classroom Implementation and Coaching	Teachers implement their AI-supported lessons in their own classrooms. Each teacher is paired with a coach who observes the lesson via video (or live observation) and offers targeted feedback. Teachers reflect on how the tool impacted their instructional choices, real-time decision-making, and student learning, as well as potential ethical AI issues experienced.	Active Learning, Coaching & Expert Support, Feedback & Reflection	i-TPACK, AI Ethics
Reflection and Sharing	Teachers return to the AI PD space to debrief in peer groups. Using structured reflection prompts, they share their successes and struggles, revisit ethical questions, and revise their lesson plans for future use. They also rate and provide feedback on each other's adaptations using a rubric co-developed with facilitators.	Feedback & Reflection, Active Learning, Use of Models & Examples	All domains revisited through synthesis

include several sessions) is intentionally designed to engage participants across the four AI PD pathways while supporting the development of all five i-TPACK knowledge domains. This design ensures a coherent, recursive learning journey grounded in practice and responsive to teachers' evolving instructional needs.

This fictional scenario illustrates how the principles of effective AI PD (recursive learning, differentiated entry points, coherence, collective synergy, ethical grounding, and practical implementation) can work together in practice. The design supports recursive growth through ongoing experimentation and revision, allows teachers to engage at different levels of expertise (differentiated entry), and maintains coherence across sessions through a unifying classroom tool. Reflection on AI ethics is embedded, not treated as an afterthought.

4.3. Practice and research suggestions on using i-TPACK-based PD framework

These suggestions are intended to guide both designers and researchers in developing, testing, and refining AI-related teacher learning experiences grounded in i-TPACK and integrated learning pathways.

Practice Suggestions

- The ideal way to use the framework is to embed all four AI PD pathways (active learning, modeling, coaching, reflection) across each i-TPACK domain to ensure comprehensive teacher learning.
- Design AI PD programs that include sufficient contact hours and unfold over extended durations (e.g., semester- or year-long) with time for experimentation, iteration, and classroom application with reflection.
- Create customizable AI PD blueprints and models aligned to subject areas and grade levels, with sample lesson plans, AI toolkits, and scenario-based cases tied to each i-TPACK domain.
- Integrate AI ethics components into relevant phases of teacher learning, rather than confining them to one-off discussions or isolated modules.
- Utilize AI tools within the AI PD process itself, such as for providing feedback, facilitating collaboration, and co-designing instructional materials.

Research Suggestions

- Investigate the longitudinal development of i-TPACK through repeated measures (e.g., pre/post/mid-year) to capture sustained growth.
- Compare different AI PD formats (online, blended, face-to-face) in terms of their effectiveness for developing specific i-TPACK domains.
- Explore teacher outcomes beyond knowledge, such as shifts in motivation, efficacy, or instructional decision-making, as a result of i-TPACK-based PD.
- Study the integration of AI ethics into practice, focusing on how teachers make ethical AI decisions with AI tools in real classroom contexts.
- Evaluate the interactions between AI PD pathways, such as how coaching amplifies the impact of modeling or how reflection reinforces understanding of AI ethics.
- Conduct comparative studies examining how the intentional integration of AI ethics within this i-TPACK-based PD framework impacts teacher learning, in contrast to earlier AI PD models that lacked a systematic AI ethics component. Such studies could generate critical insights into the role of AI ethics-focused design in shaping teacher decision-making and classroom implementation.

5. Limitations and anticipated challenges

While it is not possible to anticipate all the challenges that may arise in designing and implementing i-TPACK-based PD, prior research

studies highlighted several recurring issues (e.g., [5]). The limitations outlined below apply to both research and practice, offering guidance for future studies and more effective AI PD design.

The first design-related limitation is about the duration and contact hours of i-TPACK-based PD. Since the proposed model is still conceptual, it would be premature to suggest an ideal number of hours or a period of time required to foster i-TPACK growth. Previous research studies have shown that AI PD programs exceeding 20 h (e.g., [20]) or 45 h of face-to-face AI workshops combined with 30 h of online content (e.g., [9]) are more likely to be effective in shifting teacher knowledge and practice. However, Dogan et al. [5] didn't suggest any time and duration from the 15 reviewed studies of AI PD. Thus, one recommendation emerging from this model is the need for sustained and sufficient contact time. Longitudinal AI PD that spans at least a full semester or a school year, rather than one-off workshops disconnected from other workshops or actual classroom needs, is preferable.

The current i-TPACK-based PD framework does not explicitly specify whether direct instruction or lecturing is included as a component of teacher learning activities. Evidence from previous studies suggested that no single instructional mode alone (whether direct instruction or active learning) fully accounts for the development of AI competencies. For instance, Xiao et al. [83] reported that teachers were more satisfied when AI PD programs included elements of direct instruction, while Sun et al. [9] introduced the Five Big Ideas about AI through structured presentations. However, both studies also incorporated Q&A sessions, expert team support, problem-based learning, coaching, and modeling activities. Moreover, the available literature provides little detail on how direct instruction was implemented in these contexts; in most cases, lecturing was embedded within broader interactive designs that included models, prototypes, classroom cases, or engagement tasks. Therefore, further research is needed to examine how direct instruction interacts with other pedagogical elements in fostering sustained teacher growth within AI PD design.

Delivery format and modality are other areas that require further investigation. While most existing AI PD programs have utilized blended formats, the reviewed literature lacks transparency in reporting how these were implemented. There were positive results in AI PD studies that had 40% online components of the whole AI TPACK PD program (e.g., [9]). However, Dogan et al. [5] highlight the ambiguity around the role of online components, whether they are integrated seamlessly with face-to-face activities or function independently. Future research should explore how various delivery modes (online, asynchronous, hybrid, or blended, etc.) of the i-TPACK-based PD programs support or hinder different elements of the model.

The framework's focus on i-TPACK as the primary outcome limits its applicability for understanding broader teacher or student impacts. While the framework provides a rich conceptual foundation for assessing AI knowledge, it does not directly capture how the AI PD affects other outcomes such as teacher motivation, self-efficacy, or student achievement. Future empirical work should explore whether i-TPACK in teachers' growth correlates with these broader indicators to build a more comprehensive understanding of the model's long-term effects.

Despite strong alignment with i-TPACK domains, translating AI PD into sustained classroom practice remains challenging due to a range of contextual barriers [84]. Even the most thoughtfully designed AI PD programs may falter when confronted with practical constraints such as limited instructional time, rigid curriculum pacing, and reduced teacher autonomy. Institutional resistance or lack of systemic buy-in can also undermine teachers' ability to meaningfully apply what they've learned. Cost-related challenges, including subscription fees for AI tools, licensing issues, and hardware requirements, are frequently overlooked in the literature but pose significant equity concerns, particularly for under-resourced schools and districts. Moreover, the success of i-TPACK-based PD is highly dependent on contextual alignment, leadership support, coherent school and district policies, and technological infrastructure. All shapes how effectively teachers can implement new

strategies. Unfortunately, these enabling conditions are often treated as peripheral rather than integral to AI PD design, leaving a critical disconnect between learning and practice.

Another challenge related to AI PD design and delivery is related to the lack of research in AI ethics. Two cells in the framework (AI Ethics x Coaching & Expert Support and AI Ethics x Feedback & Reflection) contained fewer cited studies compared to other areas. This gap likely reflects both the limited emphasis on AI ethics within existing AI PD research and the broader uncertainty surrounding how to effectively teach and engage educators in ethical dimensions of AI-based tools. Future research should investigate evidence-based methods for fostering ethical awareness of AI-based tools and reflective dialogue in AI PD, helping educators critically navigate fairness, accountability, and bias in AI integration. Moreover, while the i-TPACK framework positions AI ethics as a foundational domain, its full implementation may require time, sustained commitment, consistent reinforcement (facilitation), and access to knowledgeable experts [2,27]. Meaningful ethical AI integration cannot be confined to isolated sessions or surface-level discussions. Previous studies showed that AI ethics is a predictor of AI TCK, AI TPK, and AI TPACK [23]. Therefore, it must be woven into the fabric of teachers' ongoing learning journeys, with dedicated space for reflection, practical dilemmas, and dialogic inquiry. This is particularly challenging in time-constrained or rigid AI PD formats, where AI ethics is often treated as an optional add-on rather than a critical component. Moreover, when designing i-TPACK-based PD programs, ethical AI considerations must be embedded from the outset (since data governance, privacy, and bias are important ethical issues [27]). As teachers work with student data, evaluate AI-generated feedback, or analyze instructional examples, AI ethics should guide their decisions and reflections [85,86]. PD designers should therefore intentionally integrate transparency, fairness, and accountability into every stage of teacher learning, not as an add-on, but as a lens for responsible practice. Ultimately, the success of the i-TPACK-based PD framework depends in part on how well ethical awareness of AI is cultivated not only during training sessions, but also in the everyday realities of classroom AI use.

One of the most research-related challenges in i-TPACK-based PD is evaluating teacher learning across complex and interconnected knowledge domains. While self-report instruments, such as the validated i-TPACK survey by Celik [16], offer a cost-effective and scalable method to gauge teachers' perceived growth, they are not without limitations. These tools are best suited for identifying general shifts in understanding and can be employed in pre- and post-test, or longitudinal tracking formats throughout a school year to observe developmental trends over time. However, they cannot establish causal effects or reliably capture how teachers enact i-TPACK in real classroom settings. To address these limitations, researchers must go beyond perception data and adopt multi-modal assessment strategies [87]. There is a growing need for performance-based tools (e.g., lesson plan analyses, case or scenario-based teaching tasks, video reflections, peer feedback cycles, and teaching portfolios) that provide richer, more authentic insights into how i-TPACK domains translate into practice (e.g., teacher-designed activity analysis [84]). Observational protocols and classroom artifacts, particularly when focused on areas such as ethical decision-making or the adaptive use of AI tools, can provide more actionable data on implementation fidelity and pedagogical depth. Yet, such tools are still underdeveloped, expensive to use, or inconsistently applied in the current literature, leaving a gap for future work to refine measurement frameworks that align with the goals of i-TPACK-based PD.

6. Conclusion

As AI continues to reshape educational landscapes, supporting teachers in this transition is not just a technical challenge; it is a pedagogical and ethical imperative. Teachers must be equipped not only to understand how AI works, but also to engage with it critically and

responsibly in diverse classroom contexts. This study argues that current AI PD efforts often fall short because they lack sustained engagement, feedback, support mechanisms, and an ethical foundation of AI. By aligning the AI PD landscape with the i-TPACK framework, this study presents a structure that recognizes the multiple domains of teacher knowledge needed for meaningful AI integration. The integration of i-TPACK into AI PD design offers a timely and strategic pathway forward.

Notes

*In this study, the definition of AI PD by Dogan et al. [5] is embraced. "It refers to PD programs that incorporate AI as the primary content focus (learning about AI itself) and/or AI-based tools and their applications to enhance pedagogy or subject-specific content of teachers" (p 5).

¹While some AI PD programs include recorded expert demonstrations or curated video examples of AI use, live modeling, where an expert demonstrates best practices in real-time while teachers observe and engage simultaneously, has not been prominently featured in the AI PD literature due to limited empirical evidence. Therefore, this review does not elaborate on live modeling as a standalone element within the current framework.

²We do not draw strict distinctions between coaching, mentoring, and expert support. Our emphasis is on ensuring that teachers have access to sustained and responsive support mechanisms, regardless of format or expertise, that facilitate teachers' professional learning, pedagogical decision-making, and confidence in using AI tools effectively.

³This mapping process was driven by the recognition that effective AI PD should not treat knowledge domains and learning pathways as isolated elements but as mutually reinforcing components of a cohesive learning experience. Drawing on insights from education technology for teacher learning [41–44], effective PD literature [18–20,39,40,88], TPACK-based PD work [68–72], and AI PD-specific studies [9–11,14,47, 89–91], each i-TPACK domain was analyzed for its alignment with AI PD activities that promote meaningful teacher engagement and application.

⁴The fictional scenario was co-designed using ChatGPT 4o and the i-TPACK and integrated pathways frameworks presented in this paper. While ChatGPT contributed to shaping the structure and examples, the scenario reflects intentional, pedagogically grounded choices made by the human authors. The goal is to illustrate how this framework can inform authentic, meaningful, and research-aligned professional development experiences for teachers.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors utilized ChatGPT-4o (OpenAI) and Consensus AI to help organize human-generated notes during the manuscript drafting process. Grammarly was used for language editing and proofreading, while Napkin was utilized to aid in the creation of conceptual visuals. After using these tools, the authors carefully reviewed, edited, and revised all content to ensure accuracy and quality, and took full responsibility for the final content of the published article.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Selçuk Dogan: Writing – review & editing, Writing – original draft, Visualization, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

I have previously collaborated with the editor of this special issue on a few research manuscripts (Ismail Celik). However, I did not have any involvement in the editorial process, peer review, or decision-making related to our collaborative work before.

If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Thank you, Umran Y. Nalbantoglu, for her support in revising this manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.caeo.2026.100337](https://doi.org/10.1016/j.caeo.2026.100337).

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